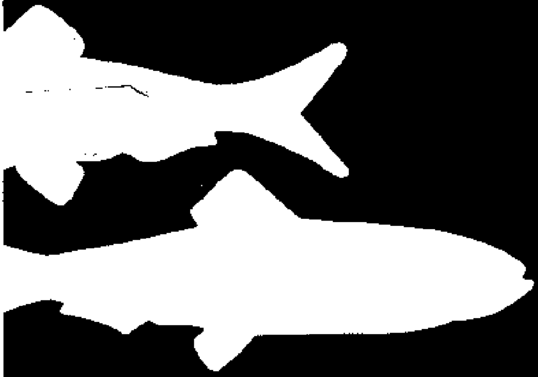
Lowell
Wakefield
Fisheries
Symposium

Proceedings of the International Herring Symposium

Anchorage, Alaska USA
October 23-25, 1990



Alaska Sea Grant
College Program

Report No. 91-01
1991

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Alaska Sea Grant College Program
University of Alaska Fairbanks
138 Irving II
Fairbanks, Alaska 99775-5040
(907) 474-7086

AK-SG-91-01
1991
Price: $14.00

Elmer E. Rasmuson Library Cataloging-in-Publication Data.

International Herring Symposium (1990 : Anchorage, Alaska)
Proceedings of the International Herring Symposium, Anchorage, Alaska USA, October 23–25, 1990.

(AK-SG-91-01)
(Lowell Wakefield fisheries symposium ; [9th])

1. Herring—Congresses. 2. Fishes—Alaska—Congresses. I. Alaska Sea Grant College Program. II. Title. III. Series: Alaska Sea Grant report ; no. 91-01. IV. Series: Lowell Wakefield fisheries symposium series ; [9th].

QL638.C64I58 1990

About This Publication

The International Herring Symposium is ninth in the series of Lowell Wakefield fisheries symposia. The symposium was coordinated by Brenda Melteff of the University of Alaska Sea Grant College Program. Members of the program planning committee are: Jeremy Collie and Doug Coughenower, University of Alaska Fairbanks; Fritz Funk, Alaska Department of Fish and Game; Erlend Moksness, Institute of Marine Research, Bergen, Norway; Max Stocker, Department of Fisheries and Oceans Canada; Hal Weeks, North Pacific Fishery Management Council; and Vidar Wespestad, National Marine Fisheries Service.

Symposium sponsors are: Alaska Department of Fish and Game; Arctic Alaska Fisheries Corporation; National Marine Fisheries Service; North Pacific Fishery Management Council; and University of Alaska Fairbanks, Alaska Sea Grant College Program and Marine Advisory Program.

Most of the papers in this book were provided camera-ready by the authors. Sue Keller and Lisa Sporleder compiled the proceedings. The workshop was recorded and transcribed by Gemini Reporting Services and edited by Vidar Wespestad, Jeremy Collie, and Elizabeth Collie. Karen Lundquist designed the cover and title page.

This book was produced by the Alaska Sea Grant College Program, which is cooperatively supported by the U.S. Department of Commerce, NOAA Office of Sea Grant and Extramural Programs, under grant no. NA90AA-D-SG066, project A/75-01; and by the University of Alaska Fairbanks with funds appropriated by the state. The University of Alaska is an affirmative action/equal opportunity employer and educational institution. This book is printed on recycled paper.

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Symposium Summary

The International Herring Symposium dealt with several aspects related to fisheries biology and management of the two species of herring, *Clupea harengus pallasi* and *Clupea harengus harengus*. Both species have supported commercial fisheries for centuries, and have an important place in the history of fisheries science. In Europe the research started in the second half of the last century, in North America somewhat later. Herring have played an important role for people living along the coast, both in Europe and North America. The introductory lecture given at the symposium clearly showed the importance of herring to the Native people in Alaska and how they utilize the resource without overfishing the stock. However, throughout this century, and especially during its second half, there has been a gradual increase in the fishing pressure on herring stocks, both in the Atlantic and in the Pacific oceans.

Since the 1950s several stocks have been heavily overexploited, and some of them collapsed or were seriously depleted. The most important overfishing started in the northeast Atlantic with the introduction of the ringnet/powerblock technique in combination with sophisticated acoustic devices for detecting the stocks. Parallel to this the trawling technique also became more efficient.

During the last 20 years the management has been directed toward rebuilding overfished and depleted stocks and developing strategies to prevent overfishing of healthy stocks. Some stocks recovered almost to former levels of abundance, whereas others have remained low, e.g., the Norwegian spring spawning herring as well as the Icelandic spring spawners.

In recent years there has been an increasing interest in the international scientific community to study problems related to management of fish stocks. More data have been provided, and new techniques been developed, to keep the fishery at a reasonable level in accordance with the stock size.

This must be taken as evidence that scientists look at this issue as a great challenge and are eager to obtain better knowledge of the biology of herring and to develop new management systems suitable for regulation of the fisheries.

To explore the substantial new developments in population regulation and stock structure, to consider harvest policy evaluation, and to report important biological aspects concerning early life history of herring, the symposium invited papers in the following topics:

- Early life history, migration, and transport
- Population biology
- Stock assessment and methodology
- Population dynamics
- Management
- Human uses and impact on herring

Early Life History and Population Biology

Within these two topics 12 papers were presented. A substantial amount of work has been carried out during the last years concerning early life history of fish, including herring. At the present symposium the papers mainly concentrated on:

- Spawning/egg deposition
- Drift, migration, distribution, and retention
- Otolith studies

The incubation period is a critical stage during early life history of herring. Egg loss in herring spawns with time was reported from studies carried out in southern British Columbia. Total egg loss was found to be about 60%, of which 3% could be ascribed to birds and 4% to invertebrates. The rest was difficult to account for. This is a rather high loss compared to some results reported in the northeast Atlantic, although similar high loss rates have been observed.

Six papers dealt with drift migration and dispersion of newly hatched larvae from the West Coast and two from the East Coast of North America.

Most of the spawning sites in the west are located in shallow waters close to the shore and in the fjords, and the larvae therefore are distributed near shore. As a consequence the newly hatched larvae will not be transported into open offshore areas by the current system. On the East Coast spawning is taking place in more exposed and open areas. However, here the drift migration and distribution patterns are more restricted than in the northeast Atlantic (North Sea, Norwegian offshore areas and Icelandic waters), where the larvae are transported long distances (several hundred nautical miles) by the great current systems in the region. The different environmental conditions (physical and biological) can explain why the distribution pattern during the early stages of herring vary in the three regions. Both at the West and East Coasts of North America retention mechanisms are more frequent than in the northeast Atlantic.

Two papers dealing with biological information obtained from otolith studies were presented. The paper from the Norwegian coast tried to estimate the hatching curve from daily otolith increments and relate these results to field observations. The technique gave some promising results and should be developed further. The paper by Radtke was a basic study on structure and composition of the otoliths and how information is stored on a chronological basis. The study is fundamental and can elucidate the details of the ecological history of the fish and represents technological advance.

Stock Assessment and Methodology

Four of the papers in this session dealt with acoustic methods applied to Pacific and northwest Atlantic herring. In both areas the history of herring acoustic surveys is rather short. So far, the work has been performed along two lines: Technical development and echo integration survey.

The acoustic technique has proved to be useful in abundance estimates of herring. However, there are reasons to consider the best time/place for applying the technique; whether the herring is on the spawning grounds, in feeding areas, in the migration phase, or in a wintering situation. To apply this technique, knowledge of the target strength is essential. As a consequence, the papers dealt with factors having influence on the target strength, e.g. density versus depth, swimbladder size, fish size, day/night recording, frequency, etc. Nevertheless, it still seems necessary to carry out fishing experiments to identify the composition of the scatterers.

Stock identification is another important topic in relation to management. A number of different techniques have been used to establish the stock structure of herring. Analyses based on morphometric and meristic characters, supported by information on spawning areas, distribution patterns, tagging data, and frequency of occurrence of parasites have shown a great complexity in population structure. The techniques applied to separate herring stocks in the North Atlantic into management units are largely based on stock structure derived from morphometric and meristic studies. Herring from different management units are frequently harvested in nonreproductive areas where they mix. This makes the allocation of catches to the various management units difficult. Methods to separate catches of mixed origin are therefore needed.

Multivariate analysis of morphometric and meristic characters is suggested to have promising value as a diagnostic tool for identification of the stock structure of herring. Successful application of the method was demonstrated for adult herring in the North Sea, Skagerrak-Kattegat, and the Baltic. Application to mixed aggregations of juvenile herring is, however, more complicated. But this work is in progress. Similar techniques were also used to demonstrate segregation by age of herring schools during the summer feeding migration in the eastern Bering Sea. Parasites as biological tags is also suggested to be a useful method for identification of spawning stocks.

For application of morphometric methods in future management of herring stocks, more effort should be given to evaluation of the temporal stability of the characters. Although morphometric and meristic characters may be modified by environmental factors, reproductive isolation is indicated if the characters show temporally stable differences between spawning groups.

Population Dynamics and Management

Population dynamic studies form the basis for managing fish stocks. Papers on population dynamics of the North Sea herring, different stocks at the West Coast of North America, and herring from the Gulf of Maine were presented. The reports concentrated on problems associated with assessing recruitment and stock biomass as well as factors affecting variation in these parameters. The speeches illustrated the complexity of this issue.

To carry out proper management one needs reliable catch statistics and good series of biological data from the populations dealt with. In the northeast Atlantic long series of data from two large groups of herring exist, Atlanto-Scandian herring and North Sea herring. Fairly good observations are also available from the other regions.

At the symposium the history of the fishery management regime (type of data and methods used) of the North Sea herring was presented. The report showed that the herring have been reasonably well managed since the stock was depleted in the late 60s and early 70s. At present there seems to be fairly good agreement between the advice given by scientists and the total allowable catch.

There is still an important bycatch problem to be solved in the North Sea fishery, a problem also met with in other areas, e.g. in the Bering Sea. However, in the fishery for Atlanto-Scandian herring, no mixing with other species takes place.

The management of the North Sea herring fishery is based on several types of information. The catch quota recommended by scientists is derived from material based on catch statistics, direct observations obtained from young fish and acoustic surveys, and from models suitable for managing the fishery.

Since herring in the Pacific region are distributed in many stock units, they must be separately managed. In addition the present fishery is mainly a sac roe fishery which also complicates the regulations. Unlike the Atlantic herring fishery—which exploits herring all year round—the Pacific herring fishery mainly targets the spawning stocks. Management in the west is based on aerial surveys, dive surveys, and acoustic measurements at the spawning sites. As pointed out at the meeting, more efficient management is also possible by utilizing catch data.

Human Uses and Impact on Herring

Human activity may have influence on herring stocks in many ways. The preservation of established herring spawning areas is important to maintain abundant stocks. If spawning areas are removed, it will also have direct economic consequences. Another threat to herring stocks is of course overfishing and incidental fishing mortality in purse seining.

As oil and gas exploration have developed in Alaska, the most vulnerable period seems to be the early life stages which extend from May through August, when eggs and larvae are mainly found in surface nearshore waters in Alaska.

Oil spill effects simulation studies suggest that the risk for offshore fish resources (including pelagic eggs and larvae) is minimal. However, a shipwreck oil spill in the Gulf of Finland showed effects on herring, especially larvae.

O. Dragesund and P.T. Hognestad

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

The North Sea Herring Fishery: An Abrogation of Management

A.C. Burd (retired)
Fisheries Laboratory
Lowestoft
Suffolk, UK

ABSTRACT

The paper describes the international fishery management regime in the Northeast Atlantic. From its inception in 1946, the International Fisheries Convention was focussed on the problems of the demersal fisheries. As its initial task it aimed at preserving the stocks of fish in the North Sea and other areas which had recovered from the low abundances of pre-World War years. It sought to introduce minimum mesh sizes for trawls and other towed gears which would conserve juvenile fishes. To assist in the enforcement of such a regulation, minimum landing sizes were specified for the most important species. The species for which minimum sizes were prescribed became known as the Protected Species. Implicitly, no other species required conservation and this included the herring. Though by 1955 an extensive trawl fishery for both adult and juvenile herring had developed the only regulation concerning the pelagic species lay in the limitation of the by-catches of under-sized protected species. The possibility that herring might need conservation had never been considered in the drafting of the Convention.

With the collapse of the southern North Sea herring fishery after 1955, repeated pleas for conservation action were turned down as not being within the terms of reference of the Permanent Commission. The Articles of the new North-east Atlantic Fisheries Commission (NEAFC) followed those of its predecessor and in 1964 found it necessary to pass a resolution to examine under what powers it could act in conserving the herring stocks. By 1971 only 7 out of the 14 governments had taken steps to activate a provision to institute regulation of catch and effort. By the time ratification was complete it was too late to take any

effective action. With UK's and Norway's extension of the limits of fisheries jurisdiction following UNLOSC and UK's accession to the European Community the regulation of the fisheries passed to the European Commission in consultation with Norway. A ban on herring fishing was imposed in February 1977. Total Allowable Catches (TAC) are based on the recommendations from ICES modified in consultation with Norway who as a riparian state has management responibilities for shared stocks. These negotiations result in a agreed total package for all species and the final individual TACs may be very different from the conservative advice of ICES. The lessons of the past have not been learned and gross overfishing of the agreed TACs and lack of enforcement are currently leading to a further collapse of the North Sea herring stock.

1. INTRODUCTION

In considering the history of herring management in the North-east Atlantic area it is useful to briefly review the way the management bodies evolved. In 1902 at the setting up of the International Council for the Exploration of the Sea three activities were selected for its immediate attention, namely: hydrography, fish migration and overfishing. The two latter areas of study were specifically related to herring and plaice.

At that time, concern was being expressed over the large quantities of small plaice discarded. In 1913, a proposal was made to close the small plaice grounds of the continental coast. This would allow the small fish to put on weight as they migrated into deeper water and so become more valuable. This established a policy for the conservation of the demersal stocks and the maximization of the yield from their growth potential was the management principle behind the proposals of the unratified, 1937 Convention and its successor, the International Fisheries Convention of 1946.

In contrast, the investigations on herring were directed at describing the "racial" structures of the populations. Studies were initiated on the identification of the spawning grounds of the various stocks and the migration routes. The growth increments on the scales of the herring were established as annual; growth curves could be calculated for individual herrings and their patterns were utilized as a method of racial analysis, (Lea, 1929). The population structures by age of the various herring populations were studied with particular emphasis placed on the occurance of good and bad year-classes. It was apparent that in the Atlanto-scandian stock, one good year class could sustain the fishery for, at least, a decade. The success or failure of the fishery was considered as dependent upon natural causes, which could effect recruitment or migration. Changes in the latter were believed to be the causes of the Norwegian/Swedish herring periods.

The herring fishery was dominated by the use of drift nets and its outlets lay in the cured herring trade. This required mature herring with a moderate level of fat content and careful handling of the fishes. In the nineteen thirties as part of a programme to upgrade the quality of the cured herring the British Government set up the Herring Industry Board and it introduced a regulation banning the use of small meshed drift nets. This was directed at a juvenile fishery off the English north east coast but was purely a marketing aid and not a conservation measure.

At the turn of the century, steam trawlers conducted a short-lived herring fishery off the estuary of the River Humber but the quality of the fish landed was so poor that there was little or no market demand. Fishermen disapproved of such trawling as they felt it was wrong to disturb herring when they were on the spawning ground. However, in the late nineteen thirties a major herring trawling development took place in the central North Sea. This time, a market existed for the spawning and spent herring, particularly in Germany. The main international criticism of these trawl fisheries lay in the use of the small meshed herring trawls which also took demersal fishes (including quantities of under-sized demersal fish which were supposed to be conserved under the minimum white-fish trawl mesh proposals). Thus, there was no comparable concern for conservation of the herring stocks as for the demersal species.

Those scientists working with the demersal fisheries were aware of the overfishing problem and were introducing statistical methods for analysing their data and developing mathematical models to study the dynamics of the populations, Graham(1935). In contrast, the herring biologists were more concerned with descriptive biology of the herring populations. The annual variation in the age structures of the herring catches were described in percentage numbers rather than absolute numbers. However, in this field the most significant advance was the introduction by Hodgson of stratified age/length sampling and the extensive use of sampling for length composition of the catches of herring on the fish market.This enabled Hodgson to describe the serial changes in the age composition of the catches during the fishing seasons, to estimate annual instantaneous mortalities from the abundance indices in catches per unit effort per age. In East Anglia he forecast the timing of the peak catches and the probable catch rates in advance of the commencement of the herring season, (Hodgson,1939).

In March 1946,an International Conference met at the invitation of the UK Government to discuss the question of overfishing in the North Sea and, if possible, to draw up some form of regulatory agreement. The Conference based its proposals on those of the unratified 1937 Convention including specifying minimum mesh sizes and landing sizes for demersal fish, but in addition it recognised the need for international control of fishing effort. UK had proposed that Governments should agree to limit their fishing power to 75% of the pre-war figures or adopt some equivalent limitation. The Conference could not support such a blanket regulation. It did recommend, however, that each

Government should try to ensure that the size of its fishing fleet should be stabilized at its 1946 level or that of 1938, whichever was greater. A number of countries offered to adopt a number of interim measures for 1948 and 1949, until the proposals could be ratified. This was expected to be completed in two or three years but the last ratification was given in February 1953. By that time the opportunity was lost to control the growth of the post-war fishing fleets and with it the willingness to accept effort limitation.

At its first meeting in May 1953, the Permanent Commission of the International Fisheries Convention faced the need to arrest the renewed decline of the stocks, (Anon., 1953a). Even the mandate of the Commission was in question. Six of the twelve members held that it had general powers to discuss conservation measures , but, the four Scandinavian countries maintained that it was only empowered to consider regulation of mesh size and size limits. A second meeting was held in November 1953, (Anon, 1953b), when further discussions took place on the forms of the proposed regulations. Since 1946 there had been a major expansion of trawling for herring. This took two forms, the fishery for adult herring on and near the spawning grounds and the newly developing fishery for juveniles for reduction to fish meal and oil-the so-called industrial fishery. Article 6 of the Convention, as it was first drafted, limited the use of small meshed nets to the fisheries for mackerel and clupeoid fish, smelts, eels, great weevers and those for crustaceans and molluscs, with the requirement that any undersized fish should be discarded and returned to the sea In 1955 sandeels and norway pout were added to the list of species in Article 6. The whitefish fishermen were concerned that by-catches of legal sized whitefish could be taken by the herring trawl fisheries and could unfairly compete with them on the market. They held that some limitation should be placed on the quantity of by-catch landed. Denmark proposed that when fishing for herring and sprat up to 20% of the total catch in weight could be comprised of undersized whiting which was only to be used for animal feed or reduction to meal and oil. This new facet to the discussion was to lead to the polarization of the national fishing industries between those fishing for human consumption and those operating industrial fisheries for meal and oil.

In these formative days of the Convention, there had been the establishment of three separate groups of fish, those for which minimum sizes were prescribed which became known as the "Protected" species, those listed in Article 6 for which no conservation measures were described and a third " no man's land" of all the other fish species, such as saithe, gurnards, John Dory etc. which were not named in either Convention list. Subconsciously, politicians, administrators, many of the fishing industry and some scientists equated the concept of Conservation only with the 'protected' species. As far as the fisheries for Article 6 species were concerned, the administrators' sole interest was in preventing activities in those fisheries which might have a deleterious effect on the potential catch of the protected species. No recognition was made in the Convention's regulations or those incorporated in the Articles of the new

Northeast Atlantic Fisheries Commission that the 'unprotected' species might need conservation action in their own right. It was against this background that the attempts at obtaining conservation action for the North Sea and other herring stocks was started in 1957.

2. THE CONFLICTS FOR MANAGEMENT.

The collapses of the Northeast Atlantic herring stocks have been comprehensively reviewed by Burd, (1974, 1978, 1985), Jakobsson, (1985), and Saville and Bailey, (1980). Both the administrators and the scientific community were ill prepared in general to deal with a situation which required rapid decision making. Nor was it receptive to the idea that such an abundant species could possibly be subject to overfishing. Above all, neither the managers nor the scientists could respond to the rapid changes in activities by the fishermen. Indeed, throughout the past half century scientists and administrators have had to formulate their advice and decisions on scenarios of fleet operations from which the fishermen had already progressed. Some of the developments could not have been anticipated, being generated from events originally unconnected with the North Sea herring fisheries. Others, such as the developments in echo sounding and sonar and in mid water trawls and purse seines led to a complete changes in the exploitation pattern of the herring stocks. When in the stock-recovery situation scientists were having to make projections of the likely rates of recovery, their interpretations of the possible responses had to be based on the historic records which often refered to a very different exploitation pattern.

It is convenient to consider the recent history of the fishery in five distinct phases. Each of these introduced new elements in the exploitation and in the scientific data requirements. For each of the phases I shall draw attention to the scientific dilemmas encountered, the effectiveness of the research programmes developed and any administrative actions generated. The phases are:

1. The collapse of the Downs stock.
2. The development of the pelagic trawl.
3. The prerecruit purse seine fishery and recruitment failure.
4. The recovery of the stocks.
5. Current management.

2. 1. The Collapse of The Downs Stock.

High priority was given to the re-establishment of both the herring and whitefish fisheries in the immediate post-war reconstruction period. The herring catches quickly reached the levels of pre-war years. For the drifters, the main markets remained the cured herring trade and in Germany, margarine production based on herring oils provided an outlet for trawled herring. There was unlimited demand for whitefish. Particular stress was laid in investment in large distant water trawlers particularly by western Germany and UK. to take advantage of the recovered Arctic cod and haddock stocks. But by 1953 UK was expressing concern at the rates of decline of the fish stocks at Iceland and it was not long before discussions on conservation of the north east Arctic became a regular feature of NEAFC. With seasonally low catch rates in distant waters in summer, the Arctic demersal trawlers developed a fishery for spawning herring in August and September in the central North Sea. Later, the spawning grounds of the Downs stock. were to attract trawlers from most countries. Thus, additional to the effort of the already re-established herring fleets, a new fleet of powerful and specialist trawlers was suddenly imposed on the herring stocks concentrating its effort on the vulnerable spawning herring shoals.

The traditional East Anglian drift net fishery commenced in early October in the vicinity of the north Norfolk Banks and a continuous stream of migrating Downs herring maintained a fishery up to Christmas. The three and four year old herring arrived first, to be followed by the older fish in November and later. Due to the nature of the bottom topography of the Southern Bight the herring were funneled towards the Straits of Dover. While in the last stages of maturation of their spawning products, they aggregated for some time off the Flemish Banks. Some would spawn nearby and others would rapidly move through the Straits into the Eastern Channel spawning as far west as Dieppe, Figure 1.. The first major spawning took place in the channel between the Sandettié and Outer Ruytigen Banks, off Calais, at the end of November, when both old and young were present in the shoals. The intensity of this fishery can be judged when it is recalled that commonly 250 Arctic trawlers towed through the channel in line astern during the short winter days. The spawning itself took place on a flint and gravel bed, 3 200m long and only 300-350m wide, Bolster & Bridger, (1957). Bridger, (1961) recorded that any large shoals of ripe fish in the Sandettié-Ruytingen channel were broken up and dispersed by the trawler fleet within two to three hours of their arrival. Even when the bottom trawl catches were low, large quantities of spawn were brought up and destroyed. By 1953 the trawl catch from these grounds had reached 156kt., taken in about an eight week period. It was with alarm that the driftermen saw their catches of old fish in November decrease sharply, their average catches per effort fell by 50% between 1949 and 1952 and by a further 50% between 1952 and 1958. Until 1954, the October catches which consisted of recruit herring, maintained their post-war average but from 1955-1958 these too were reduced by 50%. The drifter catches per unit effort showed the classic symptoms of overfishing in a demersal stock with a rapid decline in abundance and increase in instantaneous mortality of the older fish.

Those countries concerned with the Downs fishery expressed concern at the rapid decline in the yields and approached the Permanent Commission to take action to halt the decline. The Commission considered itself unable to comment on the conservation needs for the Downs stock. It encouraged ICES to support cooperative research programmes, in particular, tagging programmes aimed at making direct estimates of fishing mortality

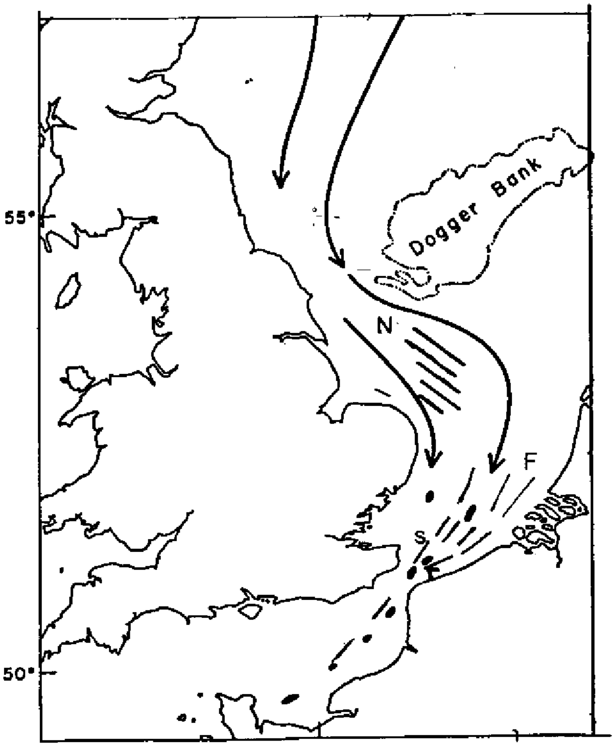


Figure 1. Spawning route of Downs herring.
N: Norfolk Banks
F: Flemish Banks

Spawning grounds indicated:
s: Sandettie Bank.
r: Outer Ruytingen Bank.

in the spawning fishery and in the newly commenced juvenile fishery on the Bløden ground. Ancellin and Nédélec(1959) estimated the fishing rate on the Sandettie spawning grounds at 1.2% per day. Over a 17 day spawning fishery following tagging, Cushing and Bridger(1966) calculated that the fishing mortality generated was of the order of 50%. This was comparable with that derived from drift-net catch per unit effort data. Fishery independent sources of stock size were also sought and in 1955 internationally coordinated larval surveys were commenced. In 1956 acoustic survsys were undertaken by England over the East Anglian area, partly, to provide more searching power for the diminishing fleet of drifters and, partly, to obtain independent estimates of abundance.

In 1957-8 the catch of the French trawl fishery on the spawning grounds had declined to about 8 kt from an average of over 20kt. in 1951-1955. Between 1955 and 1957 the mean catch per unit effort had halved, Maucorps (1964). In 1957, the Netherlands proposed that the Permanent Commission should invite the ICES Liaison Committee to advise on arresting the decrease of the herring catches in the southern North Sea and Channel. However, the Commission again considered that the proposal was outside its terms of reference, Anon.(1958). In May 1960, the fishing industry members of the French delegation to the Permanent Commission meeting again pressed for ICES to investigate the causes of the decline but, the response was similar to that three years earlier, Anon.(1961). Although there was an underlying concern about the overfishing of the Downs stock, each nation's fishermen sought that the attribution of blame should be directed at any activity in which they themselves did not indulge. Thus much vehemence was expressed over the Danish Bløden fishery for juvenile herring, mainly from the moral standpoint that it was wrong to catch juveniles and to reduce them to meal and oil. Few of these fishermen and their supporters accepted the results the ICES tagging experiments in 1957 and 1958 which estimated the fishing rate on the juvenile stock of the whole North Sea at 15-20%. At that time the autumn Bløden fishery took 70kt. This fishing mortality alone could not account for the observed decrease in the adult Downs stock. As a follow-up of the tagging experiment, annual cooperative trawl surveys for young herring were set up with the objective of obtaining estimates of the incoming recruit classes and if possible to identify the areas of distribution and abundance of the individual stocks of Bank, Downs and Buchan recruits in the nursery areas. Because of the interannual variablity of meristic characters it was found that identification of the juveniles had to be made retrospectively once they had recruited to the adult stock. Discriminant function analysis was successfully used, Andersen et al(1969). This also indicated for the first time the presence in the northeastern North Sea.of juvenile fishes from west of Scotland spawnings. This was confirmed from a later Bløden tagging experiment.

The idea that herring could be overfished was foreign to those fisheries biologists with knowledge of the Atlanto-scandian herring. It was then generally accepted that the great fluctuations in yields and in year class strengths were associated with natural causes. The commencement of the Bløden fishery coincided with the increase in growth rate of the North Sea herring which led to an advancement in the age of first recruitment by about half a year. Planktologists had also noted changes in distribution and abundance of certain plankton organisms, Glover(1957). Thus, environmental change was also cited as an explanation for the loss of Downs stock. Krefft, Schubert and Sahrhage(1955) interpreted its effect as a differential northward shift of the three populations, with Downs herring becoming Bank spawners and Bank becoming Buchan spawners. No convincing evidence could be produced to support this hypothesis. All evidence indicated that differences at recruitment between Bank, Downs and Buchan stocks in their meristic and growth characters were maintained until a year class's extinction.

Only in 1963 did the Permanent Commission accede to a further French memorandum and it was agreed that ICES would report on the situation at the meeting of NEAFC in 1964, and a Herring Assessment Working group was set up. Anon.,(1964). By this time the Southern Bight and Channel fishery had virtually ceased to be commercially viable, and the drift net fishing was being abandoned in the North Sea.

2.2. The Development of The Pelagic Trawl.

The second phase in the over-exploitation of the North Sea stocks was engendered by the invention of the Süberkrub otter board and the perfecting of the design of the single boat mid water trawl by Herman Engels. No longer were trawlers confined to grounds whose bottoms did not damage their trawls. The trawl nets could be used as bottom skimming gear and in addition the prespawning mid-water aggregations could be hunted using acoustic gear, setting the nets at the optimal depth with headline transducers. The mid-water trawlermen became opportunistic fishers shifting from one area to another where the dense pre-spawning and spawning shoals aggregated. In other seasons of the year, they turned their attention to herring stocks outside the North Sea, to mackerel, horse mackerel and pilchards. Their economic viability lay in their ability to operate intensive short-time fisheries when catch rates were high. The biologists and fishery inspectors were slow to react to the advent of these new highly efficient and very mobile fishing units Many vessels processed the fish at sea and on landing could deliver fish caught in many sea areas (from the west of Ireland to the North Sea grounds). For the Inspectors there were the problems of allocating catches and fishing time to the different fishing grounds and for the biologists difficulties of obtaining herring samples which could be related with confidence to a particular area. At a time when there was need to monitor the rapid events in the fisheries the quality of the data fell to unacceptable levels. The ICES Herring Assessment Working Group in February, 1964, only had complete statistical data up to 1961 and the ICES Liaison Committee's report gave general advice on management based on yield per recruit criteria. At the NEAFC meeting which discussed the report in 1964, some delegates considered that the current demand for herring was such that conservation of the stocks could not be justified. Others considered that more rational exploitation was required (an anti-fish meal theme) and that fishing effort should be restricted on the spawning grounds and in the juvenile fishery. Over the next 5 years a dialogue ensued between NEAFC and ICES on methods to regulate the failed Downs herring fishery with a search for equality of sacrifice in any conservation action.

The southern North Sea fishery failed completely in 1966 and 1967 and even in the absence of fishing in the southern North Sea the mortality rates remained high. It was concluded that these levels must have been maintained from catches of Downs herring taken in the northern feeding areas. Interest was again focussed on the identification of Bank, Downs and Buchan fishes in the northern and central North Sea fisheries. Though increased herring catches were being taken from the north-eastern North Sea, after years of intensive exploitation no major fishery by German trawlers took place on the Dogger Bank spawning grounds. No newly hatched larvae were taken in October Dogger Bank surveys from 1967 to 1970. NEAFC recognised that discussion of conservation measures could no longer be restricted to the Downs stock, but that more widespread measures were required. and in 1966 it set up a Working Group to make conservation proposals, Anon., (1965). It called for further investment in research, particularly in relation to the juvenile fishery It, therefore, proposed an extended Bløden herring tagging programme which started in 1969 with the objective of estimating the fishing mortalities generated. The experiment was too late to provide the diagnostic statement which NEAFC desired, on the fishing mortalities and recruitment mechanisms of the different spawning populations. The failing recruitment in the North Sea limited the tagging both in number liberated and their locations. Important observations on the migration of immatures from the nursery areas in the eastern North Sea to the areas to the west of Shetland and the northwestern North Sea were obtained. The return of the metal internal tags depended upon the reduction of the herring catches to fish meal. The chances of recovering tagged fish from the pelagic trawl catches for human consumption were very low, so few recoveries came from the central and southern North Sea.

2.3. The Pre-recruit Purse-seine Fishery and Recruitment Failure.

Following the failure of the Norwegian coastal winter fishery for Atlanto-scandian herring, over 28 000t of autumn spawning herring were taken from the Skagerrak by 16 Norwegian purse seiners in the winter of 1963-64. The catches consisted of relatively old fishes and were taken from an area which had been recognised in earlier years as an overwintering area of recovering northern and central North Sea spawners. In the following years the timing and area of the fishery changed and was directed at the immature fish (20-24cm in length), about to join the spawning shoals for the first time. This was a totally new phase of exploitation in the life history of the herring. It led rapidly to the total collapse of the recruitment in the North Sea. The development of this Norwegian purse-seine fishery in the North Sea is given below.

Table 1. The Norwegian purse-seine fishery in the North Sea. (Haraldsvik, 1968; Anon., 1970)

Year	Number of boats	Total catch(tonnes)
1963	16	32 419
1964	195	189 668
1965	284	604 754
1966	334	454 900
1967	326	335 071

The ICES Liaison Committee's report for 1967 warned that biological sampling was too poor in this northern area to allow any assessment of the nature of the stock exploited and noted the escalation in fishing mortality in the central North Sea following the increase in trawling activity. It also recommended a total closure of the whole Downs fishing area from 53°N to 1°W in the Channel for 6 to 9 years. The sudden expansion of the fishery in the north-eastern North Sea and off Shetland, again led to the speculation that the changes in stock might not be induced by fishing but by natural changes in the distribution of the herring stocks and in recruitment survival in the northern areas. Parrish and Saville, (1967) made an extensive review of the whole problem but could find no evidence for an environmental cause or how it might have operated. The comments and recommendations of ICES found little favour within NEAFC. No proposals for any form of management were considered as delegates demanded that proof of the effects of fishing on the stock should be established and that the gains and losses from any management proposal should be statistically quantifiable, Anon(1966).

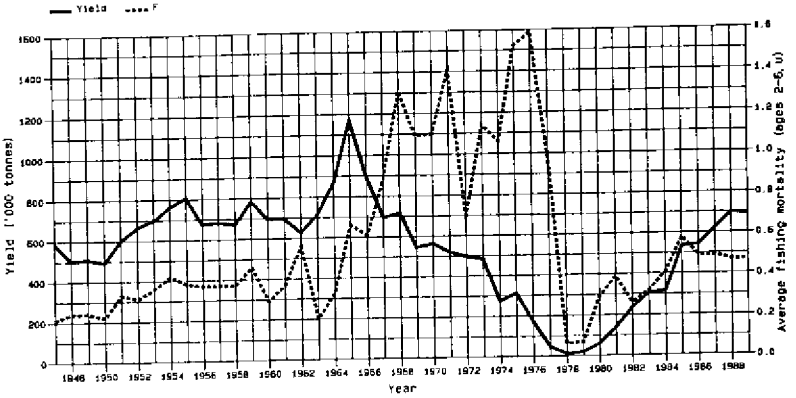
With the lack of progress on conservation action at an international level, in 1968, the UK government tried to come to an agreement with the Dutch and German governments to accept an experimental closure for five years of the Yorkshire coastal spawning grounds within the UK 12 mile limit. The discussions foundered on the problem of racial distinction of the Whitby spawners and on who might gain from the experiment. In 1970 a NEAFC Ad Hoc Study Report discussed possible actions such as a closure of various areas for the spawning period 20 August to 30 September. Its effect was recognised as below the 50% reduction in effort which ICES considered necessary. Most of the countries which would be affected by such a regulation asked for exemptions to meet special difficulties. Similarly, a proposed 22cm minimum size was considered as discriminatory against some fisheries and 'inequality of sacrifice' should be avoided, Anon(1970a). A Recommendation was finally agreed which prohibited fishing in May and from 20 August to 30 September in the North Sea and Skagerrak for the period 1 March 1971 to 28 February 1972 with various allowances. A 10% by catch by weight of each landing was allowed of herring caught when fishing for other species. This virtually left the juvenile fishery uncontrolled as many herring catches could be claimed to be by-catches and to distinguish between young herring and sprats in the 'soup' landed for fish meal was not a task relished by the fisheries inspectors. It is of little surprise that from this date the recorded sprat catches soared in both the North Sea and Skagerrak. Finally NEAFC proposed to take powers to activate Article 7(2)of the Convention which would institute measures for regulation of catch and effort and the allocation of quotas to contracting states., Anon., (1970b). Needing unanimous agreement for it to be operative only 7 of the 14 member countries had ratified Article 7(2) in 1971. As no progress could be made it was agreed to continue the regulations for 1971 into 1972. A special NEAFC meeting on herring in December 1971 recommended a prohibition on fishing for herring in the North Sea and Skagerrak for the period 1 February 1973 to 15 June 1973; the 10% by catch allowance was maintained. At a meeting of Ministers which was held immediately followed this meeting the discussions on the herring stocks was to a large extent overshadowed by the Icelandic announcement of its intention to extend its exclusive fishery limits to 50 miles. This signalled the start of a new era in fisheries management.

The final ratification was communicated in 1975 and by a unanimous decision, NEAFC banned industrial fishing for herring in the North Sea. The Liaison Committee later in 1975 recommended a total ban on all fishing for herring in the North Sea and a 20 cm minimum size, Anon. (1977). This was accepted by NEAFC but it adopted a TAC of 160kt for 1976. With the aim of supporting this TAC UK imposed a ban on all herring fishing from October to December within its limits, but despite this 175kt. was caught. Following the extention by UK and by Norway of their fishery limits under the UNLOSC formula and the accession of UK to the European Community a total ban on fishing for herring in the North Sea and eastern Channel was imposed in February 1977. The Commission and Norway became the joint management authority for the North Sea and Skagerrak fisheries.

2. 4. The Recovery of The Stocks.

During the final ten years of the collapsing North Sea fishery, it had become increasingly difficult to monitor the state of the individual stocks. This arose partly from the changes in fishing techniques which destroyed the long term series of data on catches per unit effort, partly due to the hit and miss nature of the biological sampling programmes which were not attuned to the new dynamic pelagic fisheries and partly from the unwillingness of the fishermen to provide information about their catches. This was particularly true of the Danish industrial fishermen. For them, herring was no longer the mainstay of their industry and they saw the proposed minimum size regulations as introducing restrictions which would penalize them in their legitimate fisheries for sand eel, Norway pout , and not least sprat. In 1971 the ICES Herring Assessment Working Group abandoned its previous methodology and, considering the North Sea stock as a single unit, subjected the catch at age data to Virtual Population Analysis. This has remained the method of monitoring the recovery and exploitation of the North Sea stock. Figure 2 summarizes the trends in spawning stock biomass, recruitment, yield and fishing mortality. The parlous state of the North Sea in 1977 is clearly seen. Catches from the Skagerrak have been excluded due to the difficulties with the unreliable catch data and the presence of unquantifiable numbers of herring of the Kattegat and Baltic stocks.

Trends in yield and fishing mortality (F)



Trends in spawning stock biomass (SSB)
and recruitment (R)

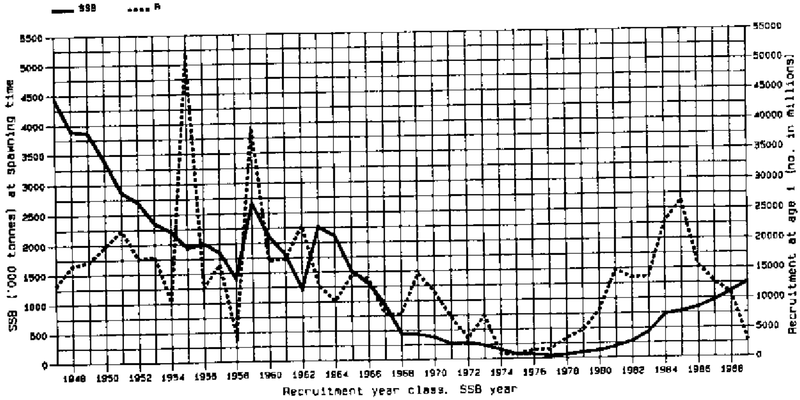


Figure 2. North Sea Herring Stock: VPA outputs.
Source: ACFM annual report for 1990.

During the period of low stock abundances a new factor came into play. This was the extraction of marine sands and gravels which were in demand for building construction. From geological marine surveys the gravel extractors identified the main spawning grounds around the Dogger Bank as prime targets. National governments controlled the allocation of dredging sites by licence, but surveillance of the dredging concessions themselves was difficult and much illegal extraction took place. Allied to this was the development of Rotterdam as a terminal for deep-draught supertankers, and other vessels. To allow these safely to enter the North Sea a dredged channel was required in the southern North Sea. The route chosen was through the Sandiettie-Ruytingen Channel, which had been the main area of the Downs spawning fishery. It is scarcely surprising that little larval production has since been observed in the Sandettie-Ruytingen area or in many of the historic Dogger Bank spawning sites.

ICES defined its primary conservation objective in 1975 as allowing the spawning stock biomass to reach an historic level which previously had ensured stable recruitment. In the absence of a fishery to efficently sample the age structure, the question arose as to how the recovery should be monitored. Recruitment as I group was estimated from the ICES International Young Herring survey. These research vessel catches per unit effort correlated with the stock estimates from VPA. The larval surveys gave independent indices of the size of the individual Bank, Downs and Buchan spawning stocks. Previously, it had been demonstrated that the larval stock indices could be correlated with catches per effort indices taken from the spawning fisheries. However, their combination in a single North Sea larval index to compare with the total population VPA was equivocal in view of differences in fecundity between the stocks, differences in timing of spawning and in possible survival. The Working Group was faced with the dilemma of having abandoned the attempts at monitoring individual stock fluctuations in favour of a North Sea unit approach only to find its material for assessing spawning stock size was by individual stocks. Attention was given to the possibility of partitioning the North Sea VPA to give estimates applicable to the individual stocks and, as a first approximation, this was based on the sub divisions, IVa, IVb, and IVc plus VIIde.

The management objective assumed the total North Sea population would respond as a single unit, however, very quickly a remarkable recovery took place in recruitment to the Downs stock alone. In 1979, an illegal catch of some 5 kt was taken from the Channel spawning grounds based on recruitment of the 1976 yearclass. The following year there was increased recruitment of the 1977 yearclass and combined with the survivors from the previous year an illegal catch of 39kt was taken out of a total North Sea adult catch of 45kt. By 1981 the European Commission (EC)could no longer hold back the demands from various industries that at least the southern North Sea and Channel should be reopened for fishing. Following advice from ICES, EC set a catch quota of 20kt to be taken between October 1981 and March 1982. In the event 42kt were taken resulting in a fishing mortality of 0.8 a value estimated at the start of the Downs collapse in 1955/6. 98kt was taken in the rest of the North Sea as by-catches. In

1982, the 1979 year class recruited to the northern stocks in much bigger numbers than expected, and with continuing increases in the Downs spawning stock biomass it appeared that.the 1983 North Sea spawning stock biomass would approach the target value. It became inevitable that the total North Sea fishery would re-open in that year despite the fact it had not reached the target recovery level. 308kt were caught in comparison with a recommended ICES TAC of 98kt and an EC TAC of 145kt. Thus the pattern of the eighties was set, with neither the national managers nor the Commission making much attempt to enforce the agreed allocations.

It was clear that the North Sea herring population was not responding as a single stock unit. The incipient recovery of the Downs stock had been missed in the larval surveys as a result of their design which concentrated on surveying in December and early January but ignored the production from the eastern Channel in late January and February. In the 1979 young herring survey, conducted in severe weather conditions was thought, to have underestimated the 1977 yearclass. The 1978 year class sampled in the following year had the same abundance as that of 1976 year class and in view of its small mean length and the very small otolith nuclei it was concluded that yet another good Downs recruitment was likely in 1981. This led to the opening of the fishery that year. Once again, research was directed at attempting to obtain indices of recruitment of the individual stocks. Wood(1983) showed that indices of 0-group Downs herring from the English coast correlated with 2-ringed recruits from the IVc VPA, and Burd and Hulme (1984) showed that both were correlated with the abundances of small fish in the Young Herring Surveys. The full potential for separation of juvenile recruitment using otolith measurements and typing as in the 1950s, or the use of meristic characters as in the discriminant function analysis of the 1960s has never fully been tested in the recovery situation.

Extensive acoustic surveys were made in the northwestern North Sea in association with a trial micro-wire tagging programme in 1983 and 1984. These acoustic surveys conducted in July/August have become a regular part of the age distribution monitoring programmes. They cover the distribution of the Bank and Buchan stocks, but it is doubtful whether coverage of the Downs component is adequate. Nevertheless, they have developed into a major feature in relation to the tuning of the VPA.

2.5. Current Management.

The ICES Herring Asseessment Working Group in 1980 had as one of its terms of reference a review of the biological criteria for re-opening the herring fisheries, Anon., (1980). A minimum spawning stock biomass had ben identified and the Working Group considerd that a very limited fishery should only be allowed before this goal had been reached if two basic criteria had been fulfilled: '<u>Firstly</u>, there should be <u>evidence</u> of a recovery of the spawning stock, and of improved recruitment. This means that, for example, a re-opening of the fishery should not be based only on expected increases in the spawning stock compared to an estimated level of a past year, and/or expected improved recruitment from an increasing spawning stock.....Secondly, the observed increases in spawning stock and recruitment should be of an order that ensures that the rebuilding to the defined goal will take place with a limited fishery operating.' The Working Group using these criteria could not recommend any fishery in 1980. It also reiterated the words of ACFM that the stock components might be recovering at different rates and as the level of recruitment to these components might differ, re-opening the total North Sea fishery might prevent one stock from recovering while another might remain lightly fished, depending on the distribution of fishing effort. The French and Dutch members of the Working Group could not agree with the management advice. They maintained that a small fishery would only prolong the period of below average recruitment and that the management objective of optimal stock size and the rate at which it should be acheived could not be based on biological criteria alone, but should take economic and social considerations into account.

With the extention of exclusive fishery limits by the member countries of EC and Norway, third countries were excluded from fishing except if they had special bilateral agreements. Between EC and Norway, agreements had to be reached on identification of those stocks which were subject to shared management and those regarded as entirely within the EEZ of either party,- the autonomous stocks. Under the Common Fisheries Policy,(CFP), an historic period dating from 1964 was chosen as the basis from which member countries shares of TACs were to be calculated. The choice of date negated the claims of those countries whose herring fisheries flourished prior to that date and recognised a major catch by Norway during the rapid decline of the stocks. EC accepted ICES as its independent source of advice on the biological management of fisheries through its Advisory Committee on Fisheries Management,(ACFM). It noted that ICES would not consider the inclusion of economic and social factors in the development of its advice on stock management. Within the Commission it set up a Scientific and Technical Committee on Fisheries, which consists of nominated scientists from member countries and gear technologists, and whose purpose is to comment on and interpret the ACFM advice in relation to the special needs of the member countries. This meant it could include the economic and social comment excluded by ICES. The Commission itself proposes the magnitude and the allocation of TACs between member countries of the autonomous stocks and acts as negotiator with Norway over shared stocks. Its proposals are discussed in internal management committees of EC, which unlike NEAFC, are conducted without industry observers. The final TACs which emerge from the negotiations may bear little resemblance to the initial proposals of ACFM having been bid up to facilitate negotiations on transfers of allocations from Norway and others countries. A comparison of recommended annual TACs, the agreed TACs and landings are given in Table 2. Examination of the record between the TACs and the annual catches is an indictment of the lack of enforcement to the agreed catch limits. The catches recorded here are those considered as most representative of the true catches and are those used for the calculation to the ACFM TACs. They include estimates of discards which particularly in the fishery for roe is an important part of the mortality generated.

Table 2. Recommended TACs, agreed TACs, estimated catch and spawning biomass thousand tonnes, (kt).

Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
ICES Divisions IVa,b.										
Recomm. TAC	0	0	62	95	166	235	600	500	484	373/332
Agreed TAC	-	-	72	-	-	500	560	500	484	385
Catch used	99	167	244	274	466	496	580	646	620	
ICES Divisions IVC,VIId										
Recomm. TAC	20[2]	60[2]	36[2]	49	62	42	10	15	30	30
Agreed TAC	20	72	73	55	90	70	40	30	30	30
Catch used	42	69	64	46	70	52	45	31	48	
Total North Sea and Division VIId.										
Spawning stock biomass.	214	293	434	732	777	847	964	1102	1256	1262[1]

[1] Predicted or assumed

[2] Season, October-March

The minimum management objective of a spawning stock biomass of 1.200kt has been reached. This was selected from the historic data series and was chosen because in that period recruitment was fairly stable(only three year classes out of 15 fell far below the median) and adult fishing mortality was fairly constant at about 0.3. How applicable is such a target? At that time the Downs herring was being heavily fished in the southern North Sea and recruitment to the individual stocks could hardly be regarded as stable. The total catch was taken by many vessels at a rather low mean catch per effort and spread over the year from May to December. In contrast, the present exploitation is by purse seine and pelagic trawls over relatively short periods of intensive fisheries at very high catch rates. Little fishing begins before July; there is concentration on spawning herring in the central North Sea; a major exploitation takes place in the northeastern North Sea(unknown in the previous period); and the spawning grounds in the south are exploited for the roe market. One might question how relevant is an objective set under the early exploitation pattern in relation to a completely different exploitation in which the mix of stock components might well be very different.

ACMF in its advice for 1990 expressed concern that in spite of a series of good year classes the spawning stock had increased very little since 1984 and the proportion of the stock taken was already at a high level (around 40%). How confident can one be that the recovery can be continued and the hard won gains maintained. Far from improving as the management regimes became established the data have continued to decline in quality and quantity. One of the major stumbling blocks in obtaining an overall assessment of the North Sea herring stocks has been the inability to make any appraisal of the effects of the Skagerrak fisheries on the North Sea. Throughout the history of these juvenile herring fisheries, the species composition of the catches landed for fish meal have been in doubt. The problem intensified when regulations to limit the industrial fisheries for herring in the North Sea began to be enforced. The reductions in catches simply reflected a change in the area of operation as boats moved to work in the Skagerrak. Of the reported 333kt of herring caught in the Skagerrak and Kattegat in 1988, an estimated 200kt were North Sea spawners of which 183kt were 0- and 1-group. This represents a very severe loss of potential recruitment to the North Sea. Regulations introduced to limit the activities of the industrial vessels and the by-catches of the sprat fisheries have been continuously ignored. Apart from this, there is a lack of adequate biological sampling which would allow the different stock components to be satisfactorily analysed.

The fears for the future of the North Sea herring industry were expressed at a meeting of delegates from the main Danish, UK, Dutch. German and French fishermens organisations. Their communique submitted to the European Commission and the EC Council of Fisheries Minister on 27 June 1990 has a marked *déjà vu* sentiment. Their summarised demands are as follows:

1 a reduction of fishing for fishmeal in the Skagerrak/Kattegat;

2 adequate control of illegal herring-fishing practices in the Skagerrak/Kattegat and in the North Sea;

3 reduction of the directed fishing for herring for fishmeal and fishoil in the North Sea, by closed periods/additional closed areas, other technical measures and reduction of sprat-fishing for fishmeal

4 any catch reductions in the next few years should not be imposed on those fishermen who are not to blame for the overfishing

5 measures are needed to control the total catch not only the landed catches.

3. THE SCIENTIFIC DILEMMAS.

In the previous section the description of the events has been restricted to those concerned with the activity of the fishery and the responses from management to advice from ICES. The scientific arguments were far deeper than indicated. Every aspect of the biology and population dynamics were studied minutely and perhaps it is fair to say that too much is known about the herring to present a sufficently simple case on which managers might act. The case for conservation of the Downs stock was confounded by the coincidence of the increased fishing mortality on the adult stock, the commencement of the Bløden fishery and the growth change with its implication of an environmental effect. The commencement of herring larval surveys required the development of a totally new quantitative sampling gear which could be used routinely with a known degree of accuracy. It initial purpose was to obtain independent evidence of the changes in size of the spawning stock. With the application of fecundity data, Bridger(1961) showed that with fewer older fish in the spawning stock the relative abundance of larvae decreased much faster than would be expected from the spawning potential in terms of eggs. One untested hypothesis was that three year old recruit spawners had lower egg viability, and for maintainance of viable spawning stock it was essential to have a buffer stock of older fish Another hypothesis drew attention to the intensity of the trawling on the spawning grounds which would disrupt the spawning behaviour of the herring-the old fishermens belief. I calculated that at the time of peak trawling, the spawning ground in the Sandettie/Ruytingen channel must have been ploughed 4 times per season by the trawl doors and ground ropes of the 250 trawlers. Perhaps the present Herring Assessment Working Group's observation of reducing larval numbers per gramme of spawning stock biomass might reflect Bridger's observation. In this case, it could be the activity of the fishery for roe which would result in reduced larvae at a period of increasing biomass.

When the growth increment increased in the 1950s it was first linked to an observed increase in the abundance of Calanus. In later years the plankton production in the North Sea decreased but growth continued to increment. Burd(1985) showed a density dependence between the mean lengths of fully recruited Bank and Downs herring and their biomass in their first year. The increased growth had a number of profound effects in diverse ways. At L_1 values of less than 11cm the Downs herring had opaque central zones to their otoliths. The size of the recruit class to the Downs stock could be forecast from the catches in the Bløden fishery. Can it be that with the current reduced growth, Downs herring could be again identified in the juvenile catches? The increased growth resulted in earlier recruitment to the adult stock changing from complete recruitment at 4 years old to three and even partial recruitment at two years old. Effectively a years natural mortality was saved. The Bløden fishery commenced just at this period. when the year class would be at its most concentrated in the nursery area. In the thirties when recruitment was only complete at five years old the main nurseries were in the north western North Sea. Is the Bløden fishery then dependent on high incremental growth, and that the present apparent low abundances of juveniles in the Young Fish Survey a reflection of a return to low growth?

Growth has been supposed to be a reflection of environmental change. If growth is simply a density dependent effect has there been an additional environmental effect? Despite intensive research no evidence could be found to support the hypothesis that the mechanism of recruitment to Bank, Downs and Buchan stocks had changed. Indeed what is most striking is the maintainance of the differences of meristic characters over the years. It has been suggested that increasing temperatures on the Dogger spawning grounds was deleterious to survival, Corten, (1986). As vertebral sum is temperature dependent one might expect some trend in their means, but this cannot be demonstrated. Munk and Christensen(1990) found unacceptable

Corten's explanation of the increased larval abundance in the southern parts of the North Sea during the early eighties as a consequence of a return to 'normal' current circulation The sudden recurrences of larval distributions in previously barren areas may be more readily explicable by the revival of spawning. stocks previously reduced to very low numbers following heavy fishing. The revival of the Whitby stock and the Channel component of the Downs herring may be cited and, more dramatically, that of the Georges Bank herring, Stephenson and Kornfield(1990).

Finally, the past controversy over the impact of the juvenile herring fishery was to some extent resolved as a result of the intensive studies of predation in the North Sea. The use of a natural mortality of 0.1 for all age groups was shown to be agross underestimate for the 0- and 1-groups. The values obtained were 1.00 and 0.30 for the two groups respectively. The very high catches of 0-group represent a very serious reduction in potential recruitment. Their contribution to the yield of fish meal and oil from the sprat fishery must be minimal as at that size, unlike sprat, their oil and protein contents are very low. It is thus also economically inefficent to utilize such fishes. and their catching should be eliminated.

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Early Life History, Migration, and Transport

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Timing and Abundance of Herring and Other Fish Larvae in an Alaskan Glaciated Fjord

R.L. Smith
University of Alaska Fairbanks
Fairbanks, Alaska
A.J. Paul and J.M. Paul
University of Alaska Fairbanks
Seward, Alaska

ABSTRACT

Plankton were sampled at three stations in Resurrection Bay, Alaska, from March to July 1988. Samples were analyzed for larval herring, their typical prey, potential predators and potential larval fish competitors for planktonic prey. Herring larvae appear in the water column after peak abundances of sand lance and walleye pollock. Herring larvae were most abundant from mid-May through June, coincident with larval flathead sole.

Copepod nauplii, a principal food of herring larvae, generally exhibited abundances similar to those reported elsewhere in Alaska during the early spring. When herring larvae first appeared on May 5 nauplii were 24 per liter. Peak abundance of 124 nauplii per liter occurred on May 18, about the second week of life for herring larvae. Thereafter nauplii usually exceeded 40 per liter which according to laboratory studies should have been sufficient for successful feeding by herring larvae. This preliminary study demonstrated that the glacially influenced bays of the Northern Gulf of Alaska may be ideal nursery areas for larval fish and these habitats deserve further study.

INTRODUCTION

Currently fisheries oceanographers are trying to understand recruitment processes of larval fish. In Alaska the most promising geographical area to carry out these studies is along the Seward Oceanographic Station Line. The Seward Line is a series of stations beginning in Seward Alaska and extending out into the Gulf of Alaska to Middleton Island. This is the only area in Alaska where physical oceanographic measurements are made on a regular basis. During the early half of the 1900s the area, and nearby Prince William Sound, supported major harvests of Pacific herring (Reid 1971), but currently stocks are reduced.

The objective of this study was to examine the suitability of the region as a nursery area for herring larvae. Our current knowledge suggests that recruitment in planktonic marine larvae is regulated largely through variations in growth rates and predation pressure (Ware 1975). Unfortunately no data exist that identify the plankton taxa present along the Seward Line. Copepod nauplii are the major food of most fish larvae and prey concentrations are important in determining their growth rates. It has been demonstrated that hatching into an environment where there are sufficient numbers and types of food is important to the survival of larvae (Theilacker and Dorsey 1980). Predation has also been shown to be important in herring recruitment in nearby areas (Purcelle and Grover 1990). Currently, except for Shelikof Strait, there is little information available on nauplii prey fields or predators coexisting with fish larvae in the embayments of the northern Gulf of Alaska. This study was a preliminary examination of the fish larvae and their prey at the beginning of the Seward Line of stations, designed primarily to be a rudimentary data base from which future studies could evolve.

METHODS

Study Site

All work was done at the head of the Institute of Marine Science, University of Alaska's line of oceanographic stations known as the Seward Line. Three stations R1, R2.5 and R4 were sampled (Fig. 1) in Resurrection Bay. Resurrection Bay is a fjord estuary approximately 30 km long, 6 to 8 km wide and oriented in a north-south direction. An inner basin, 290 m deep, is separated from the outer reaches of the fjord by a sill at approximately 250 m deep and the outer basin opens directly onto the Gulf of Alaska. Previous information on the physical oceanography of the study area is included in Heggie et al. (1977). Generally there is temperature and salinity stratification in the upper water column beginning in April resulting from summer warming, snow melt and freshwater runoff. Much of the melt water comes from glaciers. By the end of May there is usually a strong pycnocline in the 20–25 meter depth region (Heggie et al. 1977 their Figure 15). The geology of the area protects the bay from east and west winds and the prevailing north and south winds are generally mild during May and June. Therefore the mixed layer depth is probably shallower than the pycnocline. Thus by mid May the water column is generally stable in the vertical plane.

Measurements

Phytoplankton samples were taken at 10 m depth with water bottles at stations R1, R2.5 and R4 during the spring and early summer of 1988. Chlorophyll concentrations were determined by the fluorescence method for acetone extracted 250 ml samples (Strickland and Parsons 1972). These samples were processed by the Oceanic Institute.

Copepod nauplii were sampled with a 10 liter water bottle with samples taken only at 10 m depth at stations R1, R2.5 and R4 during the spring and early summer of 1988. Each week a single bottle cast was taken at each of the three stations. Water from the bottle was passed through a 64 micron bag net and the concentrated sample preserved for microscopic analyses. Nauplii were measured with an ocular micrometer and divided into three groups: less than 150

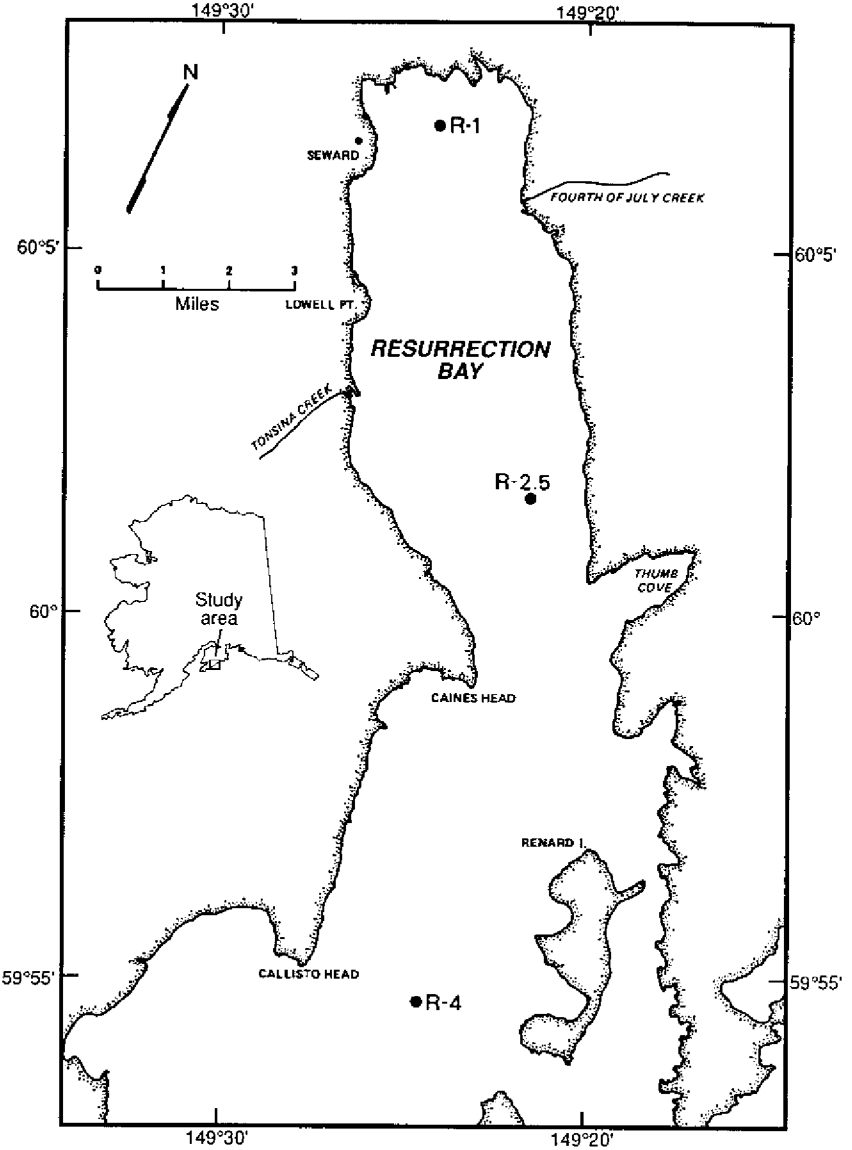

Figure 1. Map of sampling stations for fish larvae and copepod nauplii in Resurrection Bay, Gulf of Alaska during spring of 1988.

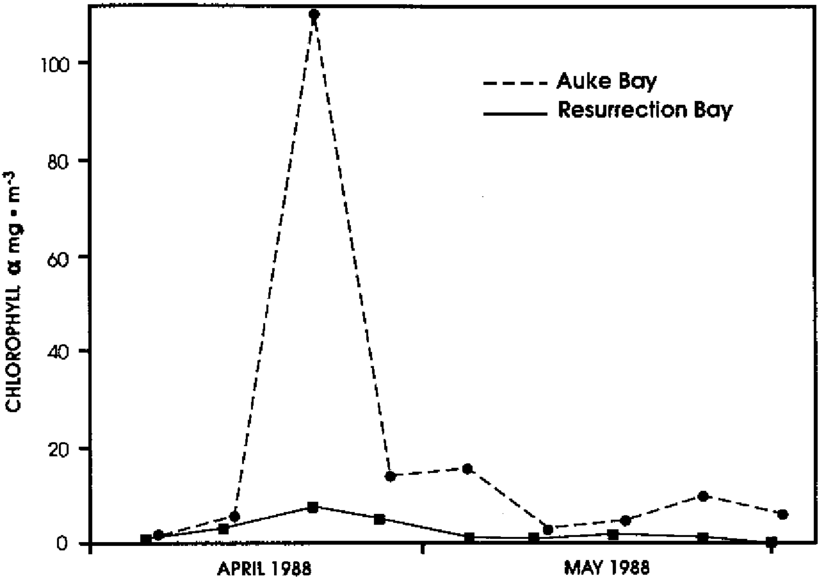

Figure 2. Chlorophyll at 10 meter depth at station R2.5 in Resurrection Bay (solid line) and Auke Bay (dashed line) Alaska.

micron, 150–350 micron, and larger than 350 micron body length. The number of each size category per liter was estimated.

Larval fish were collected with a 1-m Tucker trawl (NIO net) towed double obliquely from 30 m to the surface. Mesh size was 505 micron. The samples were preserved in 10% formalin and populations are presented as number per cubic meter. Only samples from every other week were processed for larval fish abundance.

RESULTS

Chlorophyll

Figure 2 provides estimates of chlorophyll and pheopigment during the 1988 sampling period. The low chlorophyll measurements during the spring are indicative of a highly coupled system where zooplankton grazing pressure is a major factor modifying phytoplankton standing stocks.

Nauplii

During April copepod nauplii (150–350 micron length) were present at less than 10 per liter during the first three weeks of April (Table 1). Throughout May they were above 20 per liter with over 100 per liter in mid-May. Our sampling was restricted to the 10 m depth so it is probable that maximum densities of nauplii were often missed. Nauplii less than 150 micron, and over 350 micron

Table 1. Copepod nauplii counts (number per liter) collected at 10 m depth at stations R1, R2.5, and R4 in Resurrection Bay, Alaska in 1988.

Date		Nauplii length (µm)		
		<150	150-350	>350
31 March	R1	0	1.2	0.1
	R2.5	0	6.3	0.3
	R4	0	1.0	0
6 April	R1	1.7	6.1	0.1
	R2.5	0.5	5.6	0.2
	R4	0	3.8	0.3
13 April	R1	0.1	4.6	0
	R2.5	0.1	8.0	0.7
	R4	0.1	5.8	0.4
21 April	R1	0.8	9.0	0
	R2.5	0.3	6.9	0.1
	R4	2.2	11.9	0.6
27 April	R1		no sample	
	R2.5	1.2	18.9	0.2
	R4	0.2	9.0	0
5 May	R1	0.4	23.7	0
	R2.5	1.0	24.2	0.4
	R4	0.4	25.8	1.0
11 May	R1	0.8	59.2	0
	R2.5	2.8	63.2	1.2
	R4	0.8	51.2	0
18 May	R1	0	139.2	0
	R2.5	16.0	128.8	0
	R4	6.4	105.6	0
6 May	R1	0.8	87.2	0
	R2.5	3.2	71.2	0
	R4	3.2	34.4	0
1 June	R1	0	39.2	0
	R2.5	3.2	32.8	0
	R4	4.0	45.6	0
8 June	R1	0.2	55.6	0
	R2.5	7.2	60.8	0
	R4	6.8	45.2	0
15 June	R1	0.8	79.6	0
	R2.5	2.0	46.4	0
	R4	5.6	20.8	0
22 June	R1	1.2	59.6	0
	R2.5	2.4	33.6	0
	R4	3.2	20.0	0
28 June	R1	1.2	57.2	0
	R2.5	8.4	60.4	0
	R4	0.6	8.8	0
5 July	R1	0	69.6	0
	R2.5	14.0	43.2	0
	R4	22.4	47.2	0
12 July	R1	0	49.2	0
	R2.5	5.6	46.0	0
	R4	11.0	43.2	0.2
20 July	R1	0.4	36.8	0
	R2.5	2.8	48.0	0
	R4	6.6	27.2	0

length were typically less than 1 per liter at 10 m depth. Perhaps if shallower samples were collected the smaller nauplii would have been more abundant. However, the general population trends were similar to those observed in other areas of Alaska with low abundances of nauplii in early spring followed by increasing numbers as the spring phytoplankton bloom progressed.

Fish Larvae

The most common fish larvae at the head of the Seward Oceanographic Station Line were pollock (*Theragra chalcogramma*), flathead sole (*Hippoglossoides elassodon*), herring (*Clupea harengus*) and sand lance (*Ammodytes hexapterus*). Herring larvae (Table 2) were most abundant in mid-May (about 0.1–0.2 per m^3) through the end of June when nauplii prey-fields were well

Table 2. Abundance (number per m^3) of *Clupea harengus* larvae at stations R1, R2.5, and R4 in Resurrection Bay, 1988.

Date	R1	R2.5	R4
6 April	0.00	0.00	0.00
21 April	0.00	0.00	0.00
5 May	0.16	0.0052	0.00
18 May	0.23	0.02	0.0007
1 June	0.0066	0.036	0.30
15 June	0.22	0.023	0.13
28 June	0.077	0.07	0.41
12 July	0.019	0.20	0.11

Table 3. Abundance (number per m^3) of *Theragra chalcogramma* larvae at stations R1, R2.5, and R4 in Resurrection Bay, 1988.

Date	R1	R2.5	R4
6 April	0.13	0.20	0.09
21 April	0.50	1.09	4.13
5 May	0.80	1.14	0.60
18 May	0.37	1.37	1.27
1 June	0.12	0.57	0.84
15 June	0.13	0.07	0.04
28 June	0.02	0.01	0.00
12 July	0.003	0.00	0.00

Table 4. Abundance (number per m^3) of *Ammodytes hexapterus* larvae at stations R1, R2.5, and R4 in Resurrection Bay, 1988.

Date	R1	R2.5	R4
6 April	0.079	0.59	0.068
21 April	0.012	0.23	0.27
5 May	0.0008	0.12	0.019
18 May	0.00	0.12	0.0007
1 June	0.00	0.00	0.00
15 June	0.00	0.00	0.00
28 June	0.00	0.00	0.00
12 July	0.00	0.00	0.00

Table 5. Abundance (number per m^3) of *Hippoglossoides elassodon* larvae at stations R1, R2.5, and R4 in Resurrection Bay, 1988.

Date	R1	R2.5	R4
6 April	0.00	0.00	0.00
21 April	0.00	0.00	0.00
5 May	0.0053	0.0052	0.0146
18 May	0.129	0.236	0.0792
1 June	0.0065	0.254	0.265
15 June	0.0051	0.0078	0.0258
28 June	0.011	0.0019	0.0022
12 July	0.00	0.00677	0.00

developed. Figure 3 illustrates the relative abundance of herring larvae and copepod nauplii. From mid-May until mid-June they were most abundant near the head of the bay at station R1 and afterwards most abundant at the outer station R4 (Table 2). We can not attribute this observation to either migration or transport, since the fish have not been measured or aged as yet and current measurements were not taken during the study.

Pollock (Table 3) were most abundant at stations R4 and R2.5 from late April though mid-May. Their peak abundance was in general one to two weeks earlier than that of herring larvae, but they were present as competitors throughout most of the time that larval herring were present.

Sand lance larvae (Table 4) were most abundant in the earliest samples. This suggests that their peak abundance may have occurred previous to the initiation of sampling.

Flathead sole larvae (Table 5) first appeared on May 5 and were present until the end of June. Thus their planktonic period overlaps that of herring. They were present in abundances similar to herring and were most common at the R2.5 mid-bay and R4 outer station.

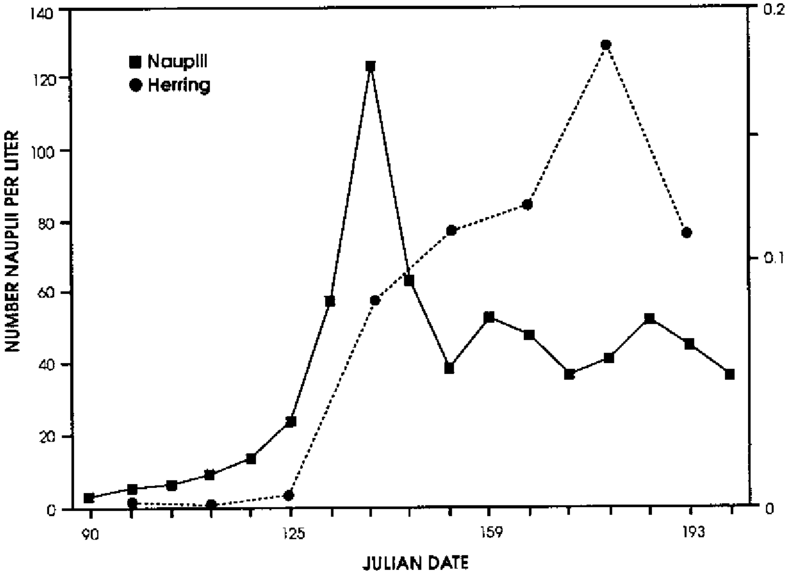

Figure 3. Mean abundance of copepod nauplii (150 to 350 micron length) at 10 meters depth and herring larvae in the upper 30 meters of the water column in Resurrection Bay, Alaska during spring of 1988.

Competitors

While several other species of fish larvae were present in the spring plankton it is probable that neither they, nor other types of copepod nauplii predators, negatively affected the feeding success of herring larvae.

Predators

Most zooplankton and micronekton species that are potential predators on fish larvae are diurnal vertical migrators. These include the large calanoid species and euphausiids. Since all of the net samples were collected during the day, the above taxa were not sampled. Every year wind rows of dead euphausiids, primarily *Thysanoessa spinifera* wash onto the beach of the study area during late April (unpublished). This species is the largest euphausiid in Alaskan coastal waters, and where it occurs in large numbers, it may prey on larval fish. Cnidaria and ctenophores may also be important predators on larval fish (Purcell and Grover 1990). Cnidaria were never present at high concentrations during the sampling. Ctenophores could not be adequately sampled by the nets deployed because they are too fragile. Nevertheless, when present their combs can be seen in the sample material. We did not note the presence of large numbers of ctenophore combs in the samples and therefore assume that they were not abundant. In the future, night samples need to be taken to assess larval fish predator abundance.

DISCUSSION

Chlorophyll

The chlorophyll concentrations at 10 m depth in Resurrection Bay are low when compared to the shallow bays of southeastern Alaska like Auke Bay. Auke Bay, near Juneau Alaska, is a classic example of an "uncoupled" system where a large percentage of the spring bloom diatoms sink to the bottom uneaten (Laws et al. 1988). In "uncoupled" systems the grazing community is inadequate to consume all the cells produced during the spring phytoplankton bloom. The much lower chlorophyll levels of Resurrection Bay suggest that copepod biomass must be relatively high and heavy grazing pressure is exerted on the phytoplankton creating a tight coupling between primary producers and grazers. In addition to the neritic copepods usually associated with fjords oceanic types such as *Calanus* spp. are transported into Resurrection Bay by the Alaska Coastal Current. These large copepods are very efficient grazers. The role of primary production transfer to secondary levels in "uncoupled" systems has been studied (PROBES, APPRISE), but not in "coupled" systems like the head of the Seward Line. Most of Prince William Sound and perhaps the Kodiak bays which historically have had high herring spawning stocks may have production systems like Resurrection Bay.

Nauplii

In general copepod nauplii abundances in Resurrection Bay were similar to other values reported of 1-30 per liter for Auke Bay in southern Alaska (Haldorson et al. 1989) and the southeastern Bering Sea (Dagg et al. 1984). But the 18 May samples contained some of the highest nauplii concentrations ever reported, mean concentrations of 124 per liter.

The abundant nauplii are probably due to the high populations of copepods. In Auke Bay the number of female *Pseudocalanus* was found to be more important than primary production rates or temperature in determining the number of nauplii available to larval fish (Paul et al. 1990) and likely the high abundance of female copepods in Resurrection Bay is responsible for the higher than average nauplii abundance. The zooplankton biomass in the NIO net samples was dominated by copepods (authors, unpublished). The major copepod taxa contributing to the biomass were *Calanus plumchrus*, *C. marshallae* and *Pseudocalanus* spp. The *Pseudocalanus* spp. are permanent residents of the bay and the others probably originated in the Gulf of Alaska. The transport of large *Calanus* into Resurrection Bay from the Gulf of Alaska is certainly a major source of nauplii. An alternative explanation for the high nauplii abundance observed in the study area is the possibility that the fjord's strong pycnocline may facilitate the formation of vertically oriented "patches" of nauplii. Only vertical sampling of the nauplii would verify this theory. The similarity in nauplii abundance at the three stations suggest that good feeding conditions exist throughout the fjord and there were no strong horizontal "patches."

Previous studies in the southeastern Bering Sea demonstrated that there fish larvae did not significantly depress copepod nauplii concentrations by predation (Dagg et al. 1984). Given that copepod nauplii are roughly twice as abundant in Resurrection Bay as in the above mentioned area, it seems unlikely that larval fish predation on nauplii could be a major factor in modifying nauplii abundance or a limiting factor in determining survial and growth of those fish larvae.

Fish larvae

Herring. Generally it is thought that larval fish have better survival rates if they hatch during the period when copepod nauplii are most abundant. Herring larvae first appeared in any numbers on 18 May and 1 June, in perfect timing with the major cohort of copepod nauplii (Fig. 3). In a recent review of prey concentrations necessary for herring larvae (Purcell and Grover 1990) it was concluded that nauplii at 0.5 to 0.8 per liter is needed for larvae to survive while at 5 to 12 nauplii per liter good growth and survival can be expected. In the laboratory, herring larvae saturation feeding response occurs around 30 nauplii per liter (Munk and Kiorboe 1985) thus during 18 May to 1 June with nauplii between 34 and 140 per liter they should have encountered adequate prey concentrations for maximum growth rates if they could exploit the nauplii at 10 m depth. Munk et al. (1989) reported that herring larvae use vertical migration to located patches of prey. Off the Scottish coast nauplii are generally less than 10 per liter when herring larvae are present (Munk et al. 1989). If the 1988 observations of nauplii abundance in Resurrection Bay are typical for the glacially influenced fjords of the Gulf of Alaska, then they must be considered very desirable nursery areas for herring larvae.

Pollock. Pollock larvae were most abundant on 21 April which was earlier than the mid-May nauplii peak of abundance. However there were still pollock larvae in the samples from mid-May into early June so some of them began feeding when their prey were most abundant. After 5 May, nauplii were 24—129 per liter which is a relatively rich prey-field (Haldorson et al. 1989; Dagg et al. 1984) and pollock should have been very successful at capturing prey at these concentrations (Paul, 1983; Haldorson et al. 1989). At 0.8 to 4.1 per m^3 larval pollock were several times more abundant than those occurring over the mid-shelf region of the southeastern Bering Sea (Dagg et al. 1984). These values are lower than peak abundances of pollock larvae in Shelikof Strait but within the range of values observed (Kendall et al. 1987). Our observations suggest that many embayments along the northern Gulf of Alaska may serve as pollock nurseries and that not all gulf pollock go to Shelikof Strait to spawn.

Flathead Sole. The larvae of flathead sole hatch from very large eggs and appear to be very competent at capturing prey. They reach saturation feeding levels at nauplii concentrations below 15 per liter (Haldorson et al. 1989). All samples after the first week of May had nauplii concentrations that exceeded 15 per liter. Since the temporal and spatial patterns of abundance of flathead sole and herring larvae are very similar, flathead larvae must be considered a potential competitor of herring larvae. Further information on the interannual variability of prey is critical in order to evaluate competition.

Sand Lance. Sand lance larvae were most abundant in our early April collections, but probably hatched before we initiated sampling. Obviously sand lance larvae are not dependent on hatching when spring copepod nauplii are abundant nor do they compete with herring larvae.

General Conclusions

The question posed prior to compiling this report was, "what are the physical and biological characteristics of the study area that historically made it a good herring spawning site (Reid 1971)"? The glacial fjord exhibited several attributes that might explain why it is a better than average nursery area for herring and other fish larvae. The existence of a strong pycnocline creates vertical stability in the water column (Heggie et al. 1977). This may allow for nauplii to concentrate in patches vertically and create ideal feeding conditions for fish larvae. The fjord probably benefits from having both a resident neritic copepod population plus the transport of oceanic types into the area by the Alaska Coastal Current. This influx of copepods enriches the community of nauplii producers. The high nauplii concentrations found at all stations demonstrated that there was no strong horizontal patchiness for nauplii and thus the whole area was a good feeding ground for fish larvae in 1988. The interannual variability in nauplii abundance remains undescribed, so it cannot be stated that this is always the case.

Future Studies

Future larval fish studies at the head of the Seward Line should focus on pollock, herring, flathead sole and sand lance due to their relatively high abundance and ease of identification. Studies of sand lance larvae would have to start earlier in the spring than April. Yellowfin sole are commonly caught in benthic trawl samples in Resurrection Bay, but their larvae were not in the ichthyoplankton samples, probably because they spawn in July.

Topics of interest would include the role of physical transport in modifying larval fish and copepod distribution, links between the Alaska Coastal Current and zooplankton populations in the bay, links between primary production and the rich copepod populations, interannual variations in nauplii production and clarification of the roles the many fjord estuaries of the Gulf of Alaska play in fisheries production. This preliminary study demonstrated that the glacially influenced bays of the Northern Gulf of Alaska may be ideal nursery areas for larval fish and these habitats deserve further study.

ACKNOWLEDGMENTS

This work is a result of research sponsored by the Alaska Sea Grant College Program, cooperatively supported by NOAA, Office of Sea Grant and Extra Mural programs Department of Commerce, under grant number NA86AA-D-SG041, project M/81-01, by the University of Alaska with funds appropriated by the state. Facilities were provided by the Seward Marine Center, Institute of Marine Science, University of Alaska. K. Coyle, P. Shomaker and D. Simms aided in the plankton enumeration. This is contribution 848 from the Institute of Marine Science, University of Alaska.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Estimation of Daily Growth Rate and Birthdate Distribution in Norwegian Spring Spawning Herring (*Clupea harengus* L.), from Daily Increment Studies of 2–4 Month Old Juveniles

P. Fossum
Institute of Marine Research
Bergen, Norway
E. Moksness
Institute of Marine Research
His, Norway

ABSTRACT

This study has been performed on field caught herring larvae and juveniles of Norwegian spring spawners of the 1985, 1988 and 1989 year-classes. Daily increments in the otoliths have been counted and the increment size measured, to estimate birthdate-distribution and backcalculate daily growth rate respectively. The observed birthdate-distribution and daily growth rate from the otolith studies are compared with field observation on yolksac and first feeding larvae in the same three years. The results shows differences in hatching period and daily growth rate of the herring juveniles sampled during July compare to the one sampled in May the same year, indicating that the juveniles do not belong to the same cohort. The daily growth rate was initially high (0.40 mm/d), decreasing to 0.2 mm/d at an age of 60 days (approx. 27 mm).

INTRODUCTION

The recruitment in Norwegian spring spawning herring was almost equal to zero during the period from 1967 to 1982. In 1983, however, the recruitment was similar to the average recruitment of the year-classes before 1967. The spawning stock in 1983 was only 0,5 million metric tons, compared to more then 2,5 million metric tons in the years before 1967 and as high as 13.9 million metric tons in 1955. Since 1983, the year-classes strength has been far below the 1983 year-class, however, above the year-classes in the period from 1967 to 1982. The spawning stock of the Norwegian spring spawning herring have increased in the past years, and approximately 90 % of the spawning stock in 1989 (1,2 million metric tons) consisted of progeny from the 1983 year-class (Anon, 1990). In the process of rebuilding the Norwegian spring spawning herring, it is of importance to understand the recruitment mechanisms for the species, as also concluded by Toresen (1990). Dragesund (1970) dicussed important factors affecting recruitment in Norwegian spring spawning herring. He concluded that strong yearclasses seemed to occure when there is a widespread distribution of spawning, long duration of the spawning period and a rapid dispersion of larvae from the spawning ground.

Several hypothesis has been presented in the past 80 years to explain the variation in year-class strength in general and these have been reviewed by Anderson (1990). He concluded that a growth-mortality hypothesis provide a rational framework for future research. The growth-mortality hypothesis says that there is a inverse relationship between growth and mortality and the hypothesis have been discussed in more detail by Beyer (1989) and Houde (1987). Both authors indicates that by backcalculating the growth rate, the mortality rate can be estimated. Houde (1987) suggest the use of otolith analysis to estimate the growth rate of marine fish larvae. Counting of daily increments has turned out to be a delicate instrument in larval ecology studies. A recent mesocosms experiment concludes that the number of increments in the otoliths of Norwegian spring spawning herring are formed daily and that the increment size express the growth rate of the larvae (Moksness, in prep.). By estimating the age and the daily growth rate several questions can be answered, like from which part of the spawning season the recruiters origin and the growth history of the recruiters. If the age structure of the fully recruited year-class is compared with other parameters, like temperature, drift, micro-zooplankton and predator abundance, one can move further against solving the questions about recruitment variability.

In the present study, the birthdate distribution and daily growth rate have been backcalculated from otolith microstructure and compared to field observations the same year, in 1985, 1988 and 1989.

MATERIAL AND METHOD

Sampling of the yolksac and early post-yolksac herring larvae were carried out in March and April in 1985, 1988 and 1989 over the central spawning areas of the Norwegian shelf (see Fig. 1A). The larvae were sampled with conical dip-nets with 0.5 m^2 opening and 375 μm mesh size. The nets were hauled from 150-0 m with a speed of 0.5 ms^{-1}. The larvae were sampled in nonfiltering cod ends and 50 larvae were measured to nearest mm below. The larvae were preserved in 2% formaldehyde and staged according to Doyle (1977). For further information of the sampling program, see Bjørke et al. (1986) and Bjørke et al. (1990). The original number of newly hatched herring larvae were later backcalculated from the number of larvae in different stages with 10% daily mortality rate. Stage duration was set according to Bjørke et. al (1986) and the hatching curve was made with basis in these data. In 1985 the sampling took place within a short time period in the middle of April with RV "Eldjarn", while in 1988 and 1989, in addition to larval surveys with RV "Eldjarn" and RV "M. Sars", a separate investigation was carried out to measure the hatching activity of the herring larvae. RV "Opal" went out twice a week, during April in both years, to cover the main spawning fields of the herring (H. Bjørke and L. Rey, pers.comm., Institute of Marine Research, Bergen).

The Norwegian spring spawning herring juveniles were sampled during four different cruises on the Norwegian continental shelf, north of 62°N, between May and July in 1985, 1988 and 1989. The sampling locations are indicated in Figure 1B. A mid-water capelin trawl with a 10 m fine (8 mm) meshed net inside the cod end was used as the gear in these three years. More information about the sampling is given in Bjørke et al. (1987). In 1985 and 1988 the larval samples were frozen, while the larvae were preserved in 80% buffered ethanol shortly after capture in 1989. The sagittae from each herring larvae were removed and mounted on glass slides for later examination in light microscopy. The examination and measurements of the microstructure in the sagittae were done using the same techniques as described by Moksness and Wespestad (1989). To get the real age of the larvae, nine days were added to the number of increments counted to compensate for the yolk-sac stage (Moksness, in prep). The standard length of the examined larvae ranged from 17.0 to 46.0 mm. The total number of examined larvae were 272. A summary of statistics of the larvae used are given in Table 1.

Table 1. The average standard length (SL) with standard deviation (SD), minimum (Min) and maximum (Max) standard length and the number of examined herring juveniles (N). The total number of examined larvae were 272.

Cruise	SL ± SD (mm)	Min (mm)	Max (mm)	N
May 1985	29.1 ± 3.5	22.0	39.0	41
July 1985	39.2 ± 3.9	32.0	46.0	28
July 1988	36.6 ± 2.9	32.0	46.0	21
May 1989	26.4 ± 2.8	17.0	32.0	182

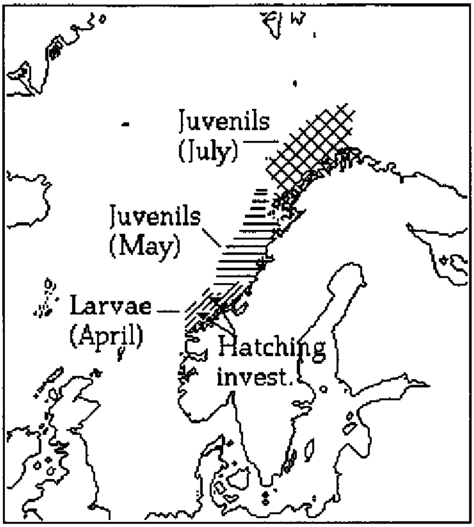

Figure 1. Indication of sampling locations of Norwegian spring spawned herring larvae and juveniles in the years 1985, 1988 and 1989.

RESULTS

Temperature

The average temperature in °C at 20 m depth in the Norwegian Coastal current for the years 1985, 1988 and 1989 are shown in Table 3. There was just seen small differences in temperature between the three years, typically 5-6 °C in the water over the spawning beds in April, 7 °C on the coastal banks in May and 8 °C on the banks off Northern Norway in July. A comparison between 1985 and 1989, show one degree higher temperature in 89 than in 85 in May and July.

Table 3. Average temperature (°C) at 20 m depth in the Norwegian Coastal current for the years 1985, 1988 and 1989.

Year	Mid April	May	June/July
1985	5-6	6-7	7-8
1988	5-6	7	8
1989	6	7-8	8-9

Microstructure

There is difference in the initial increment size of the herring juvenile caught during the July surveys compared to the May surveys. During age 10 to 16 days, the average increment size is below 1.2 µm for the larvae caught during the May survey and above 1.2 µm for the July survey. The results shows that from age 25 days the increment widths is wider in the juveniles caught during the May surveys compare to the July surveys (Fig. 2). For the juvenile herring caught during May and July 1985, the increment size is about 0.2 µm wider initially in July, changing after 21 days (Fig. 2B) with increment size up to 0.5 µm wider in May compare to July (Fig. 2A).

The relationship between standard length of the larvae and the otolith radius is shown in Figure 3. The larvae in this study were all greater than 17.0 mm. To establish a relationship between of larvae from hatching to juveniles of a maximum 46.0 mm, data from 15 newly hatched Norwegian spring spawning larvae have been included in the calculations. The main portion of the larvae and juvenile herring (63 %) in this calculation were sampled during May 1989 (Table 2). The observed average distance from the nucleus to the first observed increment (hatch check) was greater in the herring caught during the May 1985 cruise compare to the other three cruises. This difference probably will give a higher calculated growth rate for May 1985 herring during the yolk-sac stage.

Table 2. The average distance from the nucleus to the fist increment (hatch check) with standard deviation (SD), average increment number (Increments) with standard deviation (SD) and number of examined larvae (N). The total number of examined larvae were 272.

Cruise	Hatch check (µm) ± SD	Increments ± SD	N
May 1985	14.0 ± 6.3	48.7 ± 6.4	41
July 1985	11.9 ± 0.6	77.9 ± 11.0	28
July 1988	11.3 ± 0.6	81.1 ± 14.0	21
May 1989	11.5 ± 0.9	40.4 ± 5.5	182

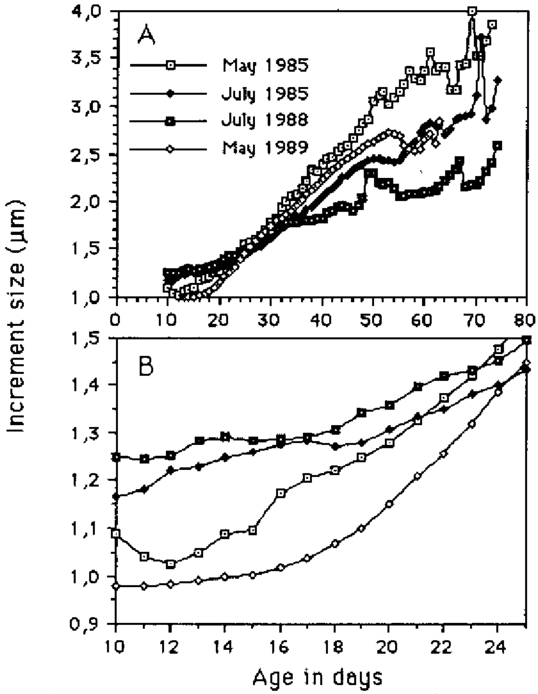

Figure 2. The average increment size (µm) from the cruises from age 10 days to 75 days (A) and a close-up of the age range 10 to 25 days.

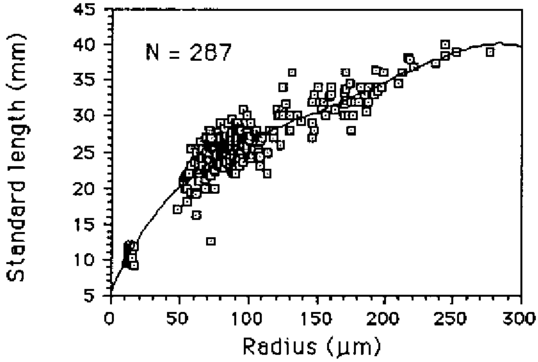

Figure 3. The relationship between standard length (SL) and otolith radius (r) of the examined herring larvae, with addition of 15 newly hatched Norwegian spring spawning herring larvae: SL = 5.6253+0.42757*r - 3.3221*e-3*r^2 + 1.3522*e-5*r^3 - 1.9779*e-8*r^4; r^2 = 0.921

Hatching period

The estimated hatching curves of Norwegian spring spawning herring in the years 1985, 1988 and 1989 are shown in Figure 4, 5 and 6 respectively. In 1985, the hatching curves were made from material sampled on three different cruises. A survey for larvae in the middle of April (Fig. 4C), and two surveys for larvae and juveniles in May (Fig. 4B) and July (Fig. 4A) respectively. The hatching curve from the April data was made from stage determinations, while daily increments were counted in the juveniles sampled in May and July. Of the three hatching curves the two based on the material sampled in April and May are quite similar. The hatching started in the middle of March and had a maximum in late March and early April. However, because the hatching curve from April are based on the survey data, no larvae hatched later than 15 April are included in Figure 4C. When the backcalculation was done with the material from July (Fig. 4A), the result shows that the maximum hatching took place around 10. April, about 14 days later than the previous results. This results was also more widespread in time with larvae hatching from late February until early May.

In 1988 the hatching were measured direct on the spawning grounds (Fig. 5B),which were covered twice a week from the beginning of March until the end of April. The results indicates a different situation than in 1985. Figure 5B shows that the hatching was more widespread. The starting point was the same as the previous year, in the middle of March , but the hatching went on all through April. The highest density of larvae was measured on the last day of the investigation period. These results indicate that hatching took place beyond 24 April and probably in the beginning of May. The result from the daily increment counting in the otoliths of the herring juveniles caught during July indicates that these juveniles had hatched during the first fifteen days of April. The large amount of larvae hatched during the last days of April could not be traced in this material, however a small number of larvae were examined.

In 1989 there was a direct measuring of the hatching at the spawning grounds during March and April (Fig. 6B), like the previous year. The daily increments were counted in a large number of herring larvae (N=182) sampled during May. Figure 6B shows that there was a peak in the hatching 2. April, and that the hatching was very restricted in time. All the newly hatched larvae were found between 28. March and 9. April. The data based on backcalculation from daily increments (Fig. 6A) shows the same, a restricted time period when the hatching took place, but there is a time lag of 5 days between the mean hatching data of the two data sets, 28. March from the otoliths and 2. April from the survey.

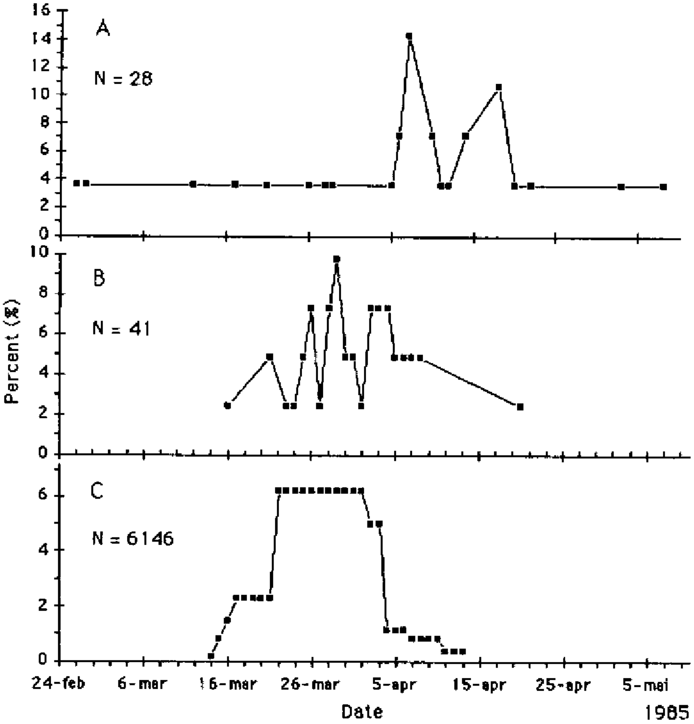

Figure 4. Hatching distribution of the Norwegian spring spawned herring larvae and juveniles sampled during July 1985 (A), May 1985 (B) and April 1985 (C). The average hatching date were 13. April 1985, 31. March 1985 and 27. March 1985 respectively.

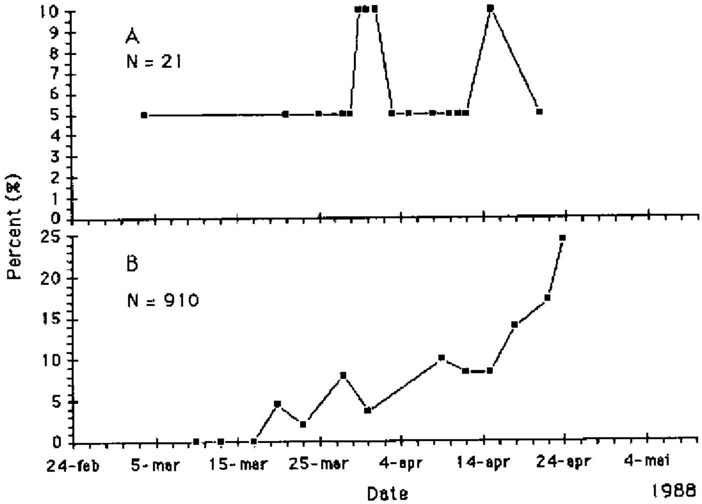

Figure 5. Hatching distribution of the Norwegian spring spawned herring larvae and juveniles sampled during July 1988 (A) and March-April 1988 (B). The average hatching date were 9. April 1988 and 15. April 1988 respectively. Figure 5B is based on data from H. Bjørke and L. Rey (pers.comm., Institute of Marine Research, Bergen).

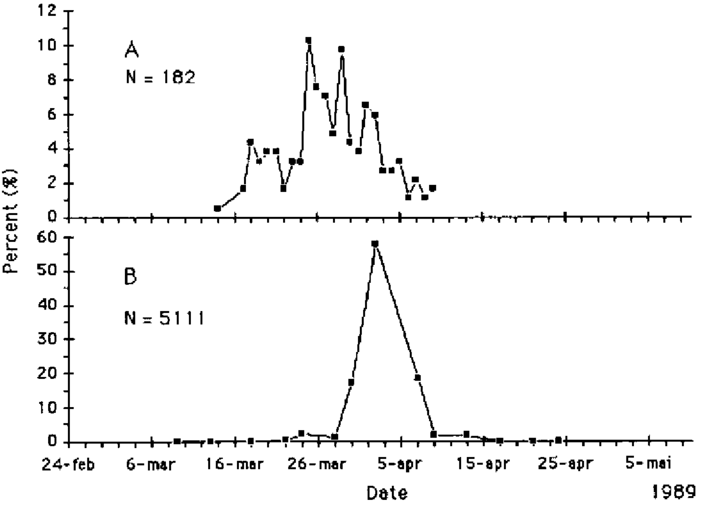

Figure 6. Hatching distribution of the Norwegian spring spawned herring larvae and juveniles sampled during May 1989 (A) and March-April 1989 (B). The average hatching date were 28. March 1989 and 2. April 1989 respectively. Figure 6B is based on data from H. Bjørke and L. Rey (pers.comm., Institute of Marine Research, Bergen).

Growth rate

The backcalculated growth rate based on the increment width in the otoliths is shown in Figure 7. The highest initial growth rate of 0.4-0.45 mmd^{-1} was calculated from the juveniles sampled during July 1985 and 1988. The initial growth rate of the larvae sampled in May 1985 and 1989 was 0.35 mmd^{-1}. However, the observed initial difference between the herring larvae and juveniles sampled in May and July levels off, and in the period about 3 weeks age the growth rate is 0.37-0.38 mmd^{-1} in all the fish. In the larvae older than 3 weeks the highest growth rate was observed in the larvae sampled during May with a maximum growth of 0.40 mmd^{-1} at age 30 days. From this age the growth rate decreases and was observed as low 0.20 mmd^{-1} at an age of 60 days.

The calculated standard lengths of the larvae are presented in Table 4. The table indicates that even the differences in length between the different groups are small the larvae caught during May 1985 were all times largest. The table also shows that the herring at an age of 50-60 days have an average size of 24 -28 mm, indicating that the herring at this age starts to school. The calculated growth rate of the juveniles sampled during July 1985 and 1988 indicates an improved growth rate after 60 days.

The growth rate in the yolksac and early post yolksac period was estimated on basis of the stage distribution, and compared to the backcalculated growth rate from the otolith. The results are shown in table 5. There is a good agreement between the results except for the yolksac larvae in 1985 that was estimated to have a higher growth rate than the rest of the yolksac larvae.

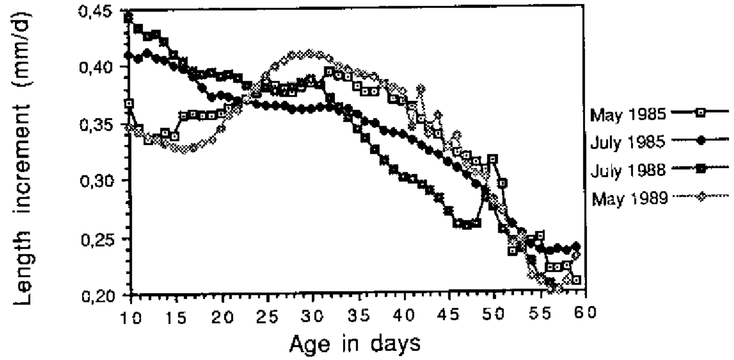

Figure 7. Backcalculated length increment (mm d^{-1}) of the sampled herring juveniles.

Table 4. Backcalculated average standard length (mm) of the examined herring larvae at different ages.

Age (days)	May 1985	July 1985	July 1988	May 1989
20	14.6	14.2	14.2	13.4
30	18.4	17.9	18.0	17.3
40	22.1	21.5	21.5	21.2
50	25.4	24.6	24.3	24.6
60	27.7	27.1	26.5	26.8

Table 5. Backcalculated length increments (mm d^{-1}). Based upon data from the otoliths and from developmental stages (Stage).

	1985			1988		1989
Period (Days)	May	July	Stage	July	Stage	May
1 -11	0,35	0,27	0,23	0,24	0,21	0,24
11 -17	0,34	0,40	0,41	0,42		0,33
17 -25	0,36	0,38	0,43	0,39		0,35
1 -24	0,35	0,34	0,36	0,34		0,30

DISCUSSION

The presented material consists of Norwegian Spring spawning herring, caught as juveniles in 1985, 1988 and 1989. In 1985 the sampling were performed both during May and July, and in 1988 and 1989 during July and May respectively. The results shows a general discrepancy both in backcalculated daily growth rate and hatching distribution between the juveniles caught in May compare to July. In a field study on North Sea herring juveniles, Heath and Duun (in press) shows that there is a increased in gear avoidance from a length of 25 mm, due to development of sensory abilities in the fish. In the present study the same gear were used in all four cruises and most of the herring caught were longer then 25 mm. This indicates that gear avoidance is probably not the cause of the observed discrepancy. The microstructure in the otoliths from the juveniles caught in July was harder to read, compared to the otoliths from the juveniles caught in May. However, there is no indication that this caused the discrepancy.

The observed difference, as between May and July 1985, both in measured zone widths, backcalculated daily growth rate and hatching distribution, indicates that the sampled juveniles belong to different cohorts. On average, the juveniles sampled in May consist of herring hatched approx 2 weeks earlier Then the juveniles sapled in July. Initially they had a slower growth rate, but a higher growth rate beyond age 30 days, resulting in larger larvae at an age of 60 days. If the larvae had the same geographical origin, the initial high growth rate of the July sample, indicates that these herring met better feeding condition in addition to a higher temperature during the first feeding stage. Newly hatched Norwegian spring spawned herring larvae will be taken by the Norwegian coastal current (Loeng and Sætersdal 1987). North of Buagrunnen (63 °N), parts of the coastal current can be drained off and drift offshore along the edge of the coastal banks. However, most of the time the current flow east- and northwards along the coast (Ljøen and Nakken 1969). The dominate portion of the hatched herring larvae will be taken by the near shore branch of the coastal current, and probably enter fjord systems in Northern Norway. Therefore, the observed discrepancy might have been caused by such a mechanism that most of the larvae sampled in May, with a mean hatching date in late March, have followed the main branch of the coastal current and recruited to the fjord systems of Northern Norway. A large amount of the larvae that hatched from mid April can have been brought out into the outer branch and compose the bulk of the catch in July.

The backcalculated hatching period for the fish caught during May, both in 1985 and 1989, matched well with the observed hatching distribution close to the spawning areas the same year. This indicates that the juveniles caught during May those two years might origin from this spawning area. The examination of the herring juveniles caught during July 1988 indicated a widespread hatching distribution, which is also confirmed by the field investigation at the main spawning area. Even the number of juveniles examined is low, the results indicates that also the juveniles caught during July 1988 might origin from the same spawning area. Since the juveniles caught during July 1985 differ both in backcalculated daily growth rate and hatching distribution from the juveniles caught during May 1985, the most likely conclusion is that these fishes do not origin from the main spawning area.

When backcalculating the daily growth rate of the sampled herring, the data used to establish the otolith radius/fish length relationship was dominated by the juveniles caught during May 1989. This might bias the backcalculations of growth rate for the other three samples since the fish/otolith size ratio will change systematically with the somatic growth of the fish (Campana, in press). Of the examined juveniles, the juveniles caught during May 1989 is probably the slow growing fish. This indicates that the backcalculated growth rate of the other three components should have been even higher then the values given here. There is a general trend in the growth history of the juveniles from all four cruises. Initially with a maximum growth rate (0.37 - 0.44 mm/d) within the first 30 days from hatching. Then decreasing to between 0.20 and 0.24 mm/d at an age of 60 days. This correspond with herring with a length above 26 mm, indicating that the fish have started to school. This is in accordance with earlier observations on the growth pattern both on Atlantic herring in the Gulf of Main-George Bank region (Lough et al., 1982) and on a tropical herring (Thorold 1988), where the daily growth rate decreased from the first feeding stage to metamorphoses. The growth rate in the presented material indicates a improved growth rate after age 60 days. This is probably is caused by increased feeding efficiency of the herring juveniles due to schooling.

The spawning stock of Norwegian spring spawners was 0.5 million metric tons in 1985, had increasing to 1.5 million metric tons in 1989. The logarithmic index of yearclass was 0.23, 0.32 and 0.59 in the years 1985, 1988 and 1989 respectively (Anon, 1989). This supports the indications made by Dragesund and Nakken (1973), that there is a relationship between the parent stock size and recruitment. They also concluded that such a relationship would only be valid when favourable conditions for spawning and hatching exist. Dragesund and Nakken (1971; 1973) investigated the mortality of the Norwegian Spring spawning larvae of the year-classes 1967 to 1969. Beside a heavy mortality during the egg stage (> 95%) due to predation, they estimated that between 70 and 95% of the hatched herring larvae died during the first 20 days from hatching. These observations indicates that if growth rate is an important factor to decrease mortality, this should be observed during the first 30 days from hatching and not in the period beyond the 30 days. This is also supported by other observations which indicates that the growth rate in Norwegian spring spawning herring probably is density dependent in older larvae and juveniles. Pashkova and Seliverstova (1987) compared the the length distribution of the weak 1985 yearclass with strong 1983 yearclass as 0- and 1-group fish. In both cases the 1985 yearclass was longer on average then the 1983 yearclass. They also compared the 1983 yearclass to the really strong year-classes in 1950 and 1959 as 2- and 3- group fish. The results indicates that the fishes in the 1983 yearclass in these age groups were larger then the two others.

The examined year-classes in this study have all been weak. To study the effect of growth rate during the early stages of herring on the mortality and yearclass strength, a strong yearclass is needed to do the comparison. Since 1983, such a strong yearclass has not yet been produced. The otolith microstructure, however, have in this study been demonstrated as a useful method to obtain data on growth history of herring and birthdate distribution.

ACKNOWLEDGEMENT

We would like to thank Inger Henriksen at Institute of Marine Research, Flødevigen Marine Research Station for reading most of the otoliths. We also like to thank our collages Herman Bjørke and Laura Rey at the Institute of Marine Research, Bergen for kindly let us use their data on herring larvae hatching.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Herring Life History Parameters Resolved from Structural and Chemical Analyses of Otoliths

R.L. Radtke
University of Hawaii
Honolulu, Hawaii
D.W. Townsend
Bigelow Laboratory for Ocean Sciences
W. Boothbay Harbor, Maine

ABSTRACT

Research on the dynamics of larval fishes is predominantly devoted toward understanding factors that control survival and eventually recruitment. The examination of variables influencing recruitment has been augmented by dramatic advances in the study of microstructural and chemical patterns in fish otoliths; structures that effectively serve as storage sites of chronological environmental information. The present research, supporting a reliable estimate of environmental conditions encountered by an individual larva or juvenile, offers a new approach to the evaluation of critical periods in the early life histories of fishes. Microstructural otolith analyses, in addition to strontium/calcium concentration ratios measured at various positions in the otoliths, provide a reliable indication of past environmental temperatures, and enable an estimate of spawning sites, overwintering movements, and distributions of fall-spawned herring larvae in the Gulf of Maine, specifically those individuals which survive to metamorphosis in the spring and ultimately to recruitment to the juvenile fishery.

INTRODUCTION

Larval recruitment and its implications

The processes that govern recruitment in marine systems are thought to be of critical importance to the population dynamics of individual species. A basic problem in fisheries science is an adequate understanding of the influences that density dependent and stochastic processes have on recruitment in larval fishes and ultimately, on year-class strength. For many fish populations, recruitment seems largely independent of adult spawning stock size, i.e., the production of a larger number of eggs does not necessarily translate into a relative abundance of new recruits. So, large variations in recruitment are generally attributed to agents that affect the growth and the eventual survival of fishes during early life-history.

In many marine populations, recruitment from a planktonic larval stage to an adult existence plays a key role in population structure and life-history patterns (Thorson, 1950; Sale, 1980; Roughgarden *et al.*, 1985; Strathmann, 1985). Fundamental to this larval-adult variation is year-class strength that depends on the survival in the larval population (Rothschild, 1986). Still, the size and structure of the adult population is controlled, at least in part, by environmental factors that are both temporally and spatially removed from the adult habitat (Sette, 1943; Gaines & Roughgarden, 1985; Warner & Chesson, 1985). It is not surprising that it has been difficult to demonstrate the causal relationships between egg production, recruitment rate and adult population structure.

With many factors affecting viability and/or growth of fish larvae, this life-history stage has been considered crucial to the species' survival (Hjort, 1914; Kiørboe & Monk, 1986). Briefly, rapid growth in the earliest stages may be crucial to the survival of individual larvae, and therefore recruitment into latter stages. Besides food, there are other factors that could affect growth rates and subsequent recruitment: 1) level of predation (Murphy, 1967; for herring, Purcell & Grover, 1990), 2) temperature (Laurence, 1973; Houde, 1974; Houde, 1989a; for herring, Townsend & Graham, 1981; Chenoweth, 1970; Purcell & Grover, 1990), 3) ocean currents (Sette, 1943; Parish *et al.*, 1981; Houde, 1989b; McGurk, 1989), and 4) a multi-factor process encompassing all the aforementioned processsess (McGurk, 1989).

Availability of food and predation levels, both density dependent factors, could regulate population size. Temperature, a density independent (stochastic) process has pronounced effects upon the growth and development of an individual larva (Laurence, 1973; Houde, 1974; Townsend & Graham, 1981; Stocker *et al.*, 1985; Houde, 1989a; Purcell & Grover, 1990). Variability in temperatures can result in reduced growth (smaller size at a particular age), thus increasing a larva's vulnerability to predation. This would indicate that temperature can affect larval survival directly and indirectly. Transport by ocean currents, which is also density independent, can carry eggs and larvae to or from areas favorable to survival (McGurk, 1989; Houde, 1989b). The concept of current transport has been used to explain successful year classes of Atlantic mackerel (Sette, 1943), Atlantic haddock (Walford, 1938) and Atlantic herring (Graham *et al.*, 1984, Townsend *et al.*, 1989). These studies underline the importance of developing new techniques and refining existing ones that will enable one to trace life histories in fishes of all ages. Recently, new techniques have been used to delimit life histories in larval and adult fishes (Radtke, 1989b; 1990; Radtke *et al.*, 1988; Radtke & Morales-Nin, 1989; Radtke *et al.*, 1990; Townsend *et al.* 1989).

Growth dynamics clearly differ within and among species and also may play a significant role in regulating recruitment (Houde, 1987; Houde, 1989a; Savoy & Grecco, 1988). Modest changes in daily growth and mortality rates may cause major fluctuations in recruitment (Houde, 1989a). Recruitment fluctuations may be most pronounced if these changes occur in the larval stage (Barlsch *et al.*, 1989) when growth and mortality are high and the initial cohort numbers are large (Houde, 1987). Small deviations from typical daily mortality or growth rates may have a major impact on recruitment (Houde, 1987; Houde, 1989a; Houde, 1989b). Recruitment failure can occur if daily growth rate declines and daily mortality increases simultaneously. Therefore, it is a worthwhile adventure to determine the age of larval and adult fish, the past environmental conditions to which an individual fish has been subjected and the determination of growth patterns as they have been related to these environmental conditions, i.e., temperature, food, etc.

Recruitment variability and the density dependent and stochastic processes responsible for fluctuations in recruitment are key issues in population studies of fish (Sissenwine, 1984). Fisheries of herring have expanded progressively (Graham *et al.*, 1984; Townsend *et al.*, 1989). In the face of overexploitation (e.g., Barlsch *et al.* , 1989), it has become evident that we need to understand the importance that stochastic processes and fishery pressures have upon herring population dynamics. The scientific study of processes that influence population dynamics has been augmented by dramatic advances in the study of microstructural and chemical patterns in fish otoliths - structures that have been shown to serve as storage sites of environmental information (i.e., Radtke, 1984; Radtke, 1989b; Radtke, 1990; Radtke *et al.*, 1987; Radtke *et al.*, 1988; Radtke *et al.*, 1990).

In the ensuing discourse, we will assert that a fresh approach is required to understand the manifold subtleties that affect recruitment processes and life-histories. An advance that takes full advantage of the information stored in calcified tissues. These techniques are urgently needed if we are to proceed with meaningful field studies on the process that modify herring recruitment and population dynamics.

Delimiting larval recruitment, age and growth conundrums using innovative otolith techniques

Otolith microincrement enumeration has proven to be extremely useful in estimating the age and growth of larval and juvenile fishes (Barkman, 1978; Brothers, 1981; Methot, 1981; McGurk, 1984a;

Jones, 1986; Geffen, 1982; Campana, 1989; Radtke, 1989a; Radtke *et al.*, 1989; Tzeng & Yu, 1989; Radtke & Kellerman, 1990- in press). Otoliths are calcium carbonate concretions in the endolymphatic sac of the inner ear of teleost fishes (Lowenstein, 1971; Popper & Coombs, 1980). In addition, otoliths are an exact means by which to age larval fish (Campana & Neilson, 1985; Mugiya & Watabe, 1977). As a result of these emerging methodologies, otolith microincrement and chemical studies have been used to estimate age, growth and life histories in field caught larval Atlantic herring, *Clupea harengus harengus*, in the Gulf of Maine (Townsend & Graham, 1981; Lough *et al.*, 1982; Radtke *et al.*, 1987; Radtke *et al.*, 1990; Townsend *et al.*, 1989).

An enormous amount of concern still exists regarding the rate of otolith increment formation in larval herring. Studies performed by Graham *et al.* (1984) and Townsend and Graham (1981) have shown the effectiveness of adopting the traditional assumption that microincrements are deposited at a daily rate. This critical assumption allowed them to identify and track multiple cohorts of Atlantic herring (Maine) larvae, their success and hatch dates. They were able to examine the polymodal age structure of the larval herring. Previous studies that had relied entirely upon length-frequency methods (Tibbo *et al.*, 1958; Tibbo & Legaré, 1960; Das, 1968, 1972; Sameoto, 1972; Boyar *et al.*, 1973) in evaluating larval populations, were confounded by the inability to identify the occurrences of polymodal length-frequency distributions of larval Maine herring occurring in one geographical location.

Townsend and Graham (1981) made an important assumption that allowed them not only to solve these former difficulties, but also to extend our understanding of the processes that contributed to the polymodal length-frequencies, and the subsequent survival of identifiable discrete cohorts of larval herring. They assumed that otolith microincrements were deposited at a daily basis and back-calculated the date of first increment deposition, hatch dates and cohorts. Many other aspects of larval Maine herring survivability were resolved. First, they were able to identify periods of fast growth (autumn) and periods of slow growth (Jan.-Feb.). The latter was the most critical period to larval survivability - mid winter mortality due to the harshness of the winter environment (Chenoweth, 1970; Graham & Davis, 1971). Yet, the survivors that had contributed to the polymodal length-frequencies would not have been identified as the prodigy of two spawning efforts along the Maine coast, if it were not for the assumption regarding daily otolith deposition rates. Considering these results, they were able to qualify the hypothesis of Graham (1972) while tying its significance to their results: that the polymodal distribution of herring larvae in the Gulf of Maine is due to an earlier hatching east coast larval cohort that eventually drift westward with the Booth Bay Currents, (resulting in more than one age and size class) thus intermingling within the latter hatching west larval cohort. Their growth estimates, based on otolith techniques, were comparable to previous studies and differences were attributed to the problems introduced by the polymodal length-frequencies of multiple age groups and cohorts (Das, 1968; 1972). They were also able to correlate their growth estimates and dates of first increment deposition with previous length-frequency data (Townsend & Graham 1981).

Clearly, one can realize the effectiveness in assuming daily increment formation in larval herring, i.e., its utility in back calculating the time of first increment deposition, thus delimiting larval cohorts (that were a result of consecutive spawning events) that entered embayments and estuaries and their subsequent demise during harsh winter months - January and early February (Townsend & Graham, 1981; Lough *et al.*, 1982; Graham *et al.*, 1984).

Additional otolith studies (chemical studies using the electron microprobe) may provide information on environmental conditions to which a fish has been subjected. Many ions are known to contaminate skeletal aragonite (Magnesium, Iron, Strontium, Calcium, etc.), however, the concentrations may vary according to environmental conditions, such as geography (Calaprice, 1971; Gauldie & Nathan, 1977; Macpherson & Manriguez, 1977), temperature (Gauldie *et al.*, 1980; Gauldie *et al.*, 1986; Radtke, 1984; 1989b; Radtke & Morales-Nin 1989, Radtke *et al.* 1988, Radtke *et al.*, 1989) and pollution (Papdopoulou *et al.*, 1980; Papadopoulou & Kassimati, 1976). Previous studies have also confirmed that age (Bennett *et al.*, 1982) affects levels of contamination and that there are significant correlations with otolith ion content, temperature, body length, and otolith weight in salmon (Gauldie *et al.*, 1986).

With recent advances in electron microprobe techniques, it is theoretically feasible to measure elemental differences within areas of one-square-micron. Such analyses will undoubtably provide us with new levels and capabilities of understanding behavior, migrations, growth and other ecological parameters of commercially important fishes. These techniques have been readily applied to different species (Radtke, 1984; Radtke, 1989b; Radtke & Morales-Nin, 1989; Radtke *et al.*, 1988; Radtke *et al.*, 1990; Townsend *et al.*, 1989).

In our laboratories, we have been refining these techniques to decode the information that is stored in calcified tissues of fishes. Although, it is still in its preliminary stages (Townsend *et al.*, 1989), this aspect of research has involved the systematic verification of the relationship between structural and chemical patterns in otoliths, and the experimental and environmental conditions that contribute to these interactive relationships. The relationships in otolith chemical and structural patterns in experimental and field-caught populations have been identified. Still , the research into relationships in Sr/Ca ratios and temperature should be considered as preliminary, but promising. Thus, we have used otolith microincrements for aging purposes and the measure of Sr/Ca ratios to establish water temperatures during the $CaCO_3$ deposition process. Radtke (1984) has presented data that suggest daily growth increments, when combined with chemical analysis, can be employed to monitor almost daily (patterns) changes in the water temperature to which a fish has been subjected. Within the confines of this technique, it is now conceivable to combine a fish temperature history, invaluable in reconstructing past movements and migrations, with the wealth of information that can be presently extracted from the analyses of daily age and growth rates of an individual fish.

MATERIALS AND METHODS

Sr/Ca ratios were determined in sagittal otoliths from reared and field-caught herring, *Clupea harengus* L. (Radtke *et al.*, 1990).

Microprobe analyses were performed first, then the otolith with the microprobe track marks were transferred from the circular microprobe glass discs, via cutting the glass with a diamond tool to remove the small section of glass to which the otolith was affixed. This specimen was then mounted on a Cambridge type aluminum SEM stub using epoxy resin. The resin was polymerized in an oven at 150 °C for 10 to 15 minutes.

For microprobe analysis, the otoliths were affixed to circular glass microprobe discs using an epoxy resin (Palouse Petro poxy). Otoliths were alternately ground and polished by hand, until the core was attained. This grinding was accomplished by using several grades of wet/dry paper carborundum (600-1200 grit) The polishing was done on a Buelher Ecomet III polisher using PSA backed (8" dia.) Beuhler Masterex polishing cloth with 0.05 micron deagglomerated alumina paste. The samples were washed with distilled H_2O and oven dried at 40°C for 24 hrs. and then stored over dessicant until analysis.

For microprobe analyses, the otolith sections were carbon coated with a layer of approximately 250nM. Electron microprobe analyses was carried out using wavelength dispersive fixed spectrometers on a Cameca Camebex Microbeam microprobe. Analyses were made with a square raster of (5μm) probe current and accelerating voltage were (30 nano-amp) and (15kV), respectively. Samples bombarded with an electron microprobe beam emit X-rays. The wavelength and dispersion of the X-rays is unique to each element and the amount of that element being analyzed, here Sr and Ca. To reduce diffractions of X-rays, and analytical error, specimen discs and standards (Apatite and strontium fluoride) were coated with carbon to further dampen diffraction of resultant X-rays and increase electron conductance. Strontium-calcium concentration ratios were multiplied by a factor of 1000 for presentation.

The areas that were analyzed by microprobe were delineated by increasing the beam current at each position and subsequently marking the otolith by burning the sample. This makes it possible to follow the Sr/Ca concentration ratios analysis transect when examining the otolith by SEM.

Upon completion of microprobe analyses, the samples were transferred onto SEM stubs. They were lightly polished to remove the carbon coating. The specimens were then etched with 8% EDTA (ethylene diamine tetra acidic acid, pH 8.0) for varying periods, usually 3.5 to 5 min. Before viewing these specimens on the Cambridge Stereo scan 150 SEM, the samples were coated with gold in a sputter coater.

RESULTS AND DISCUSSION

Utility of otolith techniques in larval fish studies

The growth axis of the otolith in which regular microincrement deposition occurs, also shows cycles in elemental composition that have been attributed to seasonal changes in temperature (Gauldie & Nathan, 1977; Brothers, 1981; Radtke, 1984; Gauldie *et al.*, 1986; Radtke, 1989b; Radtke & Morales-Nin, 1989; Gauldie *et al.*, 1990). The chemical response of otoliths to changing temperature is species specific (Townsend *et al.*, 1989), yet within species, the elemental composition of otoliths (most notably Sr/Ca ratios) appears to be a good record of ambient temperature patterns, but not the absolute temperatures encountered by an individual fish.

SEM examination of microprobed sagittal otoliths revealed mineral crystals in a protein matrix that formed presumed daily increments (Fig. 1).

The presence of daily microincrements allows us to associate age with elemental composition (Townsend *et al.* 1989). The monomineralic composition of otoliths makes them very favorable to Sr/Ca analysis at a refined level. Radtke (1984) demonstrated that the ratio of Sr to Ca was temperature related, but was not in equilibrium with inorganically precipitated aragonite. A comparison of slopes between the equations for inorganic aragonite and cod-otolith aragonite showed no significant difference ($p > 0.05$). The Sr/Ca ratios in otolith were temperature predictive, but shifted, possibly by biological processes. The mechanisms and processes affecting the interaction between Sr and Ca in the deposition process are most likely complicated and not well understood as highlighted by Kalish (1989).

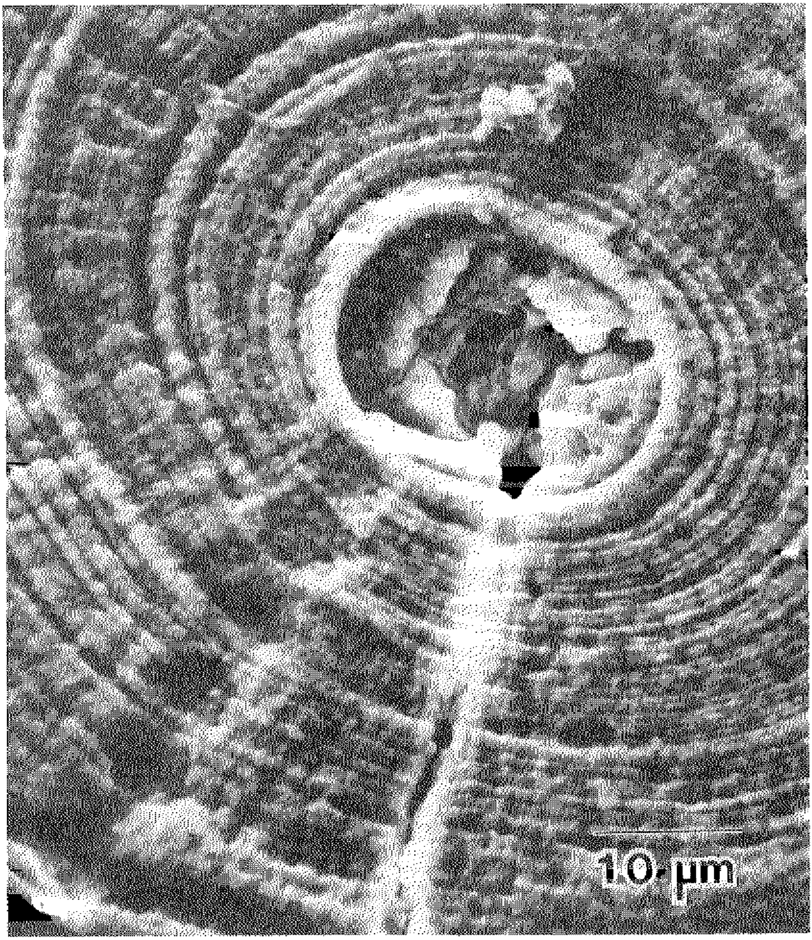

Figure 1. Scanning electron micrograph of the microstructural components of a larval herring otolith captured in Sheepscot river estuary, Maine, 27 January 1987. Note the microprobe path (track) that extends from one side of the core to the opposite edge. Fourteen points were shot, but, not all were visible because three points are in the core itself. Also, the etching and polishing process has removed the integrity of each microprobe location.

The application of the electron microprobe to measurements of Sr/Ca concentration ratios makes it plausible to detect changes on the micro level. The Sr/Ca concentration ratio profile for field caught juvenile cod indicated that the fish may have been in contact with changing water masses. This technique has been applied to blue fin tuna (*Thunnus thynnus*, Radtke & Morales-Nin, 1989), Hawaiian Gobies (Radtke *et al.*, 1988), and larval herring (Radtke *et al.*, 1990; Townsend *et al.*, 1989).

Although absolute temperatures could not be determined, it was suggested from Sr/Ca concentration ratio patterns, that field-caught cod (Radtke, 1984) moved between warmer and cooler water, suggesting that they migrated between inshore (where they were captured) and offshore areas. Sr/Ca concentration ratios from Hawaiian gobies (Radtke *et al.*, 1988) determined the age at recruitment from the planktonic marine phase to the freshwater juvenile phase. This was corroborated with SEM studies and allowed the definition of the "putative settlement mark" (Radtke *et al.*, 1988). Larval herring studies (Radtke *et al.*, 1990; Townsend *et al.*, 1989) in the Gulf of Maine suggest that the successful individuals spend the first winters in offshore waters. These results underline the potential of these techniques to characterize migratory and life history patterns. An example of Sr/Ca concentration ratios for a herring larva captured (27 January, 1987) at Sheepscot river estuary, Maine, can be seen in Figure 2.

Usefulness of otolith microtechniques in larval herring studies

Larval herring studies have been confounded by the frequent occurrence of polymodel length-frequencies of samples (Das, 1968) that cannot be resolved with length-frequency analyses alone. In essence, before aging techniques were used, investigators experienced larvae with different length modes within a single season and geographical location. They stated that earlier-spawned larvae grew faster than later-spawned larvae and modeled growth with curvilinear functions. Townsend and Graham (1981) also reported catches that were polymodel with different growth rates for Atlantic herring, one for larvae that entered Sheepscot estuary on 10 October and another for a group of smaller larvae that entered the estuary on 2 November. There was a reported mortality of the first cohort to enter the estuary, resulting in a unimodal group that was latter joined by another, but smaller group in December. Each group was modeled by regression lines to emphasize that growth was severely retarded during January to February. Evidence from the Gulf of Maine supports the hypothesis that increase in length for herring larvae hatched early in the spawning season is greater than for larvae hatched later in the season. The latter group, however, has a better chance of surviving the winter (Graham, 1982; Townsend & Graham, 1981; Graham *et al.*, 1984). These data, identifiable by multiple cohorts, reflect the spawning consistency and frequency in the Gulf of Maine (Graham *et al.*, 1984). These former, unresolved discrepancies and the resolution of the polymodel length-frequency distributions into discrete cohorts would have been arduous without the assumption of daily increment deposition.

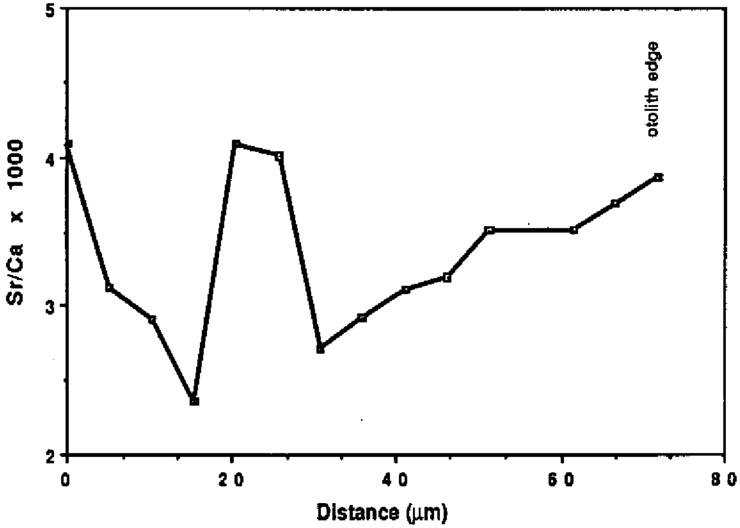

Figure 2. Calculated Sr/Ca concentration ratios for a larval Maine herring. The ratios were plotted against distance (μm). For purposes of verification, points 1 and 5 were on the outer edge of the core. Points 2, 3 and 4 are in the center of the core, thus the microprobe track extends through the otolith core to the edge of the otolith (Fig. 1). The microprobe track length is approximately 75 μm (Fig. 1) and each microprobe mark is approximately 5 μm apart. Points 1, 5 and 6 would appear to verify the microprobe precision, i.e., one could imply that the Sr/Ca concentration ratios are nearly symmetrical for readings corresponding to the same position on either side of the otolith core. The general trend, (increasing Sr/Ca ratio) from points 7-14, would indicate decreasing temperature. (see Radtke, 1984; Radtke, 1989b; Radtke *et al.*, 1990; Townsend *et al.*, 1989).

Before these various size classes are assumed to be caused by differences in growth, there are other hypotheses that should be considered to explain these observations. Differences could result from selective predation, feeding intensities (Lough *et al.*, 1982), activity (Neilson & Geen, 1982), temperature fluctuations (Brothers, 1978; Taubert & Coble, 1977; Townsend & Graham, 1981; Marshall & Parker, 1982), and subtleties in stochastic processes such as dispersal and advection losses that carry larvae from areas ("leaky systems") that are favorable for growth and survival (Houde, 1989b).

If there are intra-seasonal differences in otolith increment deposition rates, growth (change in length at age) could actually be similar, but the calculated growth rates would appear to be different because they are expressed as change in length per increment count. For this hypothesis to explain the above results, larvae hatching early in the season would be required to deposit fewer increments per time period than would those hatching later in the season. When estimated hatching dates are calculated for larvae caught early in the season, under the assumption that increments were deposited every other day, some of these larvae would have had to appear in the plankton in the middle of the summer. Yet, newly hatched larvae are not found in significant numbers in the plankton before September (Boyer *et al.*, 1973; Colton *et al.*, 1968). It is far more plausible that larvae hatch, during optimal growing conditions (Sherman & Honey, 1971; Cohen & Lough, 1983), thus depositing increments with a daily periodicity. Conversely, in order for the former hypothesis to be true, later-hatched larvae would have to deposit increments at a rate greater than 1 increment per day. There is no evidence to support such a conclusion.

Differences in population growth rates within a single spawning season also could result from a shift in size-specific mortality of larval cohorts during the season (Townsend & Graham, 1981; Graham *et al.*, 1984; Houde, 1989a). The observed differences in growth rate could result if early-hatched larvae have higher cumulative mortalities for slower growing individuals, while late-hatching larvae have higher mortalities for faster growing individuals. Progressively, fewer and fewer of these discrete cohorts would be seen in older ages. This would result in differences in population growth rates that are not significantly apparent for individuals within the population.

Although, differential mortality cannot be dismissed with the available data (Townsend & Graham, 1981), the most plausible explanation for the differences in length-at-increment counts are an actual difference in multiple cohort growth rates that have resulted from smoothing over by high mortality of one or more cohorts or differential growth rates over the multiple spawning season (Townsend & Graham, 1981; Graham *et al.*, 1984). Such differences in larval growth are inherent to their survival, since greater time spent in the larval stage (slow growth or retarded development) is thought to be related to increased predation and mortality.

The ubiquity of daily increments in fish otoliths

The discovery of daily rings in otoliths (Pannella, 1971) and its first application in determining the age of larval fish (Brothers *et al.*, 1976) have allowed investigators independently to study and construct growth curves that have served to validate and resolve the ambiguities involved with statistical length-frequency studies. Enclosure and laboratory rearing experiments (Brothers *et al.*, 1976; Geffen, 1982; Laroche *et al.*, 1982; Lough *et al.*, 1982; McGurk, 1984a; Campana, 1989; Tzeng & Yu, 1989; Moksness & Wespestad, 1989) have supported the assumption that growth rings of healthy, growing fish are deposited at rates of 1 increment per day at or soon after hatching. Although, there have been controversial results concerning the deposition rates in labortory reared larval herring, *Clupea harengus harengus* and *Clupea harengus pallasi* (reviewed by Jones, 1986; Moksness & Wespestad, 1989), the variations in microincrement deposition that is positively correlated to growth rate (Geffen, 1982; McGurk, 1984a; Moksness & Wepestad, 1989), could be attributed to the sample size (Jones, 1986; Moksness & Wespestad, 1989), the size and conditions of the rearing facilities (Geffen, 1982; Lough *et al.*, 1982; McGurk, 1984a; Moksness *et al.*, 1987) and experimental perturbations (for salmon, Neilson & Geen, 1985).

There is evidence from the field that increment deposition is not always daily in larval fish living under stress (reviewed by Campana & Neilson, 1985; Jones, 1986). Townsend and Graham (1981) reported that Atlantic herring larvae of the Sheepscot estuary, Maine, exhibited interrupted growth in length and interrupted ring deposition during a 2-3 week period in late January and early February 1979 that indicates the extreme environmental conditions and low food densities during the winter.

Light microscope studies have shown that the rate of otolith increment deposition in known-age larval herring are not daily (Lough *et al.*, 1982; McGurk, 1984a). These obvious dicrepancies point to the possibility that larval herring may lay down daily increments, but ones that are beyond the functional resolution of light microscopy (reviewed by Campan & Neilson, 1985; Jones, 1986; Campana, 1989). The resolution hypothesis provides a causal and empirical explanation of apparent microstructural anomalies through a biological and physically plausible mechanism. The hypothesis states that daily increments with widths below the functional resolution limits of the microscope-observer system can and do form in some larval otoliths. Since these increments would not be visible as distinct structures with light microscopy, an apparent increment formation rate of less than one would result. The strength of the hypothesis lies in its precise mathematical prediction of age-count anomalies and its intended explanations of apparently unrelated phenomena.

Can daily increments form with widths that are unresolvable by light microscopy? The results of an otolith daily growth model Campana *et al.* (1988) indicated that daily otolith growth in the first two weeks after hatch was insufficient to be resolved as discrete daily growth increments with a light microscope. Given the fit of the model and the magnitude of the predicted values, this conclusion is unambiguous even if increment formation started 4.5-6 d after hatch, as has been inferred elsewhere (Geffen 1982; Lough *et al.* 1982; McGurk 1984a). Support comes from the microstructural examination of chinook salmon (*Oncorhychus tshawytscha*) otoliths, where the SEM was used to detect narrow daily increments formed at 5°C (Neilson & Geen 1982), while increment formation had apparently stopped at this temperature when assessed by light microscopy (Marshall & Parker, 1982). In the latter instance, light microscopic increment counts seriously underestimated the number visible under SEM. The conclusion that narrow daily increments were formed in the otoliths of the larval herring at or shortly after the time of hatching is consistent with the resolution effects reported by other workers. As suggested by Jones (1986), it may be necessary to access those otoliths that appear not to have daily increments with the SEM. We can assume that daily increments in larval fish otoliths are a ubiquitous phenomenon (Jones, 1986) and that this presumption will serve to elucidate and circumvent problems that arise from length-frequency and growth studies that are not age validated.

Acknowledgements

Support for this study was from National Science Foundation Grants OCE-86-175221, OCE-88-17939 and OCE-88-00686 to RLR and National Science Foundation Grants OCE-86-17522 and OCE-88-17939 to DWT. Thanks are due to Brian Shepherd for reviewing and revising the manuscript.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Spring Spatial Distribution Patterns of Larval Atlantic Herring (*Clupea harengus*) Along the Maine Coast

D. Stevenson,[1] T. Aarup,[2] D. Libby,[1] and D. Townsend[2]
[1]Maine Department of Marine Resources
W. Boothbay Harbor, Maine
[2]Bigelow Laboratory for Ocean Sciences
W. Boothbay Harbor, Maine

Atlantic herring spawn in the western Gulf of Maine in the summer and fall. Larvae over-winter in coastal waters and inshore embayments and estuaries. Larvae that over-winter in coastal waters are presumed to migrate inshore in the spring before metamorphosing to juveniles. Juveniles remain in nearshore waters and recruit to the fishery a year later at age 2. The Maine Department of Marine Resources (MDMR) has monitored the abundance of herring larvae along the Maine coast in late March and early April every year since 1965 for the purpose of forecasting recruitment. Results of these surveys have never been analyzed for the purpose of determining spatial distribution patterns along the coast. The presence of a consistent distribution pattern would indicate areas of the coast where migrating larvae aggregate just prior to metamorphosis. Spring larval aggregations could be exposed to favorable or unfavorable mesoscale environmental conditions which might affect larval growth, survival and recruitment success (e.g., increased primary and secondary production during and after the spring phytoplankton bloom in areas with a shallow, near-surface mixed layer).

The purpose of this study was to examine five consecutive years of spring larval survey data for spatial distribution patterns and determine whether or not larvae were aggregated in areas with defined pycnoclines and elevated surface chlorophyll values.

Spring MDMR survey estimates of larval density (number of larvae per m^3) were compiled from 22 inshore stations in three locations and 37 coastal stations along 300 km of the Maine coast for the period 1984-88. Inshore tows were made from the surface to the bottom at the same stations every year and averaged to produce a single density estimate for each area. Offshore tows were made in the top 20 m each year at randomly selected locations within 10 minute squares of latitude and longitude. Additional larval distribution data were available from 55 tows made during a single 1984 spring survey over a larger area of the gulf.

Normalized annual latitude, longitude, and relative larval density data were subjected to cluster analysis as were the combined 1984-88 data. Selection of the most likely analysis (number of clusters) in each case was based on between and within group sums of squares values for K = 2 to 10 clusters. The 1984 larval distribution data were compared with ship-board observations of surface temperature, salinity, and chlorophyll and chlorophyll estimates derived from two satellite passes (March 24 and April 1) in order to examine possible relationships between larval distribution and physical and biological parameters.

Results indicated that larvae were more concentrated in certain areas. Although the distribution patterns shifted somewhat from year to year, densities were generally higher near the coast and inshore than offshore. High densities in the combined 1984-88 data set were clustered at five adjacent inshore and nearshore locations in the western sector of the coast (e.g., Casco and Muscongus Bays), at a single nearshore station at the western end of the survey area, and at the inshore locations (including Frenchmans Bay) and an adjacent nearshore station in eastern Maine. High larval densities in western coastal waters were associated in 1984 and 1986 with slightly lower surface salinities (and a shallow pycnocline), but not in 1985 when salinity values were high along the entire coast at the time of the survey. Surface chlorophyll values were high during the 1984 surveys in western nearshore waters and low offshore. All locations with < 3 µg per liter chlorophyll on March 24 had very low larval densities while locations with chlorophyll values of 3 to 5 µg per liter were associated with low and high larval densities. Larval densities were variable over the full range of estimated chlorophyll values obtained on April 1.

These results demonstrated that herring larvae aggregate in nearshore waters along the Maine coast in the spring, particularly in the western portion of the coast. Aggregations in western nearshore waters were associated in some years with reduced surface salinities and a shallow pycnocline produced by spring river runoff and, to some extent, with elevated 1984 spring chlorophyll values. However, in the absence of any convincing or consistent relationship with either of these parameters over the entire survey area, we were unable to demonstrate that larvae congregated in areas with increased primary or secondary production in the spring.

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Diel Vertical Movements of Atlantic Herring in Relation to Food Availability and Abundance

R.L. Stephenson and M.J. Power
Department of Fisheries and Oceans
St. Andrews, New Brunswick, Canada

ABSTRACT

Herring larvae remain aggregated, or are retained, off southwest Nova Scotia in the Bay of Fundy for a period of months in spite of considerable residual flow through the area. Repetitive discrete depth sampling (at approximately 3-hour intervals for 3-7 days) within the patch on three separate occasions (1985, 1987, 1989) showed distinct vertical movement. Although vertical movement provides a potential mechanism for retention, the explanation is confounded by the fact that the pattern of movement is apparently diel rather than tidal. Depth-stratified plankton samples corresponding to the larval herring series were taken with a pump on two occasions (1987, 1989) to test the hypothesis that the pattern of vertical movement was related to prey availability. The 1987 pump data were found to be non-representative due to the use of a 85-µm mesh sieve which allowed extrusion of small invertebrate eggs, a key diet item of herring larvae. The 1989 pump samples using a 53-µm mesh sieve was more appropriate for retention of larval food items of a size found in their guts. Gut contents were dominated by calanoid copepods, the copepod *Oithona* and invertebrate eggs. Pump samples indicated that items were all prevalent in the water column but that there was preference for calanoid copepods. Major food items showed no vertical structure which would help explain the diel vertical movement of larvae. A pilot study of the horizontal distribution indicated heterogeneity in larval herring distribution on scales of less than 200 m and greater than 1000 m, suggesting horizontal as well as vertical patchiness.

INTRODUCTION

The dynamics of herring larvae have been studied for a variety of reasons, ranging from the use of larval abundance as an index of stock size through the role of the larval stage in determination of recruitment to the potential importance of the larval period in the determination of herring stock structure. Indeed, Atlantic herring larvae have featured in the development of several major hypotheses which have been extended to larval fish dynamics generally including: "match/mismatch" (Cushing, 1975), "larval retention" (Iles and Sinclair, 1982) and "member/vagrant" (Sinclair, 1988).

The distribution of larvae from the southwest Nova Scotia (NAFO Div. 4WX) herring population (which is the largest in the western Atlantic) has been documented in annual autumn surveys for 18 successive years. Results of the annual larval surveys are used in an abundance index for stock assessment (Stephenson et al., 1990a, b). Perhaps more significantly, observations on this large and well defined larval aggregation have been critical to development of both the larval retention and member/vagrant hypotheses. It was in this context that we began studies of the dynamics of herring larvae off southwest Nova Scotia in 1985. Of particular interest at that time was the question of vertical movement, which had been hypothesized by Iles and Sinclair (1982) as a mechanism for larval retention. Interestingly, this was one of three studies of vertical movement of herring larvae which evolved independently about the same time (the others by Munk et al.(1989) and Heath et al. (1988)) - likely the products of similar interest in larval herring dynamics and improved technology (surface-controlled opening and closing nets).

We set out in 1985 to test for vertical movement and have continued with site-specific field work every second year to elucidate further aspects of vertical movement by herring larvae. Previous papers (Stephenson and Power, 1988, 1989) have described semidiel and diel patterns of vertical movement observed in 1985 and 1987. Another paper in this symposium (Stephenson and Sochasky, 1990) deals with the occurrence of herring very near bottom.

In this paper we i) present the 1989 pattern of vertical distribution and compare it with previous years; ii) discuss results of a preliminary investigation of the scale of horizontal distribution; and iii) present initial findings from a study of the interaction between vertical movement and food distribution.

METHODS

Studies were undertaken in late October or early November 1985, 1987 and 1989 (Table 1) at a single site of 60 m depth off southwest Nova Scotia (43°55'N, 66°25'W). This site has been shown by annual synoptic spatial surveys (using standard "sawtooth" bongo sampling; Stephenson et al., 1990a) to be within a persistent aggregation of high larval abundance (Fig. 1). Sampling of larvae was based upon repetitive tows at discrete depths using the MININESS (Reid et al., 1987), a device with a square mouth opening of 0.25 m^2 equipped with nine nets of 0.333-mm mesh, monitored and triggered from the surface.

The pattern of vertical movement of larvae was assessed from samples collected at six (5, 10, 20, 30, 40, 50 m) or seven (additional sample at 55 m)

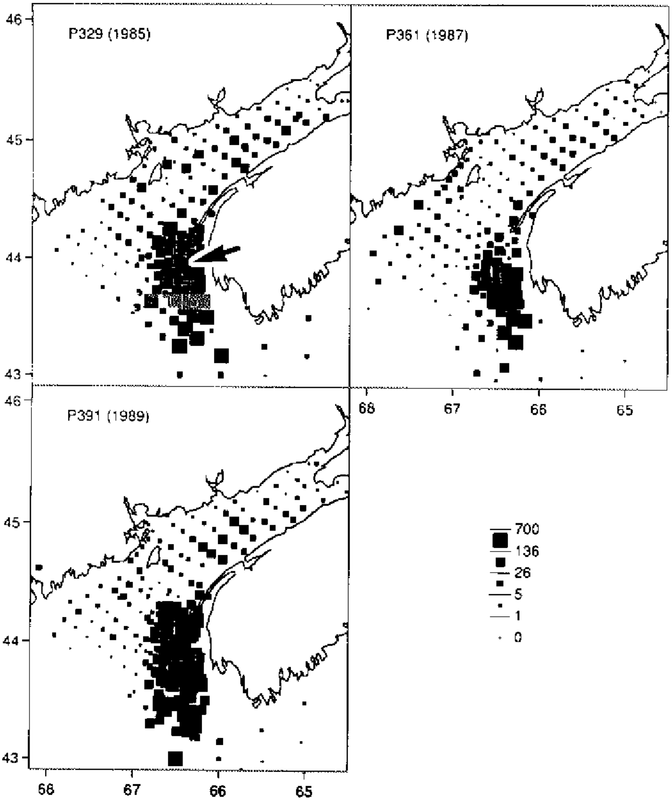

Fig. 1. Density (number·m^{-2}) of herring larvae from synoptic spatial surveys of the Bay of Fundy using oblique bongo tows from the research vessel "E.E. Prince" in 1985 (Cruise P-329; 22 October-13 November), 1987 (P-361; 21 October-11 November) and 1989 (P-391; 23 October-9 November). The arrow marks the location of site-specific studies of vertical movement.

Table 1. A summary of sampling of herring larvae in site-specific studies of vertical movement off southwest Nova Scotia in 1985, 1987 and 1989.

Year	Dates	Cruise	Study	Notes
1985	Nov. 7-13	Lady Hammond; H145	48-h vertical movement	ca. 3-h intervals Nov. 8-10
1987	Oct. 24-30	Lady Hammond; H181	-7.5 d vertical movement -60 h pump -5.0 d horizontal series	ca. 3-h intervals " "
1989	Oct. 29-Nov. 1	Lady Hammond; H207	66-h vertical movement alternating with pumps	3-h cycle throughout

discrete depths from the bottom to the surface (Fig. 2) with a tow duration of 10 min (1985), 5 min (1987) or 3 min (1989) at each depth at a speed of 3.5 knots. Repetitive samples during the time series (Table 1, Fig. 3) started from the station at approximately 3-hour intervals. Additional sampling (of food items and of horizontal distribution, for example) was undertaken after the ship returned to the sample site, between standard MININESS sets.

Whole MININESS plankton samples were preserved immediately in 5% buffered formalin in the field, and herring larvae were sorted, measured and enumerated in the laboratory within 6 months of collection.

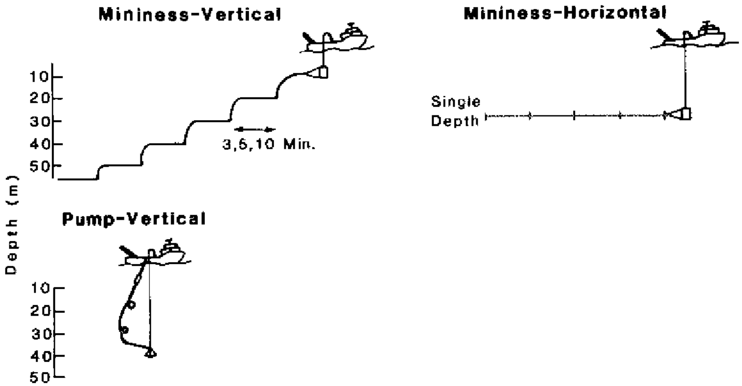

Fig. 2. Diagramatic representation of sampling protocol using the MININESS for vertical and horizontal sampling and the pump for potential food items during studies of the dynamics of herring larvae off southwest Nova Scotia.

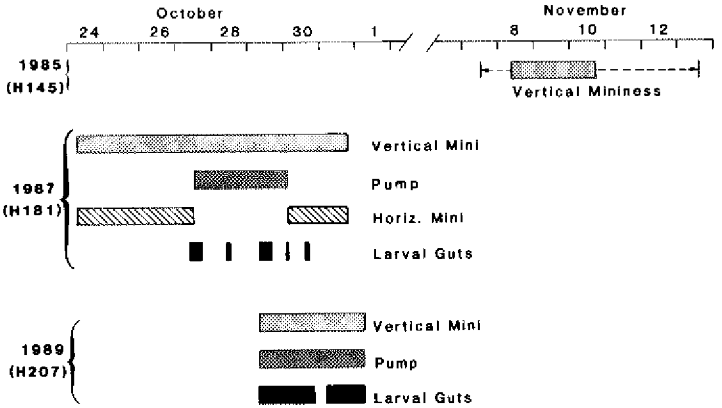

Fig. 3. Sample plan for studies of herring larvae at a single site off southwest Nova Scotia in 1985, 1987 and 1989.

In 1987, and again in 1989, samples were collected to test whether the vertical movement of larvae was related to that of food items. Larvae for gut content analysis were picked from MININESS samples at sea immediately following each tow, and were preserved in vials of 95% ethyl alcohol. Additional larvae stratified by 1-mm length groups were obtained during sorting of the plankton sample up to a maximum of 15 per sample. Individual larvae were dissected under 50x magnification and gut contents identified to species where possible and to developmental stage where relevant. Invertebrate eggs were enumerated and unidentifiable "organic residue" noted.

In a preliminary study to test for horizontal patchiness of larvae, the MININESS was used to sample variation in density in the horizontal plane. In a series of tows at approximately 3-hour intervals, between Oct. 24 and 30, 1987, the MININESS was flown at the depth corresponding to the maximum larval abundance (as estimated from the previous vertical MININESS set, 1-1.5 hours earlier), and nets were tripped at time periods corresponding to distances of 50, 100, 200, ... 1100 m (Fig. 2). Within each set, nets were tripped at periods of equal length, but that distance was assumed without pattern for each set. Actual distances were calculated from flowmeter readings, and nets were rejected if they were not within 10 m of the target distance for 50- and 100-m intervals or if not within 25 m of the target distance for 200 m+ intervals.

A study of the abundance of potential food items was undertaken using a Flygt Model 2051 submersible pump. A 2" diameter hose was lowered on a rosette water sampler to 50, 40, 30, 20 and 10 m (Fig. 2). Water from each depth was strained, first through a 333-µm net to remove large zooplankton, then 85-µm (1987) or 53-µm (1989) within a tank of water aboard the ship for approximately 5 min (1500 L; 1989 and half of 1987) or 10 min (3000 L; half of 1987).

Whole pump samples were preserved as for the MININESS samples. In the lab, these samples were split using standard beaker or stemple pipet techniques (VanGuelpen et al., 1982) to obtain subsamples with a minimum of 200 items which were identified to species if possible.

RESULTS

Vertical distribution of herring larvae

Repetitive depth-stratified sampling showed that herring larvae were aggregated vertically and that the depth at which larvae were aggregated varied over time in each survey (Fig. 4). The depth of maximum density ranged through most of the sampled water column (5-55 m in 1985 and 1989, 10-55 m in 1987) and the pattern was also apparent in the calculated centre of mass (ZCM):

$$ZCM = \sum_{i=1}^{x} p_i \cdot Z_i$$

where p_i = proportion of larvae (for a particular set) occurring at depth i, and Z_i = sample depth in meters (Fig. 4).

The pattern of vertical movement appeared to be semidiel (two ascents per day) in 1985, but diel (single ascent per day) in 1987 and 1989. In all cases, larvae were highest in the water column by day. In analysis of the 1987 data (Stephenson and Power, 1989), the pattern of depth distribution was

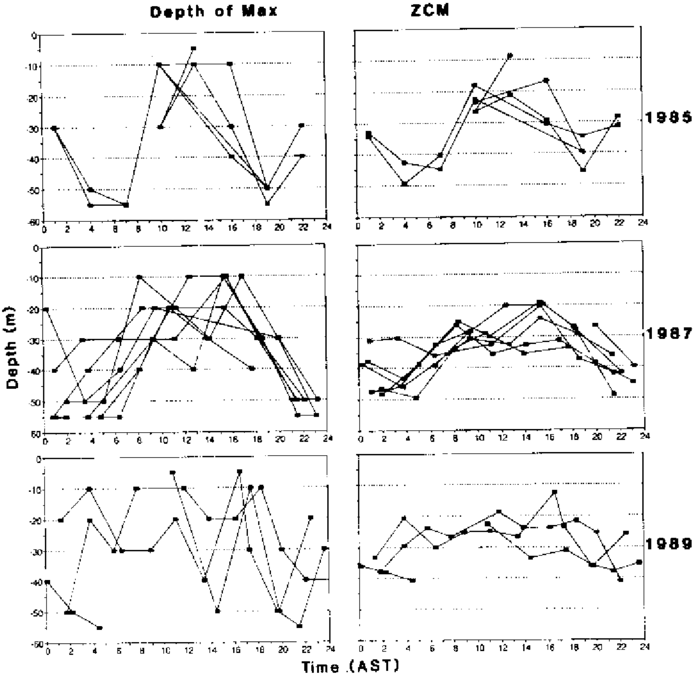

Fig. 4. Depth of maximum concentration (left) and calculated centre of mass, ZCM (right) plotted against sampling hour (local Atlantic Standard Time) from vertical series taken at approximately 3-h intervals with the MININESS at 43°55'N, 66°25'W off southwest Nova Scotia during the periods 7-13 November 1985 (upper; from Stephenson and Power, 1988), 24-30 October 1987 (middle; from Stephenson and Power, 1989) and 29 October-1 November 1989. Results from adjacent samples in each survey are joined by lines.

linked to time of day rather than to tide, and this is again indicated in 1989 results.

Horizontal variation in larval abundance

Sampling in the horizontal plane indicated changes in variances and mean estimates of larval density over the 50-1100 m scales examined (Fig. 5a). At distances of 200-1000 m, the mean ranged from 1-5 larvae/10 m with a standardized variance (variance/distance^2) generally less than 0.15. At short (50, 100 m) and long (1100 m) distances, the variance (Fig. 5b) and mean were higher.

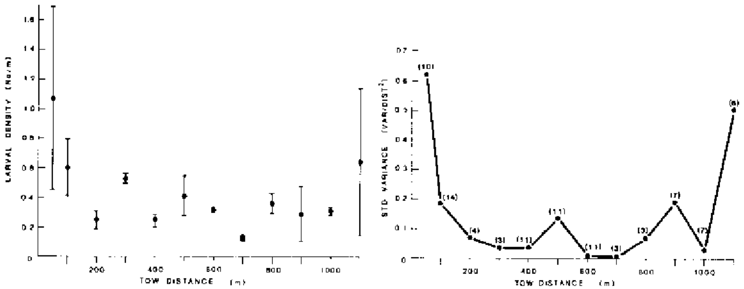

Fig. 5. Larval density (number per m ± SD; left) and standardized variance (variance/distance^2) from repetitive horizontal tows with the MININESS over tow distances of 50-1100 m. Sample size (number of valid nets at each tow distance) are shown in parentheses).

Larval gut contents and potential prey

In a preliminary study in 1987, the gut contents of 376 larvae were analyzed. Most (357) were taken in daylight sets over the depth range 5-50 m (Table 2). All larvae captured at night had empty guts. Fewer than half of the larvae from daytime sets (144; 40%) had food items in the gut, and these were dominated by invertebrate eggs and calanoid copepods. Pump samples at the same time were dominated by calanoid copepods, *Oithona* sp. and copepod nauplii. Very few invertebrate eggs were found but, unfortunately, measurements of invertebrate eggs from larval herring guts indicated that they could have passed through the 0.085-mm mesh used in collection of pump samples.

Table 2. Distribution of herring larvae (number) analyzed in gut content study.

	1987	1989			
Depth (m)	Day	Total	Day	Night	Twilight
0-5	-	12	10	-	2
5	12	144	72	46	26
10	72	187	100	50	37
20	72	184	94	50	40
30	72	180	91	49	40
40	66	169	81	54	34
50	63	148	66	43	39
55	-	113	46	51	16
Total	357	1137	560	343	234

In a more extensive study in 1989, gut content analysis was undertaken on 1137 larvae. These were distributed among day (0730-1730 h AST), night (1830-0600 h) and twilight periods, and over depth as indicated in Table 2. Most (99%) had at least unidentifiable remains in the gut. Only 31% (351) had identifiable remains, and most of these (321) had a single item. Those with identifiable gut contents occurred in all time periods and depths. Of the identifiable food items in larval herring guts, most were calanoid copepods (82%), *Oithona* sp. (9%) and invertebrate eggs (4%).

Pump sample analysis from the same time period showed a dominance of copepod nauplii, invertebrate eggs, the copepod *Oithona similis* and calanoid copepods. Pump results for the three major food items (Fig. 6) indicate temporal changes in availability. Abundance of the two copepod groups increased for about a 12-hour period during the first night of the series. There was an increase in invertebrate eggs on the second day, which persisted until the end of the series. These temporal changes were apparent throughout the water column, and there was no clear evidence of vertical structure or vertical movement in prey items.

Calanoid copepods were apparently being selected by larvae, in that they were less abundant than invertebrate eggs in the environment, but dominant in gut contents.

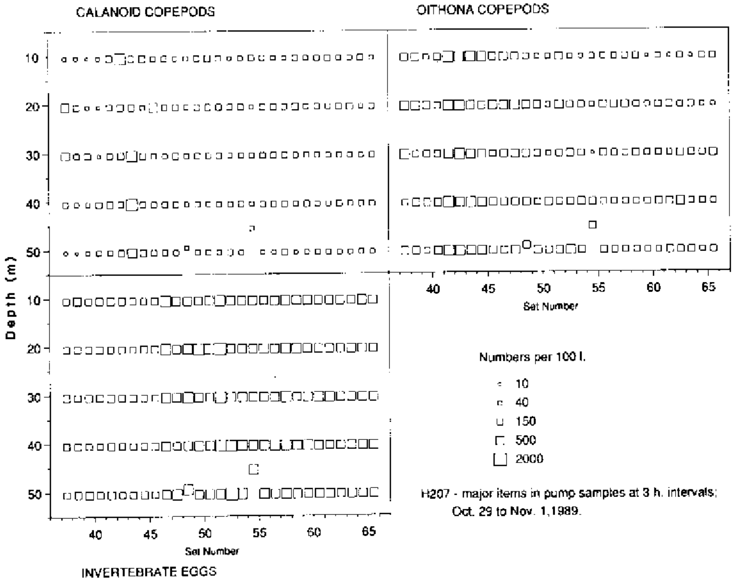

Fig. 6. Distribution (no./100 L) by depth and set of calanoid copepods, *Oithona* copepods and invertebrate eggs from repetitive pump samples at a single location off southwest Nova Scotia, 29 October-1 November, 1989.

DISCUSSION

Larval herring remain aggregated off southwest Nova Scotia in spite of a strong net residual current. Previous studies of vertical distribution of larvae within the patch showed marked vertical movement through most of the water column but with different patterns in 1985 and 1987 (Stephenson and Power, 1988, 1989). The results from 1989, presented here, are consistent with previous observations. There was clear vertical movement of larvae through most of the water column and evidence that the larvae were higher in the water column by day - but some differences in the depth of maximum occurrence at night which indicates plasticity in the pattern.

The pilot study of horizontal distribution indicates heterogeneity in larval distribution on a scale less 200 m and greater than 1000 m. This suggests horizontal as well as vertical patchiness of larvae within aggregations - and that larvae may be distributed as discs, rather than as a layer.

Gut content analysis showed that herring larvae were feeding specifically and that calanoid copepods, *Oithona* and invertebrate eggs were the most important food items. Of these, there appeared to be selection of calanoid copepods.

This study does not support the hypothesis that larvae were moving vertically to feed, in that food items were available in equivalent numbers throughout the water column and did not show the same type of aggregation or movement demonstrated by larvae.

ACKNOWLEDGMENTS

We acknowledge the support of the officers, crew and scientific staff of the LADY HAMMOND (cruises H-145, H-181 and H-207). We are indebted to Jim Reid for support with the MININESS system with which the discrete depth larval samples were collected and to John Tremblay for providing the plankton pump system. We acknowledge the role of the Atlantic Reference Centre (Huntsman Marine Science Centre), particularly Beverly McFarlane, Geirhart Pohle and Lou Van Guelpen in plankton sample sorting and identification, and gut content analysis. We thank Bill McMullon and Frank Cunningham for preparation of figures and Brenda Best for preparation of the manuscript.

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Epibenthic Occurrence of Atlantic Herring Larvae During a Study of Vertical Migration: Implications for Traditional Sampling

R.L. Stephenson and J.B. Sochasky
Department of Fisheries and Oceans
St. Andrews, New Brunswick, Canada

ABSTRACT

Herring larvae are known to undergo pronounced vertical migrations. Our studies using depth-discrete sampling nets (MININESS) at a single location near the centre of the large larval retention area off southwest Nova Scotia have shown that the major concentration of larvae available to traditional plankton gear varies sharply from a comparatively shallow depth of 10 m down to the lowest limit the gear can safely be fished - 5 m off bottom (55 m depth at this location).

To reveal whether many larvae might at times be unsampled below the limits of traditional plankton gear, an epibenthic sled with two nets arranged 0.5 and 1.25 m above the bottom was fished for a 24-h cycle at the same times and location as the MININESS. Like the MININESS nets, both of these near-bottom nets collected significant numbers of larvae, numbers sometimes as high as the maxima available to traditional gear. Moreover, the times of high catches in the epibenthic sled corresponded to the times when the MININESS showed greatest catches in its deeper samples.

We do not expect the epibenthic sled catches to be directly comparable to MININESS because of higher avoidance of the sled (the sled nets are smaller and the tow cable disturbs the water sampled). Nonetheless, it is clear that traditional plankton sampling gear systematically misses a significant and variable proportion of the larval herring population because large numbers of herring larvae appear to migrate right to the bottom at some times of the tide or day.

The volume of water filtered by the nets in epibenthic sled varied systematically with the time of the tide, revealing a hydrographic (as distinct

from biological) bias to the sampling by traditional plankton gear whose depth is not monitored continuously while it is fished. That is to say, we observed that the current experienced by the sampling gear near the bottom was different in speed and direction relative to the vessel towing it; this means that warp lengths, descent rates, warp angles, etc. may not necessarily give a representative idea of the depths actually achieved.

We present in this paper some of the results of this study with particular emphasis to its implications for the sampling of larval herring populations.

INTRODUCTION

Studies of larval fish dynamics have often documented some degree of vertical movement or "migration" on a scale of hours (see, for example, reviews by Iles and Sochasky, 1985; Neilson and Perry, 1990). These movements have usually been interpreted as diel or tidal events and linked to feeding, predator avoidance and/or maintenance of position (i.e., larval retention). Few studies, however, have attempted to describe the behavior, or even the occurrence, of larvae in close proximity to the bottom - in spite of the recognition that larvae may occur below the depth limit of traditional plankton gear, thereby causing a possible time-dependent bias in sampling (Iles and Sochasky, 1985; Stephenson and Power, 1988; Neilson and Perry, 1990).

Atlantic herring larvae are known to undergo pronounced vertical movement. Our studies using depth-discrete sampling nets (MININESS) repetitively at a single location near the centre of the large larval retention area off southwest Nova Scotia (Fig. 1) have shown vertical movement through the entire sampled water column (5-55 m, at a site of 60 m depth) in 3 years, in what appeared to be semidiel (1985) and diel (1987, 1989) patterns (Stephenson and Power, 1988, 1989, 1990: this volume). In all years, samples from as near the bottom as the MININESS could safely be fished (5 m off bottom; 55 m at this location) often contained the maximum larval densities per set, reinforcing questions (Iles and Sochasky, 1985) of whether significant numbers of larvae may have been unsampled below traditional sampling gear and, particularly, whether herring larvae occur in significant numbers very near bottom.

In addition, and of particular relevance to this study, is the presumed link between vertical movement and larval retention (Iles and Sinclair, 1982). Occurrence near the bottom would result in a great reduction in, and possibly avoidance of, the influence of major tide-induced currents (as discussed in Iles and Sochasky, 1985; Neilson and Perry, 1990) which diminish with depth (Tee et al., 1987) and thus provides a potential mechanism for retention.

Here we report the results of a study of the epibenthic distribution of herring larvae, undertaken as part of the 1987 study of vertical movement.

METHODS

The vertical distribution and abundance of herring larvae were studied with repetitive sampling at a single 60-m site of traditionally high herring abundance (43°55'N, 66°25'W) within the larval retention area off southwest Nova Scotia (Fig. 1) during the period October 24-30, 1987. In simultaneous studies by three research vessels, the near-bottom abundance of herring larvae was sampled using a benthic boundary layer (BBL) sled (Fig. 2a; J.L. HART cruise J038; October 27, 29, 30), the vertical distribution of larvae within the water column (5-55 m) was sampled using the multiple opening/closing discrete-depth MININESS sampler (Fig. 2b; LADY HAMMOND cruise H181; October 24-30) and the overall larval abundance was monitored in repetitive oblique tows with traditional bongo nets (Fig. 2c; E.E. PRINCE cruise P361; October 24-28).

The BBL sled (Wildish et al., 1990; Fig. 2a) carries two rectangular net frames of 0.22 m^2 mouth area (0.55 m across by 0.40 m tall) situated 0.33-0.73 and 1.09-1.49 m above the sled's "toboggan" bottom plate. Both frames are equipped with louvers which prevent the nets (0.505-mm mesh) from fishing except when the sled is in contact with the bottom. Standard sets involved tows of about 20 min duration (from "all-out" to the beginning of "haul-back") at a ship speed of 3.5 knots, and were undertaken into the expected current (to minimize potential damage in the event of "fetching up"). Due to operational limitations of the J.L. HART and weather, the 24-hour series of tows was split, so that sets were made hourly from 0900-1800, October 27 and at 1.5-hour intervals from 1900-0430, October 30.

The MININESS (Reid et al., 1987; Fig. 2b) had a square mouth area of 0.25 m^2 and was equipped with nine sets of 0.333-mm mesh. Gear depth and performance were monitored continuously and nets were opened and closed from the surface. Seven discrete depths were sampled (5, 10, 20, 30, 40, 50, 55 m) although, at low tide, the 55-m depth was not possible as we prefer not to use the MININESS within 5 m of bottom. Forty-seven sets were made at approximately 3-hour intervals from 0600 October 24 through 1900 October 30. Each set began at the station and involved tows of 5 min per net, working from deepest depth sampled to 5 m at a ship speed of 3.5 knots.

Paired 61-cm (0.29 m^2) bongo nets (0.505-mm mesh) (Posgay and Marak, 1980; Fig. 2c) equipped with General Oceanics Model 2030 flowmeters were fished in a sawtooth oblique fashion at a ship speed of 3.5 knots. Set and haul rates were 50 and 20 m/min, respectively. If the initial retrieval time was less than 10 min, the gear was payed out again for subsequent hauls until a minimum total retrieval time of 10 min was obtained. Two hauls were normal for this location. The gear is normally fished to within 5 m of the bottom, but in the absence of adequate telemetry, warp lengths necessary to achieve this depth were estimated trigonometrically. Bongo casts were made from the E.E. PRINCE as frequently as operational conditions permitted; 20 casts were made from 0800-2400 on October 24, 17 casts from 0600 to 1800 on October 25 and 20 casts from 0900 October 27 to 0930 October 28.

All plankton samples were preserved immediately in 5% buffered formalin, and ichthyoplankton was sorted and identified in the laboratory within 4 months of collection. Larval herring densities are expressed as numbers per cubic metre filtered or as number per square metre to bottom.

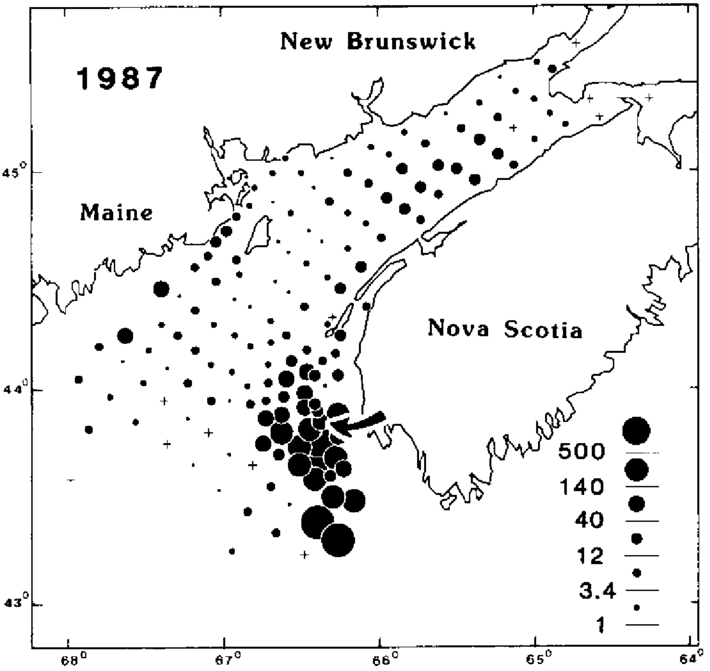

Fig. 1. Spatial distribution of larval herring (density, no. m^{-2}) in the Bay of Fundy and eastern Gulf of Maine from the 1987 synoptic survey using bongo nets (E.E. PRINCE cruise P361) October 21-November 11, 1987. Arrow marks the location of the site-specific study of vertical and epibenthic distribution.

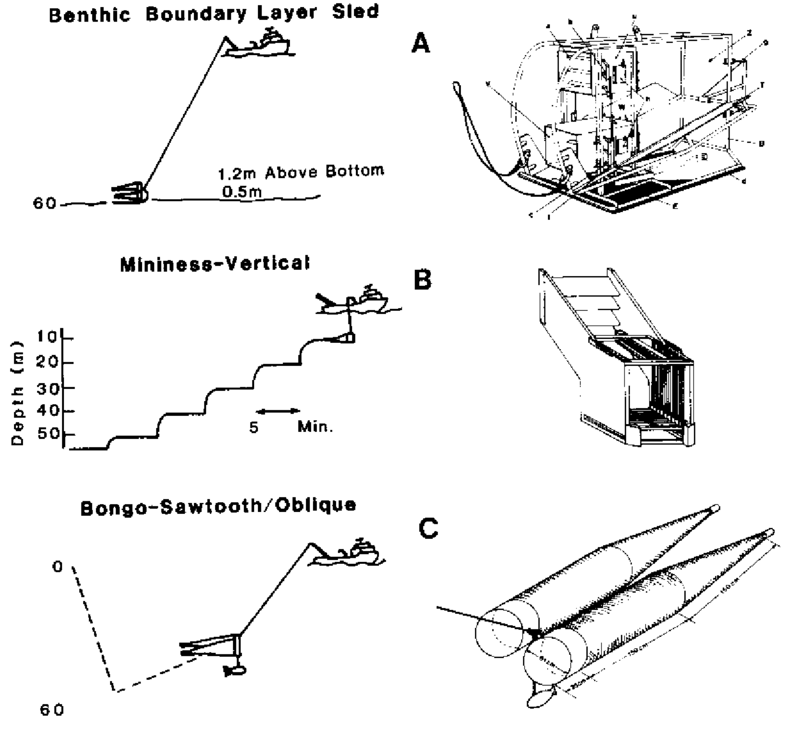

Fig. 2. Schematic diagrams of the benthic boundary layer (BBL) sled (A) which fishes only when in contact with the bottom, the multiple opening and closing MININESS (B) which was used to fish individual nets at seven discrete depths, and the traditional bongo net (C), used for an integrated (oblique/sawtooth) sample from the surface to 5 m above bottom.

For MININESS samples, the vertical distribution of larvae can also be expressed as the mean centre of mass (ZCM) calculated (as in Fortier and Leggett, 1983) as follows:

$$ZCM = \sum_{i=1}^{x} p_i \cdot z_i$$

where p_i = the proportion of larvae (for a particular set) occurring at depth i
z_i = sample depth in meters.

RESULTS

Epibenthic occurrence of herring larvae

Both nets on the BBL sled captured substantial numbers of herring larvae (Table 1), the highest catches in excess of 3 m^{-3} and the average 0.7 m^{-3}. Catch rates in the BBL sled were broadly comparable to those from the MININESS (max > 5 m^{-3}; mean 1.7 m^{-3}) and bongo (max > 6 m^{-3}; mean 1.8 m^{-3}) over the same period.

Larval abundances in top and bottom nets of the BBL sled varied together over time, with generally higher catches at night (Fig. 3a), a period with largest herring abundances in the lowest MININESS net and when the calculated mean centre of mass of larval distribution was deep (Fig. 3b). But four of the five largest sled catches (>1.5 larvae/m^3) occurred near predicted times of high or low water, day and night.

Although there was general correspondence between top and bottom nets, there were systematic differences between them. In early (daytime) sets (0900-1600), the bottom net tended to have the larger catch, but in later (nighttime) sets, the top net had larger catches (overall average 1.0 larvae m^{-3}, twice the 0.44 m^{-3} of the bottom net) (Table 1; Fig. 4a). This difference could not have resulted from differences in volumes filtered, which were similar in top and bottom nets of any given set (Fig. 4b).

Vertical movement of larvae

To place the short time series of the BBL results in the context of the full-time series of vertical movement, the MININESS and bongo, as well as sled series from October 24 through 30, are presented in Fig. 5. Bongo results show a variation over time in overall density. MININESS data show variation over time at each depth, and the diel vertical pattern typical of this area (Stephenson and Power, 1989, 1990).

Table 2 shows an integrated larval abundance for the entire water column using MININESS data (5-55 m) alone and MININESS plus corresponding BBL data. In all but one case, the integrated total with the sled is lower than that

Table 1. Numbers of herring larvae caught, volume filtered (m^3), and density (no. m^{-3}) in the bottom (50 cm) and top (125 cm) benthic boundary layer (BBL) sled nets.

		Bottom net (50 cm)			Top net (125 cm)			Position of maximum (B or T)
Date	Time	No. caught	Volume (m^3)	No./m^3	No. caught	Volume (m^3)	No./m^3	
Oct. 27	0900	49	85.90	0.58	47	99.10	0.47	B
	1000	109	178.70	0.61	141	219.30	0.64	T
	1100	217	207.90	1.04	151	206.80	0.73	B
	1200	34	145.90	0.23	19	155.50	0.12	B
	1320	373	141.90	2.63	251	136.20	1.84	B
	1400	4	9.20	0.43	3	1.30	2.34	T
	1500	13	98.90	0.13	7	98.60	0.08	B
	1600	21	38.20	0.55	21	43.70	0.48	B
	1700	16	224.90	0.07	38	222.40	0.17	T
	1800	1	217.60	0.01	17	221.10	0.09	T
Oct. 29	1900	4	113.30	0.04	31	149.40	0.28	T
	2100	2	184.70	0.02	166	180.60	1.00	T
	2245	105	219.10	0.51	677	216.70	3.12	T
Oct. 30	0001	78	230.50	0.37	343	219.00	1.57	T
	0130	31	188.40	0.16	236	186.80	1.26	T
	0300	58	152.70	0.46	309	155.40	1.99	T
	0430	19	163.40	0.18	210	159.40	1.32	T
Totals		1134	2601.20		2667	2671.30		
Avg.		66.71	153.01	0.44	156.88	157.14	1.00	
Overall total		3801						
Overall mean		.72						

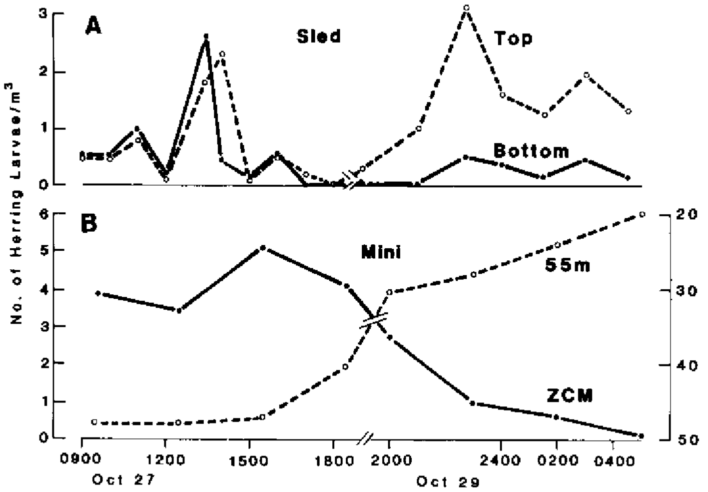

Fig. 3. Larval herring abundance in lower (33-73 cm above bottom) and upper (109-149 cm above bottom) nets of the benthic boundary layer sled (A), and in the bottom net (approximately 5 m above bottom) of the MININESS (B), and calculated centre of mass (ZCM) calculated from MININESS results - at a single site off southwest Nova Scotia, October 1987.

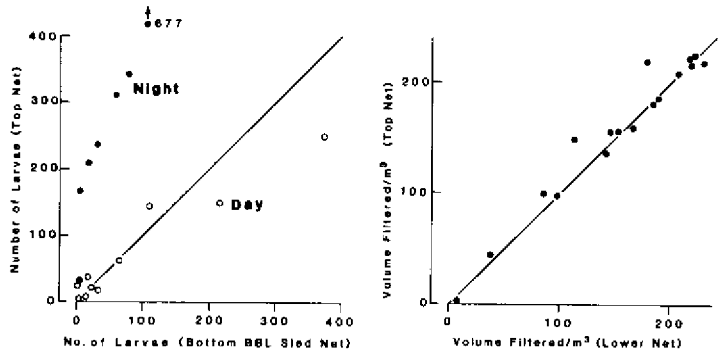

Fig. 4. Comparison of number of larvae per tow (a) and volume of water filtered (b) by upper and lower nets of the benthic boundary layer sled in repetitive tows at a single site off southwest Nova Scotia, October 27-30, 1987. Line of equivalence is shown for reference.

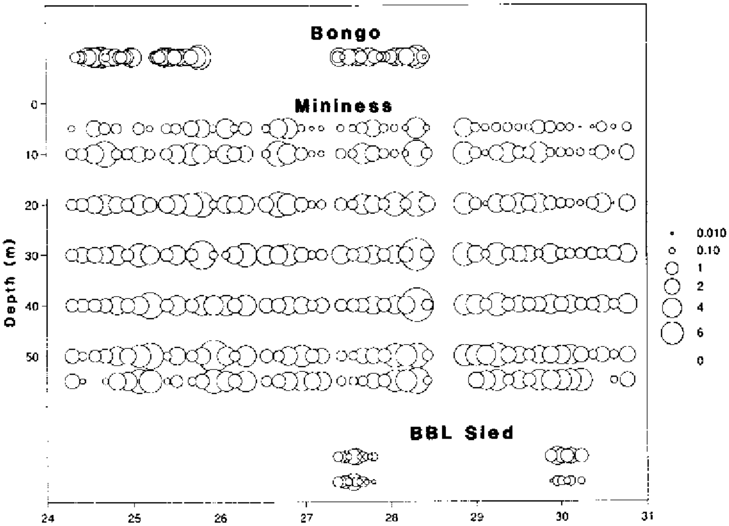

Fig. 5. Density (no. m^{-3}) of herring larvae in sawtooth oblique bongo tows (0-55 m, top), in discrete depth MININESS samples (5, 10, 20, 30, 40, 50, 55 m) and in two nets of the benthic boundary layer sled (1.25 and 0.5 m above bottom).

Table 2. Larval herring density (no. m^{-3}) in concurrent benthic boundary layer (BBL) sled and MININESS samples and calculation of the integrated total density (number beneath a m^{2}) with and without BBL sled results.

Date		Larval herring densities (no. m^{-3}) at sled height and MININESS depth intervals (m)												Total with sled as:	
		BBL sled		MININESS							Integrated total no. m^{-3}			% of	% of max
Oct. '87	Time	0.5	1.25	55	50	40	30	20	10	5	MININESS	MINI+sled	Diff	MININESS	MINI+sled
27	0430			3.42	1.79	1.73	0.73	0.36	0.12	0.07	68.70				
	1000	0.61	0.64	0.40	0.60	0.95	3.57	1.06	0.57	0.18	68.93	67.39	-	97.61	45.20
	1320	2.63	1.84	0.36	0.38	1.11	0.92	0.54	0.39	0.19	35.60	38.19	+	107.26	25.61
	1600	0.55	0.48	0.54	2.04	1.35	1.93	4.31	4.64	0.87	136.58	133.13	-	97.44	89.29
29	1900	0.04	0.28	1.99	2.03	3.31	3.64	2.86	1.92	2.69	162.83	149.10	-	91.49	100.00
	2100	0.02	1.00	3.90	2.54	3.98	4.06	1.33	0.36	0.85	151.08	131.66	-	86.80	88.30
	2400	0.37	1.57	4.40	3.42	1.87	0.72	0.53	0.45	0.27	95.25	80.30	-	84.63	54.53
30	0230	0.46	1.99	5.19	4.13	2.92	0.60	0.36	0.23	0.22	112.08	94.23	-	83.29	63.20
	0530	0.18	1.32	6.00	1.92	0.99	0.64	0.12	0.22	0.00	78.55	60.99	-	76.83	40.90
	0850				0.41	1.11	1.08	0.98	0.13	0.02	35.90				

calculated from MININESS alone; the one exception had the lowest integrated total with MININESS alone (35.6 larvae below a m^2 of surface) and the highest sled catches (average 2.24 larvae/m^3). The nighttime sled samples (October 29, 30) which had high densities correspond to a period of high catches in all the lower MININESS nets, but the good daytime sled catches (October 27) are seen to occur between two periods of high bottom MININESS catches (Fig. 5).

Flow variation and catch rate

Table 1 and Fig. 6 show the volume of water filtered by the two nets of the BBL sled. The volumes filtered in a standard 20-min tow varied greatly, from a low of 1.3 m^3 to 230.5 m^3, indicating that the speed (and perhaps also direction) of the current was different for the vessel at the surface compared to the sled on the bottom. Figure 7 compares the speed and relative distance travelled by the vessel and the epibenthic sled. Since the vessel always towed into the current, the sled was exposed to a weaker current at bottom and, therefore, passed through relatively less water. In the most extreme condition, the filtered volume corresponded to a distance of only 23 m (sled speed of 0.04 knots), and the sled never fished at an "attack speed" greater than 2 knots. A plot of the catch rate against filtered volume (Fig. 8) indicates that catches increased sharply above an "attack speed" of 1 knot and suggests a threshold for the effectiveness of this gear.

The filtering rates for a subset of the traditional bongo gear when the ship's heading was confined to 138-140° (October 24) or 158-160° (October 25) (Fig. 9) show a pattern of outliers at a seemingly tidal periodicity which, when converted to speed and distance, reveals an average attack speed of 3.5 knots, but a range from less than 3.0 to almost 4.0 knots, one-half knot faster and and slower than the vessel.

DISCUSSION

Study of the dynamics of larval Atlantic herring has drawn attention to the existence of stock-specific larval retention areas (Iles and Sinclair, 1982). In a review of the older literature linking "vertical migration and plankton movement and retention," Iles and Sochasky (1985, p. 8-10) found many demonstrations of vertical migration causing or allowing retention in fish larvae and invertebrate plankton. The facility with which some of these plankters actually moved to the bottom lead Iles and Sochasky (1985) to conclude that:

> "... this 'mixed planktonic-benthonic' behaviour ... would resolve the common embarrassing paradox of far more larvae being available to standard plankton gear at a given station at some times of the tidal or diurnal cycles than at others. We know of few studies which in their attempt to describe oceanic larval distributions have sampled the bottom surface or even 0-5 m above it. The bottom/near bottom is of immense importance to modern theories of larval transport."

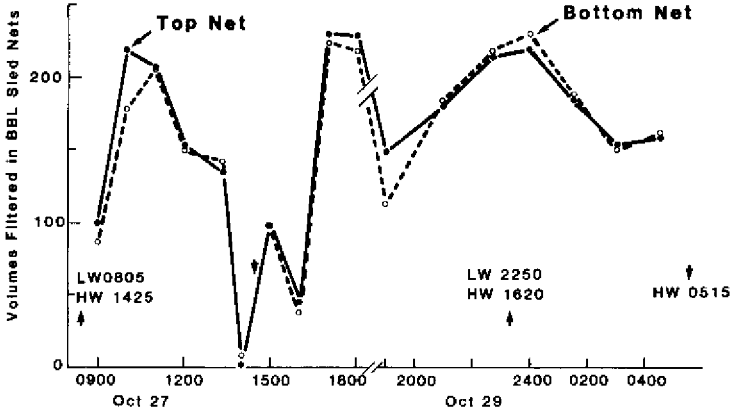

Fig. 6. Temporal pattern of water volume (L) filtered in upper and lower nets of the benthic boundary layer sled during repetitive standard 20-min tows at a single site off southwest Nova Scotia, October 27-30, 1987.

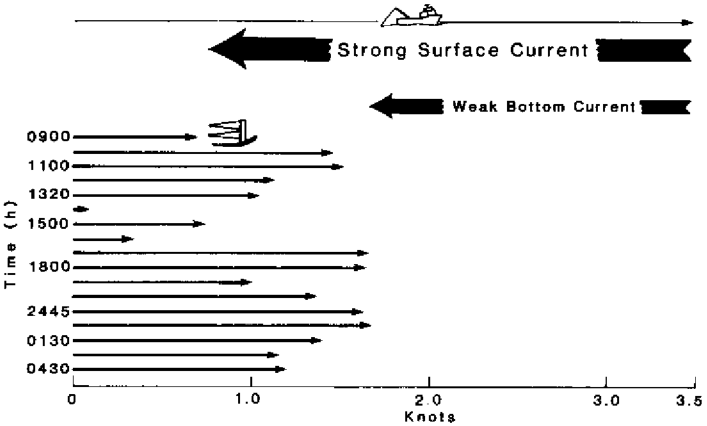

Fig. 7. Speed (knots) of the benthic boundary layer sled relative to that of the vessel in repetitive 20-min tows at a single site of 60 m depth off southwest Nova Scotia, October 27-30, 1987.

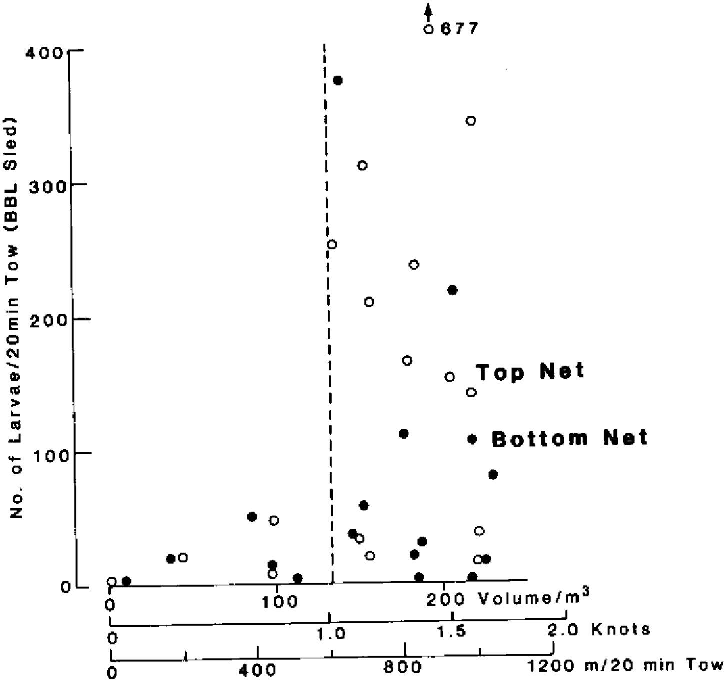

Fig. 8. Catch rates of larvae (number per 20-min tow) against distance, speed and volume filtered by the BBL sled in repetitive tows at a single location off southwest Nova Scotia, Oct. 27-30, 1987.

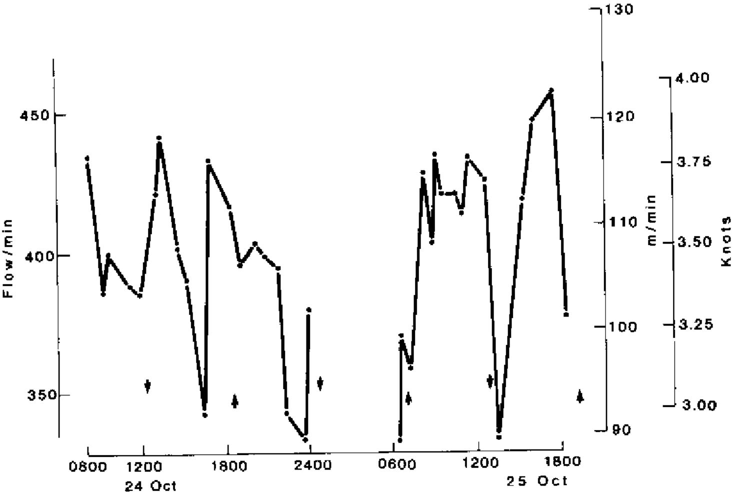

Fig. 9. Temporal variation in flow rate (m³/min retrieval time), speed (knots) and distance from bongo nets in repetitive standard oblique (sawtooth) tows at a single location off southwest Nova Scotia, October 24, 25, 1987.

Although several authors have recognized that the distribution of herring larvae may extend below the depth of traditional sampling gear (Bridges, 1958; Wood, 1971; Schnuck, 1972; Selivertov, 1974; Sjoblom and Parmanne, 1978; Fortier and Leggett, 1983), at least some authors felt there was no evidence of aggregation near the bottom (Fortier and Leggett, 1983).

Our results from the BBL sled form the first clear evidence that herring larvae do regularly occur close to the bottom, below the depths fished by traditional gear. The numbers observed were in the same order of magnitude as those in the rest of the water column. However, there is reason to expect that sled results may be underestimates, in that avoidance is expected to be greater than that of the other samples due to the smaller size of the nets, to disturbance caused by the tow cable ahead of the net and to the lower speed through the water ("attack speeds") recorded for the sled than for other gears.

The sled time series is short but demonstrates at least a day/night difference in epibenthic larval herring abundance[1], and differences in herring abundance between nets only a few centimeters apart.

These results are of particular importance in two ways. They confirm the hypothesized movement of larvae to the bottom where substantial differences in current speed (Tee et al., 1987) and direction could facilitate retention (Iles and Sinclair, 1982; Stephenson and Power, 1989). The numbers of larvae near bottom seem sufficient to imagine a "tidal modulation" associated with diel migration/selective tidal stream transport (Iles and Sochasky, 1985 discussing de Veen, 1978).

The presence of larvae in substantial numbers near bottom does raise the possibility of bias in results from traditional gear that cannot sample the epibenthic layer. The results from this study indicate generally lower densities near bottom than in the upper water column, and inclusion of sled data in integrated calculations of total larval abundance does not substantially alter the population estimate. However, the time series was short, and as was suggested, the results from the BBL may be conservative.

Repetitive sampling at this site has shown both vertical movement and temporal variation in overall abundance (see, for example, results of repetitive bongo tows, Fig. 5). The sled observations did not appear to detect the apparently large numbers of larvae sometimes "missing" from the water column samples. Catches in the sled nets were as variable (temporally) as catches in the water column as a whole, and inclusion of the sled results only slightly moderate the pattern of variation in integrated water column totals. The sled results therefore do not yet explain the large variation in the numbers of larvae available to traditional gear at different times of day or tide at a given location. There are a few alternate hypotheses including finer-scale vertical aggregation of larvae into narrow "lenses" which are occasionally missed by the gear (although an oblique or sawtooth bongo tow would sample

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[1] These may be the first such diel observations with this gear (Wildish et al., 1990).

these in most of the water column) or, perhaps more likely, the variation is the result of small-scale horizontal patchiness of larvae (Stephenson and Power, this volume).

But if we might have expected to demonstrate significant numbers of herring larvae near the bottom, we did not predict the somewhat startling systematic variation in the flow rates and "attack speeds" revealed by the epibenthic sled and bongo flowmeter readings (we have not yet examined the comparable MININESS data). These long periods of frequently repeated observations at a single station have, for the first time, provided us with clear data to describe a major factor influencing gear performance. We have had anecdotal observations that after a change in the tide we might expect to see a change in the amount of warp needed to get telemetered gear to target depths or that a change in tide might be accompanied by untelemetered bongo gear having a tendency to strike bottom. But we have not had a data series unconfounded by location, ship's heading, etc.

The implications of these results for traditional sampling are several. The relative differences between speed of vessel and speed of gear demonstrated by these results presumably apply to other gears, and consideration of slower/faster currents at gear depth may help explain some previously puzzling gear behavior and catches, and provide insights which may help increase the standardization possible in towed gear surveys.

We have revealed two separate time-dependent biases in larval sampling: one related to the vertical movement of larvae (and its timing) below the depths fished by traditional gear, and the other as a result of fluctuations in the effective gear velocity caused by the laws of relative motion as they apply to surface and bottom current speed differences. Though we would not expect the larval densities observed in the epibenthic layer to substantially alter the larval indices from synoptic bongo surveys, we nonetheless wonder whether the elimination of data from sets with low "attack speed outliers" (below, say, 100 m/min or 3.25 knots) would improve the historical correlation.

ACKNOWLEDGMENTS

We are grateful to Dr. D. J. Wildish for loan of the BBL sled and to Brian Frost for instruction in its use. We thank the captains, crew and scientific staff of the J.L. HART cruise J038, LADY HAMMOND cruise H181 and E.E. PRINCE cruise P361 on which these data were collected. Bud Holmes and Dave MacKenzie of the Yarmouth Coast Guard radio office provided a copy of the current atlas for the Bay of Fundy. Dave Wildish, Jim Reid and Art Wilson provided photographs and/or line drawings, Frank Cunningham and Bill McMullon did drafting and photography, and Brenda Best typed the manuscript. Mike Power made the survey data available.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Population Dynamics of Herring in the St. Lawrence Estuary: A Test of the Member/Vagrant Hypothesis

J.A. Gagné, J. Lambert, and F. Mongeau
Institut Maurice Lamontagne
Mont-Joli, Québec, Canada
L. Fortier
Départment de biologie
Université Laval
Ste-Foy, Québec, Canada

The Member/Vagrant hypothesis offers a unified explanation for population pattern and richness, absolute abundance and interannual variability in year-class strength of marine fish species. It states that the number of populations, their abundance and the geographic location of their respective spawning sites are determined by the number, the extent and the location of geographically stable larval retention areas (Iles and Sinclair, 1982). Temporal variability in abundance would result from intergenerational losses of individuals (Sinclair, 1988). Tidally energetic seas would not be expected to support several populations of the same species (Sinclair and Tremblay, 1984). Spawning periods for herring would be selected to ensure that, given the larval growth rate prevailing in the retention area, metamorphosis from the larval to the juvenile stage occurs during a period of higher food abundance (Sinclair and Tremblay, 1984). Homing of adults to specific spawning sites is a fundamental element of the hypothesis as it is required to insure temporal persistence of larval distributions at particular geographic locations. Populations would therefore be genetically isolated (Sinclair, 1988).

Support for various components of the M/V hypothesis has often been sought from studies of the Isle Verte herring population of the St. Lawrence estuary, Quebec, Canada (Iles and Sinclair, 1982; Sinclair and Tremblay, 1984; Sinclair, 1988). This estuary is a tidally energetic, low productivity environment (Bousfield et al., 1975; Therriault and Levasseur, 1985). The hypothesis predicts that under such environmental constraints, (1) only one herring population can exist, (2) that a fraction of its larvae will be retained within the estuary, (3) that because of slow growth the larval phase will last almost a year and, as a consequence, (4) that spawning will only occur in the spring (Iles and Sinclair, 1982; Sinclair and Tremblay, 1984).

Spring spawning herring from the St. Lawrence estuary are relatively small at age (Tremblay, 1942; Jean, 1967) and their otoliths have a large translucent nucleus of the type generally found only in fall spawners (Côté, 1979). These morphological characteristics may be a consequence of poor growth conditions prevailing throughout the pre-recruit phase (Côté et al., 1980). Since under the Member/Vagrant hypothesis, population members must return to their native grounds to reproduce, it is predicted (5) that all Isle Verte herring should be pygmies with an atypical otolith morphology (Sinclair, 1988).

To verify predictions 1 to 5 we conducted 10 ichtyoplankton surveys over most of the larval distribution area in the estuary between June 1985 and June 1986 (details in Fortier and Gagné, 1990). Eighteen samples of spawning herring were also collected between May and September 1985 to perform various biological and morphological analyses (details in Lambert, 1991).

Results from the ichtyoplankton surveys showed that spawning of similar magnitude occurred during both spring and autumn in 1985. In each case larvae were retained within the estuary, upstream from a stratification front, as predicted by Iles and Sinclair (1982) (Fortier and Gagné, 1990). An undetermined fraction of recently hatched larvae was also advected through the transition zone towards the lower reaches of the estuary (Fortier and Gagné, 1990; Mongeau, 1991). Fall larvae disappeared much more rapidly from the sampling area however, possibly as a consequence of reduced food availability and survival or, alternatively, from increased advection through a weakened stratification front (Fortier and Gagné, 1990).

Spring larvae grew at a mean rate of 0.25 mm d^{-1} between June and September and all individuals caught in early winter were found to be either metamorphosing or already juveniles when staged according to Doyle (1977) (Mongeau, 1991). Fall larvae did not metamorphose until the following spring (J.A. Gagné, unpubl. data).

Analyses conducted on spawning fish. demonstrated that spring and fall spawners were morphologically different and that only 48% of the spring spawners were pygmies with atypical otoliths. The other spring spawning fish were large with spring-type otoliths or intermediate with respect to these characters (Lambert, 1991). The "regular" fish could either originate from adjacent populations or represent the survivors of larvae initially advected away from the cold, unproductive mid-estuary towards the warmer and richer waters of the southern gulf of St. Lawrence (Therriault and Levasseur, 1985; De Lafontaine et al., 1990). Pygmy herring were not found amongst the fall spawners.

In summary, a significant number of herring larvae produced in the St. Lawrence estuary in 1985 was retained on the well-mixed side of a stratification front. Spawning occurred both during spring and fall, spring larvae metamorphosed during the winter following their birth, and only one half of the spring spawners were pygmies with autumn-type otoliths.

Only one component of the unified explanation offered by the Member/Vagrant hypothesis for the regulation of marine populations, that pertaining to population pattern, is clearly supported by our results. Indeed, both spring and fall herring spawned within the boundaries of a persistent, hydrographically-defined larval retention area. Population wise however, the estuary is richer than predicted.

The existence of the unexpected fall-spawning population indicates that the timing of reproduction is not determined as suggested by the hypothesis. This is further demonstrated by our observation that spring larvae metamorphosed during early winter when food abundance was minimal.

There are two possible explanations for the presence of two different morphological types within the spring-spawning population, none of which is consistent with the hypothesis. The larger "regular" fish could come from adjacent populations in which case larval retention and homing would not be required to insure population persistence; absolute population size and interannual recruitment variability could not be determined by the extent and the integrity of the retention area. The whole hypothesis would have to be rejected. The "regular" spring spawners could also be survivors from larvae advected away from poor estuarine growth conditions towards more favourable nurseries downstream; they would be homing back to their native grounds to reproduce.

In either case, much of the Member/Vagrant hypothesis is not supported by our test. Key components such as the explanation for population richness, population size, recruitment variability and the timing of reproduction must be rejected and new (or old) mechanisms considered.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Retention and Dispersion of Larval Herring in British Columbia and Implications for Stock Structure

D.E. Hay and P.B. McCarter
Department of Fisheries and Oceans
Nanaimo, British Columbia, Canada

ABSTRACT

Larval herring surveys in Hecate Strait examined the extent of dispersion to determine if there was mixing of larvae between adjacent spawning sites. A large (60 m) vessel made oblique plankton tows in open-water locations (1-100 km from shore) while small vessels worked in nearshore locations (1-5000 m from shore). The surveys were made approximately 3-5 weeks after the completion of the major spawning activity. The sampling was designed to test the hypothesis that each spawning site constitutes a distinct herring stock. Most prevalent definitions of 'stocks' require the maintenance of genetic distinction among stocks. Extensive mixing of larvae between different spawning sites would preclude the potential for genetic differentiation of the spawning fish from each site unless individual larvae could home or imprint to their precise area of incubation as an egg. There is no evidence to suggest this occurs in herring. Larval distributions were examined over two broad areas: (1) the northern mainland coast from Porcher Island to northern Chatham Sound; (2) the southern Queen Charlotte Islands from Skincuttle Inlet north to Cumshewa Inlet. Each of these broad areas extends about 1 degree of latitude (60 nautical miles) and each contains a number of distinct spawning sites. Results from 2 years of sampling showed that larval distributions were geographically continuous (larvae were mixed) among the different spawning sites. The results do not support the hypothesis that each spawning site represents a distinct stock.

INTRODUCTION

Surveys of larval herring in British Columbia have been conducted intermittently for more than 30 years. In one of the earliest studies, Stevenson (1962) surveyed herring larvae in Barkley Sound on the west coast of Vancouver Island. He suggested that recruitment depended on the degree of retention of larvae inside Barkley Sound and that larvae advected out into 'offshore' waters were lost. There has yet to be a definitive test of that suggestion although a substantial effort has been directed at related questions including predation or food limitation (Arai and Hay 1982; Barraclough 1967; McGurk 1987, 1989; Purcell and Grover 1990; Robinson and Ware 1988). The work described here differs from those of previous investigators in several ways. First, the prime objective has been to determine if larval distributions overlap and mix between different spawning sites. If substantial mixing occurs then maintenance of genetic isolation between spawning sites would be unlikely unless there larvae possess precise homing mechanisms. This is unlikely in small larvae. A second difference is the intensity of sampling. For a two-week period, approximately 3-5 weeks after hatching, we made about 300-600 plankton hauls in grid patterns that completely circumscribed the larval distribution. Compared to other surveys, we took more samples and covered larger geographic area in a shorter time using a combination of large and small, efficient, high speed plankton sampling vessels.

This paper presents an overview of the preliminary results from these surveys and incidental observation related to larval herring ecology. Fuller descriptions of the results will be presented in several manuscripts that are now in preparation.

METHODS

Larval surveys in Hecate Strait were made approximately 3-5 weeks after the completion of the major spawning activity. The surveys were conducted from a combination of a large (60 m) vessel and two small (6 m) vessels equipped with small electric winches to haul plankton nets. Samples were taken make with 57 cm diameter meter bongo nets hauled from the large vessel in deep water locations and with 19 cm diameter bongo nets hauled from smaller vessels in shallow water locations, often within meters of the shore. The nets were made with black 0.35 mm mesh. Flowmeters were used to measure the volume of seawater filtered. Tows were oblique, with a maximum depth to 20 m and a duration of 6 minutes.

Samples were preserved in formalin and herring larvae were counted and measured. Larval densities were estimated as the number of larvae/m^3). Herring spawning sites and dates were obtained from the annual reports made by Department of Fisheries and Oceans Fishery Officers.

Larval surveys were concentrated in the general vicinity of the largest herring spawning areas. On the northern mainland this included Kitkatla

Inlet, Porcher Island, Chatham Sound, the Southern Queen Charlotte Islands, particularly Juan Perez and Skincuttle Inlets. These larval sampling areas were designed to examine the waters within and between major herring spawning areas (Fig. 1) as identified by Hay and Kronlund (1987) and Hay et al. (1989).

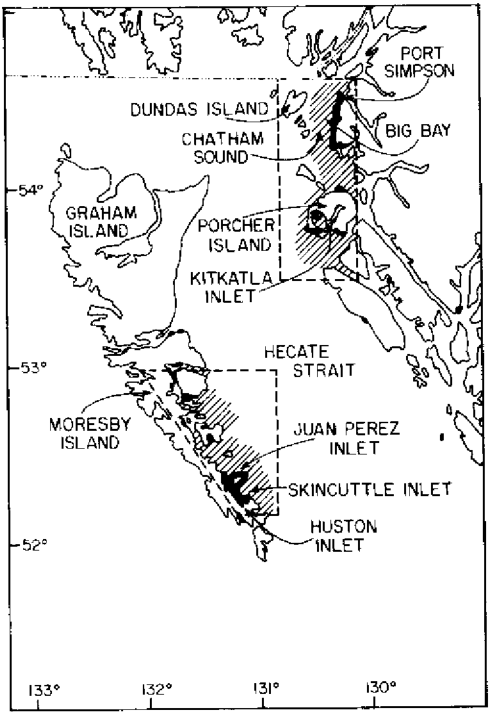

Figure 1. Major herring spawning locations and larval distributions in the north coast of British Columbia in 1985 and 1986. The dark areas indicate spawning locations. Larval distributions are indicated by the diagonal shading. The dashed lines show the geographical limits of the surveys.

RESULTS AND DISCUSSION

Distribution and relative abundance

Within the first 3-5 weeks after hatching herring larvae occurred in two principal locations in northern British Columbia. One location, from the southern edge of Porcher Island in the south to Portland Inlet in the North, encompassed three or more distinct spawning locations. (i) the outer coast of Porcher Island and Kitkatla Inlet within Porcher Island, (ii) southern Chatham Sound and Big Bay and (iii) Port Simpson. The other principal larval herring location, on the southern Queen Charlotte Islands, also encompassed three distinct spawning locations: (i) Huston Inlet and Skincuttle Inlets, (ii) Juan Perez Inlet and (iii) Cumshewa Inlet. One, on the northern mainland side, extended about 60 nm from Kitkatla Island to Port Simpson (Fig. 1). Within this range, most herring were found close to shore, rarely more than 10 nm from the shore. In all locations larval herring abundance was greatest at sampling sites close to shore. Offshore location (i.e. 10 nm) in Hecate Strait had few if any larvae in Hecate Strait (Table 1).

Larval abundance and recruitment

In Hecate Strait herring larvae were much more abundant in 1986 than 1985. This trend holds for most of the areas examined. Further, the larvae in 1985 were longer at a specific age than they were in 1986 (Table 2). Good recruitment, in terms of the numbers of age three fish entering the commercially fishery, was observed in 1988 from the 1985 year class, but relatively poor recruitment was observed from the 1986 year class (Haist and Schweigert 1990).

Other larval fishes

In all years and locations larval fishes other than herring were identified, sometimes only to family, and enumerated. An observation relevant to this discussion concerns the distribution of sand lance (Ammodytes hexapterus). Relative to herring larvae, the sand lance was more abundant in 'offshore' waters. The distances between the 'offshore' and 'inshore' locations were relatively small and strong currents (i.e. several knots) could theoretically have advected the 'offshore' species to 'inshore' sites and vice versa. However, this does not appear to have happened during the time of our surveys.

Larval distribution and herring stocks

There are several topical theories or hypotheses concerning factors limiting or regulating abundance of marine fish larvae and herring larvae in particular. Iles and Sinclair (1982) and later Sinclair and Iles (1988) argue that stocks of herring and other species are related to larval retention areas, with stock size related to the size of the retention area. Their arguments still are debated and there are two aspects to the argument. One concerns limitations on the 'carrying capacity' of larval retention area. The other concerns ecological processes occurring within the geographical range of larvae (whether or not the retention area concept is valid) that regulate recruitment and abundance in particular years. In this regard the 'match-mismatch' hypothesis (Cushing 1972) is an explanation of variation in abundance determined by the timing of larval production with the production of the food supply. In many recent papers, predation is assumed to be the main factor limiting larval abundance.

These arguments about retention areas and the role of food and predation in the regulation of abundance of marine fish populations are further

Table 1. Summary of mean larval herring densities (numbers per 1000 m3 of seawater filtered) from April 29 - May 15, 1985 and April 28 - May 10, 1986. In general, offshore sites represent samples taken by large vessels with large BONGO nets and inshore samples were taken by small vessels using small BONGO nets.

Sampling Area	1985			1986			Locality
	Sample Count	Mean Density	S.D.	Sample Count	Mean Density	S.D.	
South Porcher Is.	25	824	1787	17	128	386	Offshore
	18	5490	9510	18	6358	11933	Inshore
Kitkatla Inlet	20	4340	4837	9	3651	5102	Inshore
West Porcher Is.	26	1000	1829	22	277	408	Offshore
	0	--	--	7	9225	6447	Inshore
North Porcher Is.	31	530	583	27	571	952	Offshore
	14	3272	4808	30	1916	5170	Inshore
Rupert-Simpson	28	491	466	24	653	1138	Offshore
	42	3108	3369	32	45523	84692	Inshore
Portland Inlet	6	194	189	0	--	--	Offshore
Dundas Island	16	83	145	0	--	--	Inshore
Mid-Hecate Str.	4	5	6	5	0	0	Offshore
SE Moresby Is.	40	206	325	42	2054	7480	Offshore
Laskeek Bay	33	2299	5323	38	0	0	Inshore
Juan Perez Snd.	17	1339	1615	20	14679	41003	Inshore
Skincuttle Inlet	18	4482	6186	34	10192	19066	Inshore
All areas	338	1860	4025	325	7689	31918	

Table 2. Summary of larval herring mean body lengths at age from inshore and offshore localities. A maximum of 20 larvae were measured per sample.

Sampling area	1985				1986				Locality
	Sample Count	Mean Length (mm)	S.D.	Days After Spawn	Sample Count	Mean Length (mm)	S.D.	Days After Spawn	
South Porcher Is.	12	10.65	0.44	23	2	9.05	0.23	26	Offshore
	20	10.81	0.42	22	8	9.23	0.66	25	Inshore
Kitkatla Inlet	20	10.86	0.46	23	5	9.73	0.21	25	Inshore
West Porcher Is.	14	11.04	0.25	24	7	10.31	0.54	31	Offshore
	0	-	-	-	7	9.52	0.17	28	Inshore
North Porcher Is.	31	11.71	0.59	25	10	9.26	0.31	17	Offshore
	9	11.06	0.59	25	5	9.41	0.79	17	Inshore
Rupert-Simpson	82	12.70	0.61	40	24	9.71	0.39	31	Offshore
	39	12.42	1.91	35	22	10.01	0.41	30	Inshore
Portland Inlet	5	14.37	1.58	39	0	-	-	-	Offshore
Dundas Island	7	13.24	1.00	40	0	-	-	-	Inshore
Mid-Hecate Str.	1	16.00	-	-	0	-	-	-	Offshore
SE Moresby Is.	34	14.11	1.58	41	11	9.67	0.29	27	Offshore
Laskeek Bay	15	10.57	2.18	25	0	-	-	21	Inshore
Juan Perez Snd.	16	12.31	1.54	34	4	9.51	0.35	20	Inshore
Skincuttle Inlet	17	12.54	0.99	39	21	9.65	0.50	32	Inshore
All areas	322	12.22	1.56	31	126	9.68	0.50	25	

complicated by arguments about the stock structure and the significance of genetic variation within and between populations. For instance, Smith and Jamieson (1986) argue that there is no compelling evidence to support the view that marine fish populations such as herring differ genetically among 'stocks'. Clearly, there will be no immediate resolution of these arguments in the near future. From a population genetics perspective, such as that presented by Smith and Jamieson, it is difficult to accept the notion that there are genetic differences between 'stocks' when there is evidence of substantial mixing. Evidence of mixing has been shown through tagging studies (Stevenson 1955, Hourston 1982, Haegele 1984) and by the present work, which indicates mixing of larvae between adjacent spawning sites. On the other hand, tagging studies also can be cited as evidence of homing and the larval distribution analyses presented here can be regarded as evidence of larval retention in the general areas of the southern Queen Charlotte Islands and Chatham Sound (Fig. 1).

In the face of the present uncertainty about stocks and factors limiting or regulating them, we suggest that the advice to management is clear. For the time being, (say for the next 10-20 years) and in the absence of new evidence to the contrary, we must manage herring fisheries as if there were a genetic basis to the smallest potential stock structure. Assuming that there is a genetic basis to stocks, then small stocks, particular those adjacent to large stocks, are at risk. If fishing quotas set for large stocks were inadvertently applied to small stocks, then they could be eliminated. Scientists offering advice to managers of fisheries resources would be irresponsible if they did not appreciate the possibility of genetic variation on small geographical scales and the possible risk to small stocks by over-exploitation directed at inappropriate amalgamation of smaller, separate stocks. At the same time, we should point out that this advice, while prudent, is inefficient, costly and perhaps incorrect . Therefore continued research into the biological basis of stocks is warranted.

CONCLUSIONS

1. In Hecate Strait the distribution of larvae appears to be confined mainly to near-shore locations (Fig. 1). In general there was more dispersion of larvae along the coast than there was from the near-shore spawning areas to deeper, offshore locations. Almost no herring larvae were taken in mid-Hecate Strait.

2. The distribution of larvae between the two major north-coast spawning locations, Kitkatla Inlet or Porcher Island and Chatham Sound, was continuous in both years (Fig. 1). The relevance of this observation is that, by the mixing of larvae between the adjacent but geographically separate spawning sites, there probably is no more than one single large stock on the northern mainland coast and another on the southern Queen Charlotte Islands.

3. In 1986 herring larvae were smaller but more abundant than those taken in 1985. The difference was observed both in the estimates of mean

length and mean weight but the larval ages were approximately similar each year. The year when larvae where less abundant, 1985, produced a stronger year class than 1986.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Distribution of Pacific Herring Larvae in Sitka Sound, Alaska

L. Haldorson and J. Collie
University of Alaska Fairbanks
Juneau, Alaska

ABSTRACT

In 1989 and 1990 the distributions of herring larvae in Sitka Sound, Alaska were monitored by weekly sampling at a grid of stations covering the sound. In 1989, herring larvae hatched in at least two cohorts that were evident in length frequency distributions. Most larvae were members of the initial cohort that appeared as yolk-sac larvae in late April. Geographic distributions of larvae were mapped for six weeks. Larvae first appeared in high density near areas of extensive egg deposition on the east and north sides of Sitka Sound. In subsequent weeks, larvae dispersed throughout the northern end of the sound, but remained at low density in the central and outer sound. In 1990, larvae again appeared in high initial density near spawning grounds, with one major cohort and at least one other substantial hatch. However, in that year they were dispersed more evenly throughout the sound. In 1990, herring larvae were initially very abundant near spawning grounds, but within a few weeks densities of larvae in the north end of the sound appeared to be lower than in 1989. The 1989 distribution of larvae suggests that the northern end of Sitka Sound may be a retention area, as described in the member/vagrant hypothesis. The distribution of spawning sites in the Sitka Sound area may be the result of enhanced survival by larvae that are retained in the northern part of the sound.

Oceanographic transport of planktonic larvae is an important feature of early life for many fishes, as planktonic larvae are the rule, rather than the exception, for marine species. The possibility that variation in transport will affect later recruitment of year-classes was recognized by Hjort (1926) when he proposed that offshore transport of larvae was the principal cause of recruitment variation in Norwegian cod populations. Similarily, upwelling and offshore transport have been described as important negative correlates of year-class abundance in Pacific hake off California (Bailey 1981). Other species may rely on oceanic transport of larvae to rearing areas that are some distance from spawning areas. Ketchen (1956) found indications that lemon sole recruitment in Hecate Strait, British Columbia depended on transport of larvae from spawning grounds on the south end of the strait to rearing grounds on the north end. For fish species with estuarine rearing areas, such as the Atlantic menhaden, transport of larvae from offshore spawning areas may determine year class abundance (Nelson et al. 1977). The indications that oceanic transport is a major factor in survival of larvae imply that within populations there is strong natural selection for location and timing of spawning, with the result that fish populations will display spawning strategies that are adapted to local oceanographic environments.

For adult fish, there is obvious adaptive value in spawning at locations where conditions will enhance survival of larvae. For fish with planktonic larvae, ideal spawning locations may be identified with some feature that promotes high survival, or may be situated at places where prevailing currents will carry larvae to areas with suitable conditions. Adult herring consistently use certain nearshore areas as spawning habitat. After hatching, larval herring are entrained by currents, but have been reported to aggregate and remain in annually consistent areas by vertically migrating into appropriate tidal currents (Sinclair and Tremblay 1984). The success with which herring larvae are able to reach and remain in favorable rearing areas may determine much of the observed variation in year-class abundance for a given spawning group. On the west coast of Vancouver Island, Stevenson (1962) found indications that herring larvae transported offshore did not survive. Iles and Sinclair (1982) proposed the larval retention hypothesis, in which year-class recruitment depends on the success with which larval Atlantic herring remain in areas where conditions are condusive to successful metamorphosis.

The larval retention hypothesis has recently been expanded into the member/vagrant hypothesis (Sinclair 1988). In the member/vagrant hypothesis, stock size is determined by the extent of cohesive rearing areas for larvae. Retention in those rearing areas is accomplished through vertical migration of larvae, and/or oceanographic features that contribute to retention (e.g. fronts or gyres). Recruitment of a year class is a function of the number of larvae that remain in a retention area; thus, recruitment variation is a reflection of fluctuations in those hydrographic features that promote retention of larvae.

In this study we examined the geographic distribution of Pacific herring larvae in Sitka Sound, Alaska in 1989 and 1990. Our objective was to quantify densities of larvae on space and time scales that would allow us to identify possible areas of retention in Sitka Sound, and to determine if observed distributions were consistent with deposition of spawn and features of surface currents.

STUDY AREA

Sitka Sound is a large embayment on the outer coast of Baranof Island in southeast Alaska (Figure 1). Much of the sound is open to the North Pacific, although the northern end is protected by Kruzof Island and the southern portion is afforded some protection by the Biorka - Necker Island chain. The shoreline is almost exclusively rocky. The nearshore zones are typified by numerous small islands and rocky reefs, especially on the eastern shore. Depths usually exceed 50 m, except immediately nearshore and areas adjacent to islands and reefs.

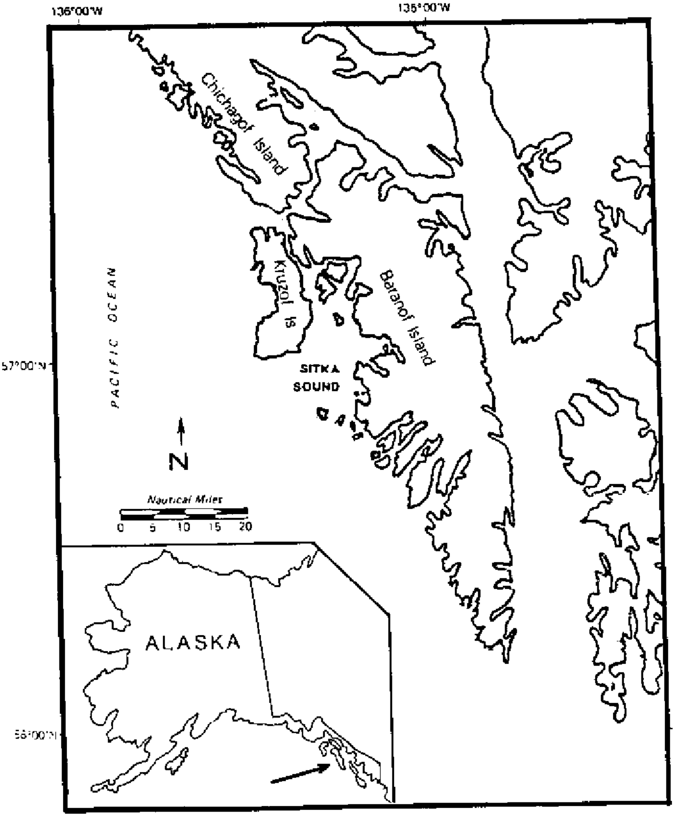

Figure 1. Location of Sitka Sound in southeast Alaska.

Current systems in Sitka Sound are poorly documented. A surface drift bottle study by Sundberg (1981) indicated that surface flows are northerly along the eastern side of the sound, with a counterclockwise flow around the northern end of the sound and westerly flow along the south side of Kruzof Island. There were indications of a counterclockwise gyre in outer Sitka Sound between the south end of Kruzof Island and Biorka Island.

Herring in Sitka Sound consistently spawn on the eastern shore, with most spawn deposition north of the town of Sitka (Sundberg 1981). Spawning activity sometimes extends as far south as Hot Spring Bay and to the north as far as the easternmost section of Kruzof Island. In 1989 the first spawning was observed on 19 March and the fishery opened on 31 March. In 1990 those events occurred on 4 and 6 April, respectively.

METHODS

Herring larvae were sampled at 17 stations arranged in a grid pattern to cover all of Sitka Sound, including Katlian Bay (Station 2) and Nakwasina Bay (Station 1) to the north (Figure 2). All stations were sampled weekly for six weeks in 1989 and four weeks in 1990, beginning approximately 3 weeks after the opening of the commercial sac-roe fishery in each year (Table 1). Station 17 was added in 1990.

Table 1. Sampling dates (days/month) in 1989 and 1990 larval herring surveys in Sitka Sound.

YEAR	WEEK					
	1	2	3	4	5	6
1989	25,26/4	1,2/5	8,9/5	16,17/5	23,24/5	1,2/6
1990	2,3,4/5	9,10/5	16,17/5	23,24/5		

Herring larvae were sampled with a 1 m diameter Puget Sound net, modified to operate as a drop net and close at the end of the drop. The net was closed at a depth of 50 m except at two stations where the depth was less than 50 m and the net was closed 5 - 10 m above the bottom. Three replicate drop net samples were taken at each station in each sampling week. Two of the replicates were preserved in 5% formalin, the other in 90% ethanol buffered to pH 7 - 8.

All fish larvae were removed from all samples, herring larvae were counted. Herring larvae from the formalin preserved samples were measured to the nearest 0.1 mm standard length. Samples with over 100 herring were subsampled for length frequency.

Estimates of the length frequency distribution for herring larvae in Sitka Sound were derived by calculating the proportion of larvae in each 0.5 mm size class at each station, and multiplying the proportions by the mean density of larvae at that station to estimate the density of each size class. These size distributions were then weighted by the measured area defined by the perimeter of each station (Fig. 2). The weighted densities of each size class were summed across all stations, and the resultant totals converted to proportions.

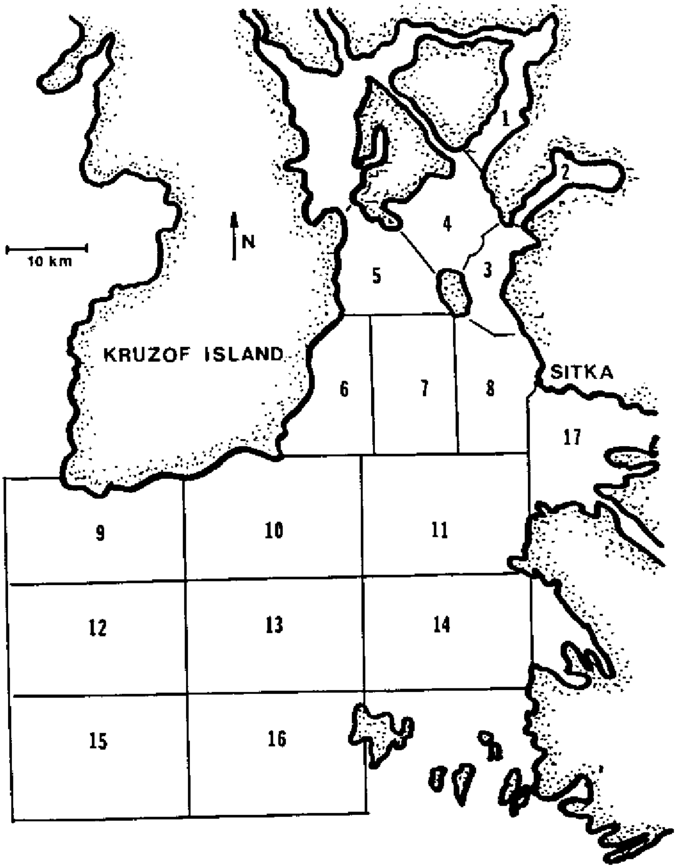

Figure 2. Location of sampling stations within Sitka Sound, Alaska

RESULTS

In 1989 herring larvae were initially found in high densities near spawning beaches. These fish were primarily yolk-sac larvae and few larger larvae were present (Figure 3). As they grew, yolk-sac larvae present in the first week continued to constitute an important component of the larval herring population in the sound, although a second and possibly a third cohort appeared later in smaller numbers. In the first week of sampling the general lack of larvae larger than yolk sac size, and the low densities at stations other than those adjacent to spawning beaches, suggest that little hatching had occurred previous to the initial sample. In the next three weeks, larvae became evenly distributed throughout the northern end of Sitka Sound; however, relatively few were found at stations outside that area (Figure 4). Nakwasina (station 1) and Katlian Bays (station 2) contained substantial numbers of herring larvae during the first four weeks of sampling.

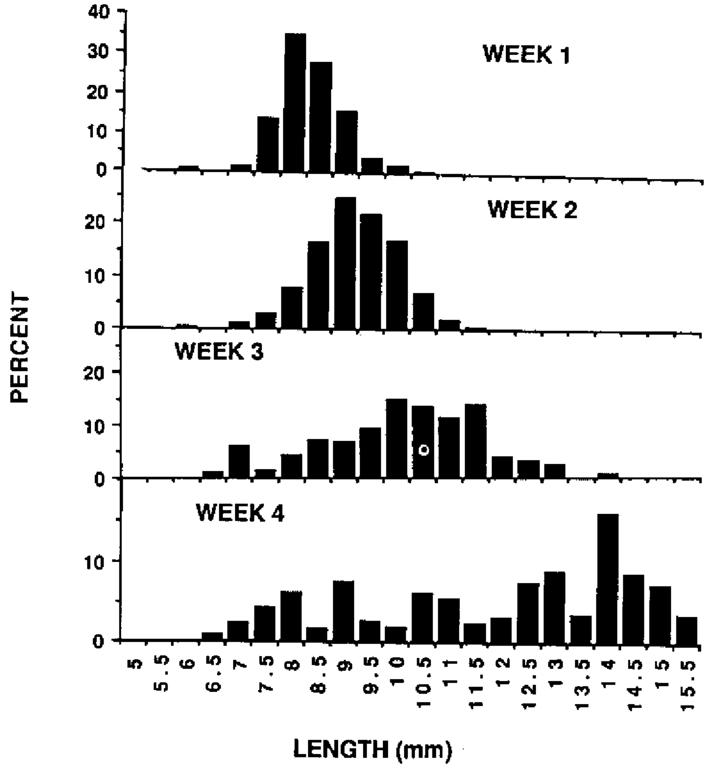

Figure 3. Length distributions of Pacific herring larvae in Sitka Sound during the first four weeks of sampling in 1989.

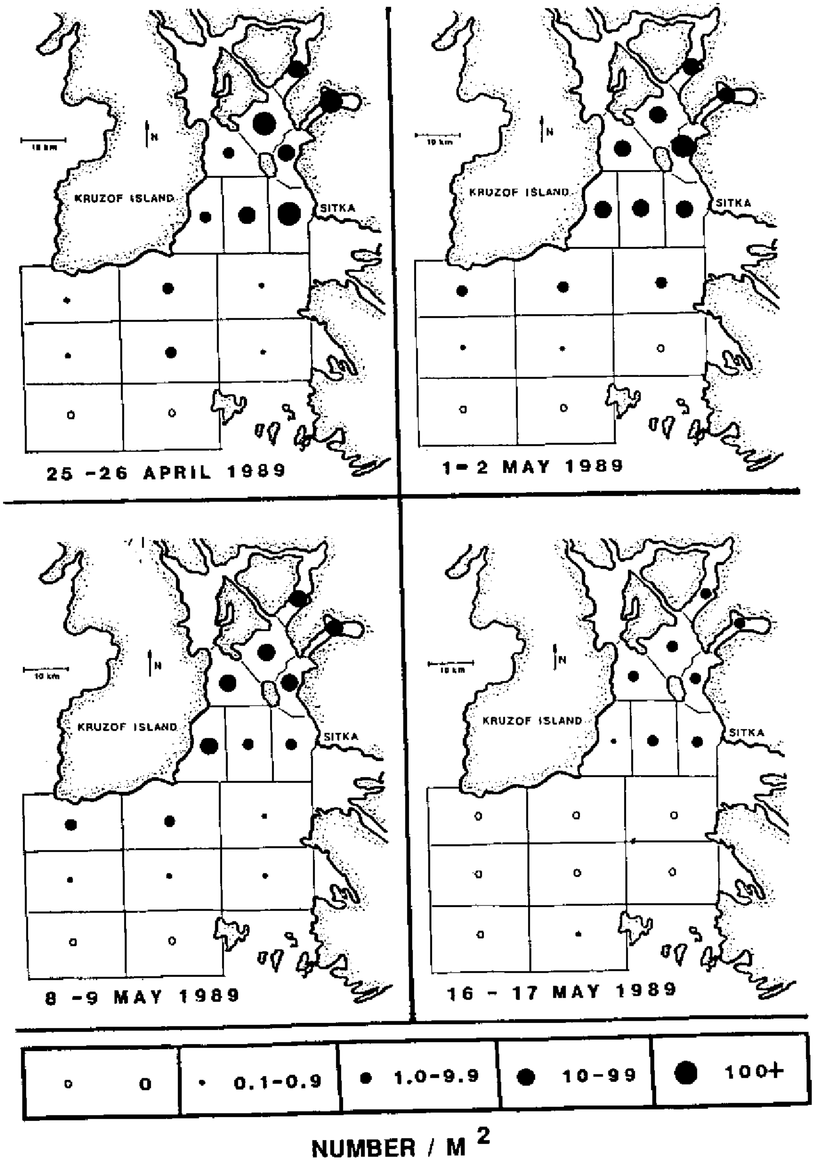

Figure 4. Geographic distribution of Pacific herring larvae at 16 stations in Sitka Sound during the first four sampling weeks of 1989.

In 1990, herring larvae collected in the first week of sampling were slightly larger than in 1989 (Figure 5). The strongly unimodal length distribution is the result of very high densities at stations on the east side of Sitka Sound, especially at station 8, where mean density exceeded 2000 larvae/m^2 (Fig. 6). However, unlike 1989, there were already larvae present at stations on the western side of the northern portion of the sound; those larvae were 1 - 2 mm larger than those near the spawning beaches, indicating that some larvae had hatched earlier than our first week of sampling. In 1990 herring larvae were dispersed relatively widely over all of our stations in Sitka Sound, and by the fourth week there were very few in samples at any station (Figure 6). The large group of larvae that were present in the first week were a dominant feature of length frequency distributions in the following two weeks, although at least one episode of later hatching is clearly evident (Figure 5).

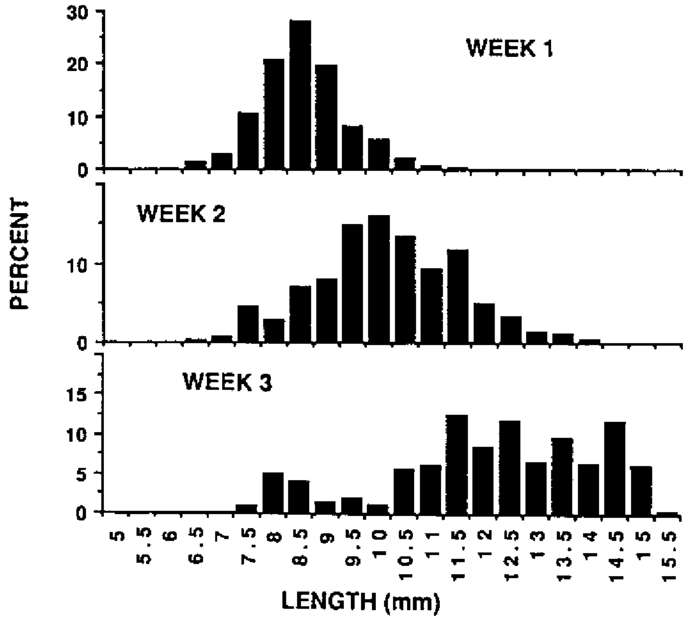

Figure 5. Length distributions of Pacific herring larvae in Sitka Sound in the first three weeks of sampling in 1990.

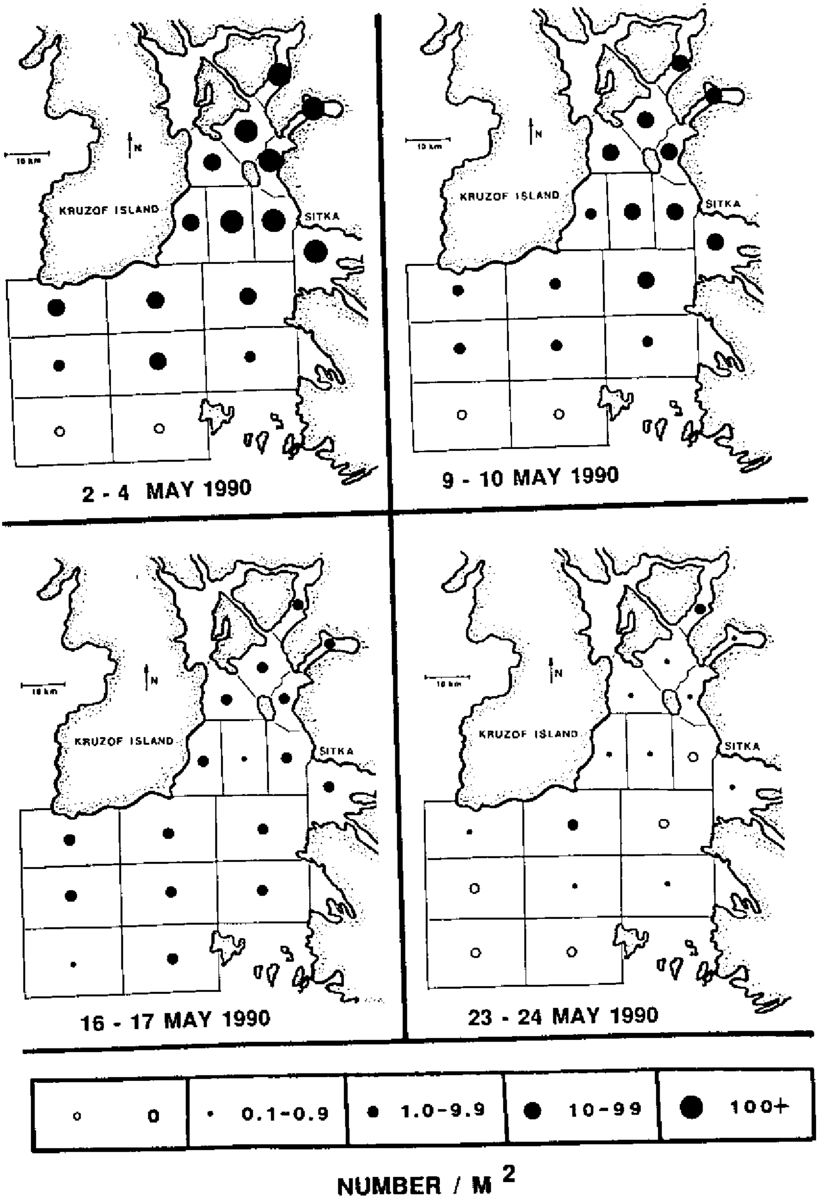

Figure 6. Geographic distribution of Pacific herring larvae at 17 stations in Sitka Sound during the first four sampling weeks of 1990.

DISCUSSION

The two years of data present an interesting contrast in the distribution and fate of herring larvae in Sitka Sound. In 1989, herring larvae were found in the northern end (stations 1 - 8) of Sitka sound, with relatively few occurring in the central or outer sound. In the fourth week of sampling the mean density at stations 1 - 8 was 4.0 /m^2. At the remaining stations the mean density was 0.04 /m^2. In the fourth week of sampling most larvae appear to have been survivors of the large initial cohort and were 12 - 16 mm long.

In 1990, larvae appeared to be relatively evenly distributed throughout Sitka sound. By the fourth week of sampling densities were low (< 1.0 / m^2) at most stations. However, the length frequencies for the two years suggest that in 1990 the weekly sample series was begun later than in 1989, relative to the hatching and development of herring larvae. Consequently, herring sampled in week three in 1990 appear to have been comparable to week four in 1989. Thus, hatching and development of herring larvae in the two years was approximately on the same calendar schedule, despite reported differences in spawning time. In 1989 first spawning and maximum spawning were reported to occur one to two weeks earlier than in 1990. In week three of 1990 the mean density of herring larvae at stations 1 - 8 was 3.0/m^2, compared to 1.8/m^2 at the remaining stations. Relative to 1989, the densities of larvae at stations in the north end of the sound was lower at the time the major cohort was 12 - 16 mm in length. However, larvae were distributed relatively evenly over the sound, and the total abundance of larvae over all stations may still have been higher at this point in 1990 than in 1989.

Our results suggest that the north end of Sitka Sound may be a retention area for herring larvae in Sitka Sound. In that case, the member/vagrant hypothesis would predict that 1989 was a year when a greater proportion of larvae were retained (and, presumably, survived), relative to 1990. However the effect could be masked in subsequent recruitment indices by different absolute abundances of herring larve hatched in the two years. In 1990 very high initial densities were observed in the first week of sampling. The mean densities at stations 1 - 8 in the first weeks sample in 1989 and 1990 were 133.0/m^2 and 424.2/m^2, respectively.

Spawning locations of herring in Sitka Sound are consistent with a hypothesized retention area in the north end of the sound, and with reported surface current flow. If currents on the east side of the sound flow to the north (Sundberg 1981), they would entrain recently hatched herring larvae and carry them to the north end of the sound. Under the member/vagrant hypothesis there would be an adaptive advantage in spawning at locations where hatched larvae would be transported into a retention area.

It is not clear why larvae would not be carried out of the north end of the sound by southerly and westerly flow around the south end of Kruzof Island.

The member/vagrant hypothesis suggests that a combination of hydrographic features (e.g. two-layer estuarine flow) and specialized behavior by larvae (e.g. vertical migration) may result in retention of larvae. The patterns of herring larvae distribution in 1989 and 1990 indicate that the two years differed in some important features that affected retention.

ACKNOWLEDGEMENTS

This work was made possible by the professional capabilities of Jeff Fitzjarrald, captain of the R/V TAKU QUEEN, and the able field and laboratory assistance of Karen Besser, Virginia Lutz, Wendy Stevens and Abdelkrim Zebdi. We also are indebted to Dr. Joe Rossillon and the staff, faculty and students of Sheldon Jackson College, who have made us welcome in their facilities.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Climatic Induced Variation in Eastern Bering Sea Herring Recruitment

V.G. Wespestad
NMFS Alaska Fisheries Science Center
Seattle, Washington
D.R. Gunderson
University of Washington
Seattle, Washington

ABSTRACT

Eastern Bering Sea herring exhibit extreme variations in the abundance of individual year-classes, similar to that observed in all of the northern hemisphere herring populations. The broad range of surviving recruits from a given spawning population level indicates a weak to non-existent spawner recruit relationship and further suggests that factors other than the quantity of eggs produced are more important in determining the size of an individual year-class. It was hypothesized that climatic factors were important determinants of year-class size, principally temperature and wind driven transport. Currents in coastal waters of the eastern Bering Sea are primarily tidal, and the majority of directed transport is wind driven. Recruitment variation relates to the degree of retention in near-coastal nursery areas where temperatures and feeding conditions are optimal for rapid growth. To test this hypothesis estimates of year-class strength were derived from catch data from Soviet, Japanese and U.S. fisheries harvesting herring in the eastern Bering Sea. Catches from 1959 to 1988 were analyzed by cohort analysis and catch-age analysis and year-class estimates were derived for the 1956-1984 year-classes. Climatic data were obtained from Cape Newenham Air Force Station located adjacent to the spawning area of the Togiak spawning stock which accounts for approximately 80% of the biomass of eastern Bering Sea herring. Results show that time of spawning is linearly related to temperature, but time of spawning has little influence on survival. The magnitude of wind driven transport does relate to year-class strength, with strong year-classes generally occurring in years of low transport and weak year-classes occurring in years of high transport.

INTRODUCTION

Herring in the eastern Bering Sea spawn in coastal waters with the majority of spawning occurring in northern Bristol Bay (Fig. 1) (Barton and Wespestad 1980). The first 2-3 years of life are spent in the coastal and inner shelf regime which are more susceptible to rapid habitat modification from air-sea interactions (Schumacher and Reed 1983). The stock shows great variability in year-class size, with a few above average year-classes and many weak ones (Fig. 2).

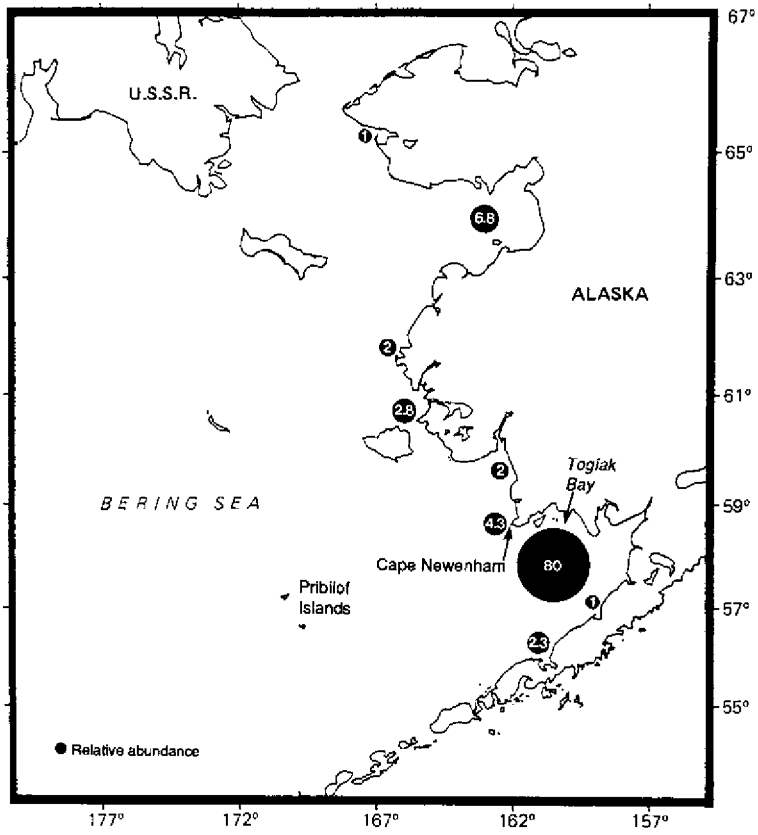

Figure 1.--Distribution of eastern Bering Sea herring spawning biomass and relative abundance in each area.

Eastern Bering Sea herring year-class strength exhibits little relation with adult abundance (Fig 3.). Spawning occurs during the transition period between winter and summer conditions, which is a period that can be calm, or have a series of intense storms. Since herring spawn in the intertidal zone, storms can physically destroy eggs and spawning habitat through scouring and siltation, or can lead to storm driven transport of larvae out of nursery areas. However, the occurrence of warm, dry weather conditions accompanied by extreme neap tides during the incubation period can also be deleterious since exposed eggs could be desiccated causing high mortality. Overall, there appears to be a significant environmental component in herring year-class variation.

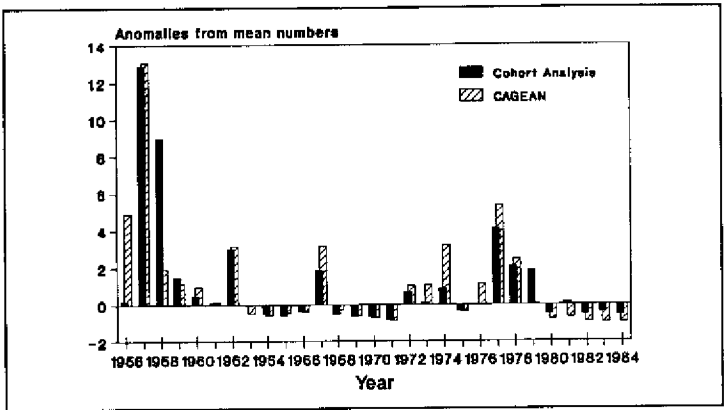

Figure 2.--Estimated year-class strength of eastern Bering Sea herring for the 1956-1984 number-at-age from cohort analysis.

Studies of year-class strength, spawner-recruit patterns and observation of weather and oceanographic events led to a hypothesis that the factors controlling eastern Bering Sea herring year class abundance relate to variations in the spring-summer weather pattern via the magnitude of larval retention in coastal spawning-nursery grounds. This hypothesis was tested by examining net water mass transport from spawning grounds computed from wind and tide data incorporated into a spawner-recruit relationship.

Retention of larvae on inshore spawning grounds was proposed as a mechanism regulating Pacific herring survival by Stevenson (1962). However, he did not propose a mechanism beyond speculating that larvae transported out of the coastal regime died. Taylor and Wickett (1967) correlated year-class strength of herring in British Columbia with onshore transport and found that good year-classes correlated with net northward surface transport during December-March which results in onshore water flow.

Oceanographic data for the eastern Bering Sea coastal region is limited, with data only from recent years available. However, since studies show a strong coupling between ocean processes and the atmosphere in coastal waters atmospheric observations were used to approximate coastal mass transport and temperature. Observations from Cape Newenham Air Force Base were analyzed. Cape Newenham is located at 58.7 N and 162.1 W, adjacent to the Togiak herring spawning grounds at an elevation of 88 m (Fig 1). Weather data from Cape Newenham were obtained from the National Climatic Data Center in Asheville, N.C. as Airways Surface Observations (TD1440) which contain hourly observations of standard meteorological measurements. The data obtained for analysis were the years 1957 to 1984, the years for which estimates of herring year-class size estimates are available. The

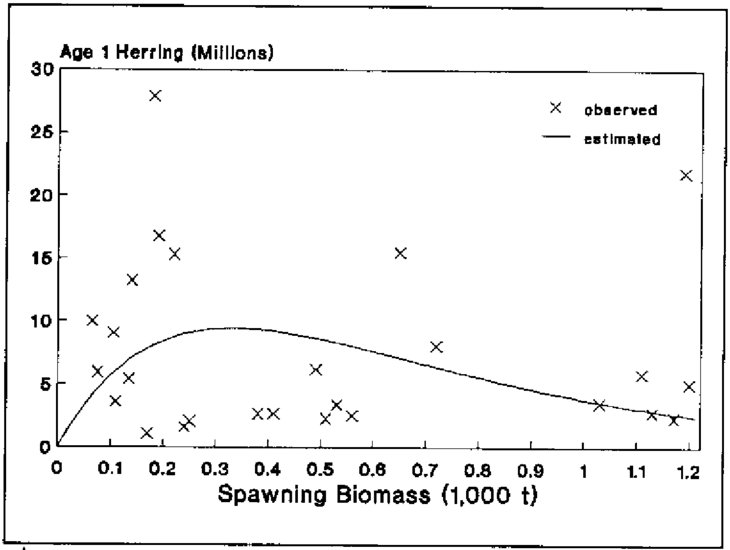

Figure 3.--Eastern Bering Sea herring spawner-recruit relationship derived from cohort analysis estimates.

months examined were April to July, months which include herring spawning, larval and early juvenile periods.

Water temperature data for the general Bristol Bay area were obtained from Ingraham (1983). This data series is a compilation of sea surface and bottom temperatures by month and grid point. The average sea surface temperature was computed for June and July from Ingraham's area 3 (Bristol Bay). Sea surface temperature could not be computed for May due to insufficient observations.

Mean water transport vectors were computed from the wind data in hourly steps. Transfer of momentum from air to water involves friction in the form of velocity reduction and angular deflection. The instantaneous surface currents were computed from wind velocity using the formula of Witting (1909):

$$C=\sqrt{W}$$
$$D=34.0-7.5\sqrt{W}$$

Where C is the surface current velocity (cm sec^{-1}) due to wind, W is the wind velocity in m sec^{-1}, and D is the angle of deflection (Ingraham and Miyahara 1989).

Progressive vectors were computed in a Cartesian plane with vectors originating at 0,0. The corresponding transport in the x and y direction were calculated and added to the cumulative transport. At the end of the period of interest a resultant vector of magnitude= $\sqrt{(x^2 + y^2)}$ and direction = arctan (x/y) was computed relative to the origin and rotated 90° to have North be 0°.

Statistical analyses were performed using SYSTAT (Wilkerson 1988) unless otherwise noted.

Herring Recruitment Trend

The most extensive data base for use in estimating the population size of eastern Bering Sea herring is age specific catch data from the fishery. Age specific catch data has been collected from the fishery since its inception in 1959 (Wespestad 1982). Currently, catch-age data are collected by ADF&G from fisheries in coastal spawning areas, but for most of the history of the eastern Bering Sea herring fishery catches were predominately taken in fisheries on the winter grounds. To utilize the entire data series it was assumed that eastern Bering Sea herring comprise a unit stock. Previous research has shown that the portion of the stock spawning in northern Bristol Bay (Togiak) is 80 percent or greater of the entire Bering Sea stock (Barton et al. 1977, Barton and Steinhoff 1980, Wespestad and Fried 1983). Therefore, modelling of the entire stock should be reflective of recruitment from northern Bristol Bay.

Two models were used for catch-age analysis of Bering Sea herring, Cohort Analysis (Pope 1972), and CAGEAN (Deriso et al. 1985). Cohort Analysis was chosen as an analytical method because it has been shown to be one of the most robust catch-age models (Megrey 1989). The CAGEAN model was also used because it allows the incorporation of auxiliary "tuning" information into the model and the separation of fishing mortality (F) into a catchability component (s) and an effort component (f).

Catch data used in the analysis were obtained from the foreign and domestic fisheries. Prior to 1977, catch data were obtained through bilateral exchanges with nations fishing in the Bering Sea. Since 1977, catch data has been reported directly to the U.S. by nations fishing in the eastern Bering Sea and verified by at-sea fisheries observers. Catch data from the domestic inshore roe fishery was collected by the Alaska Department of Fish and Game. ADF&G also collected age,length and weight data from the catch. These data are maintained on a microcomputer database and were obtained from Fritz Funk, Alaska Department of Fish and Game, Juneau, Alaska.

Cohort analysis results indicate that between 1956 and 1985 there were 8 strong year-classes, 9 slightly above average and the remaining 12 slightly below average (Fig 2). The largest year-classes were the 1957 and 1958, followed by the 1977. Other large year-classes occurred in 1962, 1967, 1978 and in 1979. The 1985 year-class was the weakest year-class and all of the year-classes spawned in the 1980's with the exception of 1981 were weak.

CAGEAN estimated the same recruitment pattern as cohort analysis, but there were several discrepancies (Fig 2). Major differences occurred in 1956, 1958, 1974 and in 1979 year-classes (Fig 2). The 1956 year-class was estimated to be average by cohort analysis while CAGEAN estimated the year-class to be strong. In the 1958 year-class the estimates by the two procedures again differed, but CAGEAN estimated the year-class to be near average while cohort analysis estimated the year-class to be very strong. The 1974 year-class was estimated to be slightly above average by cohort analysis, but strong by CAGEAN, and the 1979 year-class was average by CAGEAN, but estimated to be strong by cohort analysis.

Apart from the four year-classes above, there was good agreement on relative year-class strength (Fig 2). Through 1978 an above average year-class occurred every 5 years, but since the 1978 year-class a strong year-class has been absent with all year-classes average to below average. The recruitment pattern tested significant ($\alpha = 0.05$) using a non-parametric run test, signifying that the observed pattern is non-random.

CLIMATIC VARIABLES

Temperature

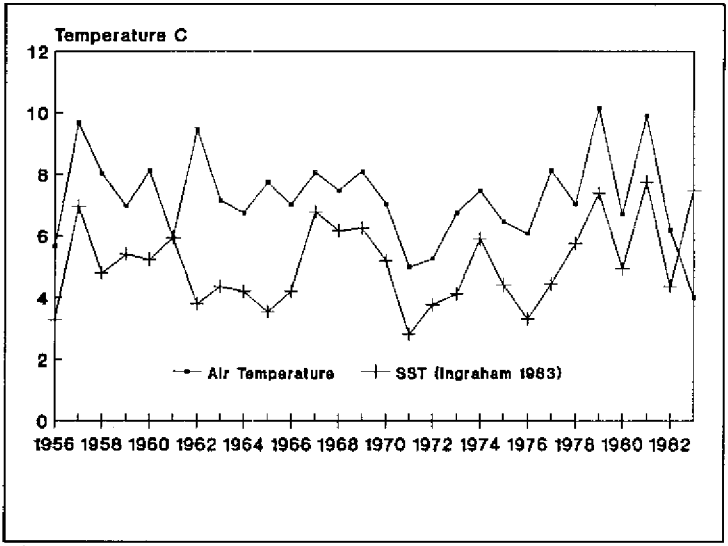

Figure 4.--Comparison of Bristol Bay sea surface temperature and Cape Newenham air temperature during June-July, 1956-1983.

Sea surface temperature recorded for Bristol Bay (Ingraham 1983) correlates ($r^2 = 0.63$) with air temperature observed at Cape Newenham for the years 1963 to 1978 (Fig 4). Sea surface temperature correlates on a monthly basis as well as interannual basis. There is a strong interannual difference in mean monthly temperature at Cape Newenham (Fig. 5). April exhibits the greatest variation. Air temperature increases during May-July and interannual variability decreases (Fig 5).

Surface winds

Surface winds at Cape Newenham are stronger during the winter months and the frequency of high winds are greater (Table 1).

Scalar mean wind velocity decreases in May and remains low until September when scalar wind velocity and the frequency of high winds increase (Table 1). The vector mean wind velocity does not exhibit a strong seasonal pattern, and winds are usually from the southeast to south-southwest.

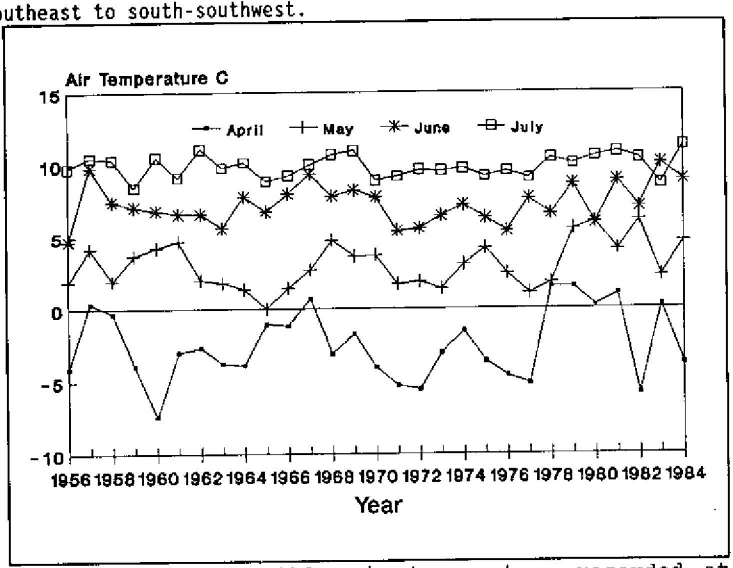

Figure 5.--Mean monthly air temperature recorded at Cape Newenham, April-July, 1956-1984.

Table 1. Cape Newenham monthly wind data, 1956-1984 average.

Month	Vector Mean wind m sec^{-1}	Dir	Scalar Mean wind m sec^{-1}	Percent wind exceeds 8.5 m sec^{-1}
1	2.35	SE	5.50	17
2	1.95	SE	5.50	25
3	1.00	SE	5.25	21
4	0.75	SE	5.50	23
5	1.25	SE	4.00	13
6	0.80	SSE	3.00	7
7	1.20	SSW	3.00	7
8	1.35	SSW	4.00	9
9	0.40	SSW	5.00	11
10	1.05	S	5.00	17
11	1.05	E	5.50	22
12	1.20	NE	5.25	24

The frequency of strong winds decreases from April to May when spawning occurs. From May to July light to moderate surface winds predominate (Fig. 6). In April winds are predominately from the south to southeast and from the north to northwest. In May the predominate winds are southerly to easterly with north to northwesterly winds of secondary importance. Wind velocitys of 3-9 m sec^{-1} are the most frequent winds in May with high winds much less frequent. In June winds from the south to southeast are dominant and winds in excess of 9 m sec^{-1} are less frequent than in previous months. July winds are primarily from the south and winds are usually light to moderate.

As with temperature there is a large interannual variation in the direction and magnitude of wind (Table 2). From 1956 to 1984 during the egg and early larval stages (May-June) were predominately from the southeast to southwest as shown in the following table. The mean vector wind velocity ranged from a low of 0.19 m sec^{-1} in 1966 to a high of 2.41 m sec^{-1} in 1971.

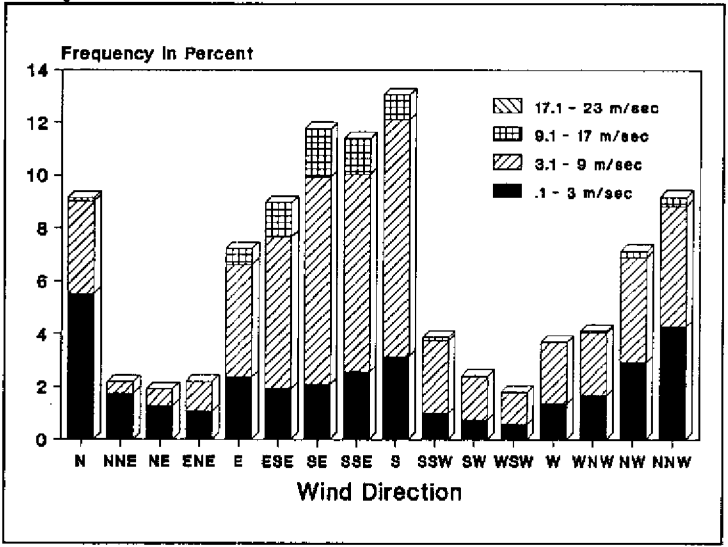

Figure 6.--Direction and intensity of winds during May and June, 1956-84.

Table 2. Interannual variation in May-June wind direction in degrees from North, vector mean and scalar mean velocities in m sec^{-1} as recorded at Cape Newenham, Alaska, 1956-1984.

Year	Dir	Vect. Vel.	Scal. Vel.	Year	Dir	Vect. Vel.	Scal. Vel.	Year	Dir	Vect. Vel.	Scal. Vel.
1956	123	1.3	4.1	1966	168	0.2	4.7	1976	208	0.5	4.1
1957	136	1.0	4.4	1967	150	1.3	3.4	1977	186	0.2	3.3
1958	120	1.8	4.5	1968	293	0.1	2.6	1978	169	1.3	3.6
1959	223	1.0	4.8	1969	151	1.6	4.8	1979	147	1.6	3.4
1960	243	0.6	3.6	1970	156	1.1	3.1	1980	161	2.3	3.4
1961	174	0.7	3.6	1971	132	2.4	5.2	1981	147	1.4	3.3
1962	205	1.1	4.0	1972	132	1.9	5.0	1982	138	2.4	4.3
1963	172	1.8	4.4	1973	144	0.7	4.1	1983	132	1.3	3.4
1964	172	1.2	4.6	1974	141	0.4	3.8	1984	160	0.7	2.7
1965	150	1.8	5.3	1975	135	1.2	4.3				

Relationship of Herring Recruitment to Environmental Parameters

The factors hypothesized to have influence on herring recruitment are temperature, wind velocity and direction, precipitation, and barometric pressure. Examination of the matrix of Spearman correlation coefficients of these variables with year-class size estimated by cohort analysis and CAGEAN show the following relationships:

	Recruits		Temperature		Transport		Sealevel	
	Cohort	CAGEAN	Water	Air	Direction	Velocity	Pressure	Precip.
RCO	1.000							
RCAG	0.841	1.000						
WT	0.435	0.415	1.000					
AT	0.173	-0.061	0.309	1.000				
DIR	-0.417	-0.445	0.018	0.162	1.000			
SP	-0.274	-0.488	-0.128	-0.111	0.294	1.000		
BAR	0.075	0.052	0.156	0.129	-0.258	-0.111	1.000	
PRE	-0.148	-0.245	0.040	-0.225	0.102	0.583	-0.176	1.000.

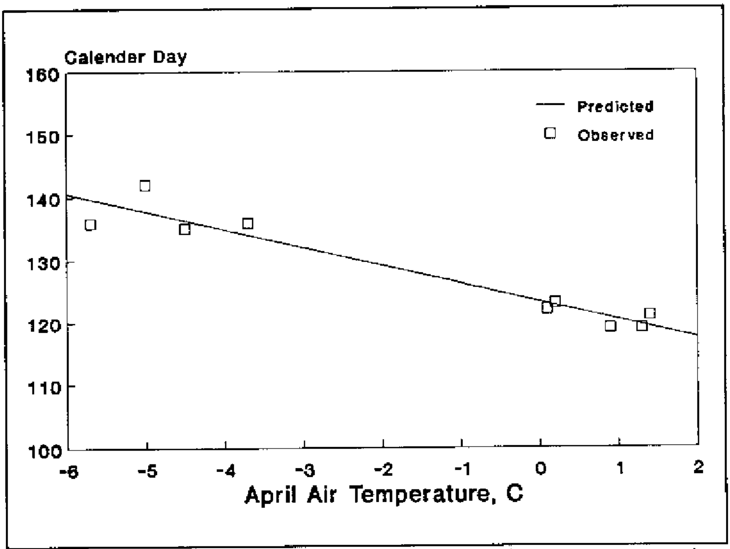

Figure 7.--Relationship between time of herring spawning in northern Bristol Bay and April air temperature at Cape Newenham, Alaska.

Year-class size as estimated by cohort analysis was positively correlated with water temperature (WT), negatively with the direction of transport (DIR) and mean transport velocity (SP). The preceding variables were moderately correlated, and the remainder: air temperature (AT), sea level pressure (BAR) and precipitation (PRE) were poorly correlated with recruitment. The CAGEAN estimates had similar correlation, except that mean transport velocity and precipitation had high correlation with year-class strength than observed for the cohort analysis results.

Temperature - time of spawning relationship

It has been observed that onset of herring spawning is variable in time, occurring from late April to late May with earlier spawning occurring in warm years (Wespestad and Barton 1980, Wespestad and Fried 1983). Recorded first dates of mass herring spawning in Togiak for the years 1977 to 1984 (ADF&G Herring Fishery Summaries, Dillingham, AK) were regressed against April and May mean air temperature data recorded at Cape Newenham. In both instances there was a high correlation between the start of spawning and the prevailing prespawning temperature, $R^2 = 0.92$ for April and $R^2 = 0.90$ for May.

The regression coefficients from April temperature and start of spawning (Fig. 7) were used to calculate the estimated start of spawning in each year, 1956 to 1984. The estimated date of first spawning ranged from April 28 in 1981 to May 21 in 1977. The estimated day of first spawning was used as the starting date to calculated transport vectors. Transport vectors were accumulated over a 61 day period in all years. It was assumed that a 61 day period would encompass the egg and all or most of the larval period, since metamorphosis has been observed to occur within this time period (Wespestad and Moksness 1990).

Residual variation and climatic variables

Multiple linear regression was used to examine whether or not the climatic variables could account for any of the variability in observed recruitment. The regression equation used was a linearized Ricker (1967) spawner-recruit relationship of the form:

$$\frac{R}{S} = \alpha + \beta S + \delta \ln(Dir) + \gamma \ln(Sp) + \lambda \ln(pre) + \psi \ln(Wt)$$

where R is the number of recruits, S is the number of spawners, Dir is the direction of transport, Sp is the magnitude of transport, Pre is total precipitation in May-June, and Wt is the average Bristol Bay summer water temperature.

A Ricker model was used because theory and observations in British Columbia (Stocker <u>et al</u>. 1985) indicate that there is a density dependent relationship between recruits and spawners of the Ricker type due to limits in spawning habitat. The cohort analysis estimate of recruits had a significant fit to the Ricker model, $P<0.001$, $F = 16.59$, with adjusted $R^2 = 0.384$. The CAGEAN results were marginally significant, $P = 0.051$, $F = 4.227$, with adjusted $R^2 = 0.114$.

The climatic variables, included as density independent variables, reduced the residual variability in both data sets (Table 3). The greatest improvement was in the regression of CAGEAN estimates, but the adjusted R^2 was only 0.441 for the CAGEAN estimates and 0.506 for the cohort analysis estimates of recruitment. Step wise regression was performed on each data set to select the significant variables. For the cohort analysis estimates the number spawners (S), water temperature (Wt), and direction of transport were significant variables (Table 3). The same variables were significant for the CAGEAN estimates, along with the magnitude of transport (Sp).

The preceding regressions did not include the 1956-1958 year-class because spawning stock size could not be estimated for these year-classes. The 1957 year-class is the largest in the time series, and cohort analysis estimates the 1958 to be the second largest. If spawning stock size in 1956-1958 is assumed equal to 1959 levels the only significant variables remaining following step wise regression on both data sets are number of spawners and water temperature.

Table 3. Results of multiple regression of eastern Bering Sea herring recruitment on spawners and climatic variables, 1959-1984.

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN SQUARE	F-RATIO	P
Full Model					
Cohort Analysis			adjusted multiple R^2 = 0.506		
REGRESSION	24.077	5	4.815	6.117	0.001
RESIDUAL	15.744	20	0.787		
CAGEAN			adjusted multiple R^2 = 0.441		
REGRESSION	44.044	5	8.809	4.943	0.004
RESIDUAL	35.644	20	1.782		
Step wise					
Cohort Analysis			adjusted multiple R^2 = 0.539		
Variables = S, Wt, Dir					
REGRESSION	23.663	3	7.888	10.740	0.000
RESIDUAL	16.158	22	0.734		
CAGEAN			adjusted multiple R^2 = 0.467		
Variables = S, Wt, Dir, Sp					
REGRESSION	44.005	4	11.001	6.475	0.001
RESIDUAL	35.682	21	1.699		

Sp = current velocity, Wt = water temperature, Dir = transport direction, S = size of spawning stock.

Retention and variation within the nursery grounds

The transport vectors computed from Cape Newenham wind data indicate that transport during the egg and larval stage in most years to the northeast to northwest (Table 4). Regression coefficients for the direction of transport were negative suggesting that transport to the north and northeast were more favorable for survival than in other directions. Year-class size also showed an inverse relationship with mean transport velocity, large year-classes being associated with low transport velocity.

Overall, wind driven transport in the Togiak region of Bristol Bay appears to be onshore and favor the retention of larvae in coastal waters. Offshore egg and larval surveys in the eastern Bering Sea, also suggest that herring remain in coastal waters, as larval herring have not been found in offshore samples (Waldron 1981).

Interannual variation in transport direction and velocity only accounted for a portion of the total variability in herring year-class strength. The three significant climatic variables in the regressions were temperature, transport direction and transport velocity. These three variables together indicate that above average year-classes can be expected in warm years when transport is to the north to northeast and transport velocity is low. Weak year classes appear more likely to occur when cold temperatures, high transport velocity and transport is to the west to northwest.

Table 4. Direction, degrees from North (0°), and mean vector transport velocity (cm sec^{-1}) of mass transport during the herring egg and larval period computed from C.Newenham wind data, 1956-1984.

Year	Dir.	Vector Velocity	Year	Dir.	Vector Velocity	Year	Dir.	Vector Velocity
1956	308	2.14	1966	236	0.08	1976	67	0.78
1957*	318	1.56	1967*	337	2.15	1977*	77	0.21
1958	316	3.78	1968	173	0.71	1978*	1	2.01
1959	76	1.81	1969-	338	2.53	1979	343	3.17
1960	97	1.25	1970-	347	1.87	1980-	358	4.35
1961	12	0.91	1971-	324	3.34	1981	340	2.69
1962*	48	1.89	1972*	323	2.78	1982-	335	4.51
1963	5	2.56	1973	341	1.10	1983-	321	2.55
1964	8	1.67	1974*	331	0.43	1984-	351	1.33
1965-	345	3.33	1975	324	1.83			

* Strong year-class in both models, - weak year-class in both models

CONCLUSIONS

Pacific herring in the eastern Bering Sea have exhibited great interannual variation in year-class size. Only about a third of the variation can be accounted for by variation in spawning stock size. Climatic effects of wind driven transport and temperature describes a portion of the residual variation in recruitment, but only about 50% of the total variation is left unaccounted. The remaining variation may relate to large scale physical processes, or local variation in biological processes, for which accurate measures are unavailable.

The spawning grounds of herring in northern Bristol Bay are situated in an area that under prevailing winds generally produces on-shore retention of water and larvae. Statistical analysis of interannual variation in wind driven transport indicate a relationship with year-class strength and the magnitude and direction of transport.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

A Study on Herring Larvae in the North Sea: The Autumn Circulation Experiment

M. Heath
DAFS Marine Laboratory
Aberdeen, UK
P. Munk
Danish Institute for Fisheries and Marine Research
Charlottenlund, Denmark

ABSTRACT

The Autumn Circulation Experiment was an oceanographic and biological study in the North Sea performed in the autumn-winter period 1987–1988. The biological part focused on the fate of the 1987 year-class of North Sea herring in their larval stage. Larval distribution and biological characteristics were measured at monthly intervals and larval advection and growth were related to circulation patterns and plankton abundance and productivity. A comparison between larval distribution and modelled circulation patterns showed the importance of the autumn circulation in the advective process of larvae. The study also emphasized the influence of larval vertical migrations (which was studied extensively) on horizontal advection.

By microstructure analysis of larval otoliths, significant growth differences between larvae from northern and southern areas were estimated. Thus, regional variability in plankton environments and growth of herring larvae, combined with a variable circulation pattern in the North Sea, might determine variability in overall growth and hence survival to recruitment.

Stock Assessment and Methodology

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

The Development of Hydroacoustic Techniques for the Empirical Estimation of Biomass for Newfoundland Herring Stocks

J.P. Wheeler and G.H. Winters
Department of Fisheries and Oceans
St. John's, Newfoundland, Canada

Abstract

Acoustic surveys have been conducted annually since 1983 to estimate the biomass of five herring stock complexes within the coastal waters of Newfoundland. There have been substantial changes in the acoustic equipment and survey design over that time. From 1983 to 1986, a sonar and sounder technique was used to map the size of herring schools along continuous coastline transects. Since 1987, herring density estimates have been derived by echo integration. Random parallel transects are used to provide unbiased estimates of the mean biomass and the variance due to survey design. This paper will review the development of these hydroacoustic research techniques, describing the evolution of survey methodology, how stock boundaries were determined, how herring schools were identified from acoustic records, and how target strengths were determined. There will also be a discussion of certain research initiatives aimed at improving the results of these surveys.

INTRODUCTION

There are five herring stock complexes along the east and southeast coasts of Newfoundland (Fig. 1) (Moores and Winters,1979; Wheeler and Winters,1984) for which annual estimates of abundance are provided for management purposes. These stocks have been managed by total allowable catch (TAC) levels since the mid 1970's. Within the past decade, there have been substantial changes in the methods of determining the biomass of these stocks.

Prior to 1983, all herring stocks were assessed analytically, using cohort analysis (Pope,1972). As Moores (1980) points out in his review of assessment methods at that time, the calibration of the level of fishing mortality in the most recent (i.e. terminal) year is

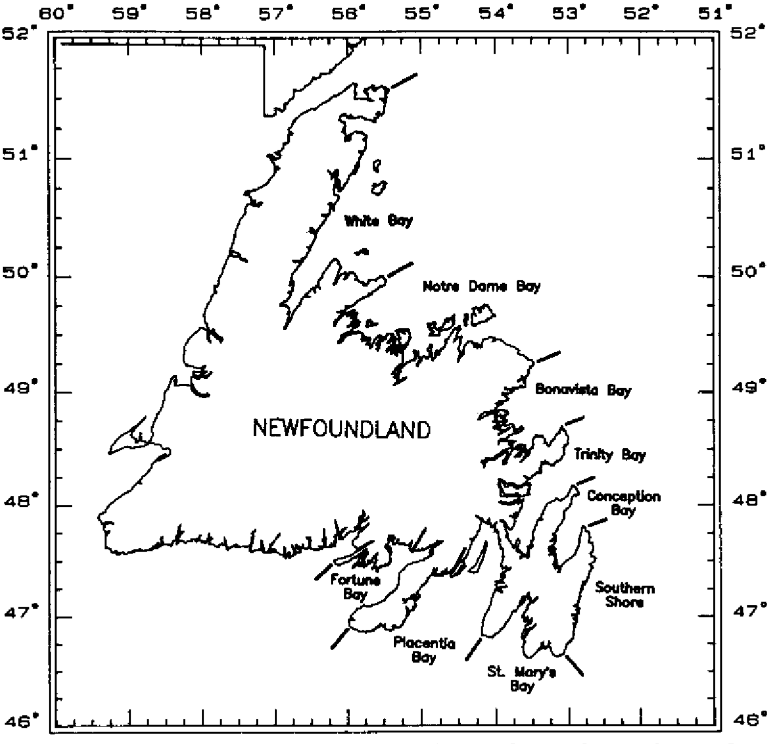

Fig. 1. Area map indicating the five herring stock complexes within the Newfoundland region: White Bay-Notre Dame Bay, Bonavista Bay-Trinity Bay, Conception Bay-Southern Shore, St. Mary's Bay-Placentia Bay, and Fortune Bay.

critical to cohort analysis. In the case of Newfoundland herring stocks, this had been estimated from commercial gillnet and ringnet catch rates which were derived from purchase slip data (Wheeler and Winters,1980; 1981; 1982; 1983). These catch rates were found to be inadequate as abundance indicators as they did not account for searching time or cooperation between vessels and therefore did not reflect stock abundance (Powles,1981; Wheeler and Winters,1982). There were also inherent problems associated with the use of purchase slips to calculate gillnet catch rates (Wheeler and Winters, 1983). These data inadequacies were compounded by the fact that stock sizes, and hence quotas and catches (Fig. 2), were declining each year. By 1983, there were no commercial catch rate data available as the fishery in all five stock areas had been closed due to recruitment failure (Wheeler et al.,1984).

The need for estimates of stock size, independent of the commercial fishery, had been foreseen and two programs were initiated to provide long-term indices of herring stock abundance independent of any future commercial fishery. A research gillnet program, begun in 1980 (Wheeler and Winters,1981), has been expanded and continued each year and now provides detailed annual catch rate at age indices for each of the herring stock complexes (Wheeler et al.,1990). Annual acoustic surveys, the focus of this paper, were begun in 1982 and have become increasingly important, now forming the basis for the annual scientific advice for the management of these stocks (Wheeler et al.,1990).

The history of herring biomass estimation by hydroacoustic methods in the Northwest Atlantic is brief in comparison to that in European and Pacific waters. Hydroacoustic abundance surveys have been used to estimate the size of the Icelandic summer spawning stock of herring since 1973 (Jacobsson,1983). Acoustic surveys have also played increasingly important roles in the assessment of the North Sea and Atlanto-Scandian herring stocks since the early 1980's (Jacobsson,1985). Similarly, acoustic surveys of Pacific herring populations in Washington and southeastern Alaska have been conducted since 1971 (Thorne et al.,1983). In the Northwest Atlantic, an acoustic survey biomass estimate was first used for herring management purposes in 1984 (Wheeler et al.,1985). Shotten and Randell (1982) conducted the first acoustic surveys of a herring stock, winter and summer surveys of the southwest Nova Scotia herring (NAFO Div. 4WX) in 1981, but because of sampling error and unavailability of the stock during the summer survey, the results were not used for assessment purposes. Buerkle (1985; 1987; 1989) has subsequently conducted winter surveys of this same stock, the results of which have become increasingly important in the annual stock assessment (Stephenson and Power,1989). Acoustic surveys have also been conducted to estimate herring biomass in the southern Gulf of St. Lawrence (NAFO Divs. 4T and 4Vn) each fall since 1984 (Shotten 1986; Shotten et al.,1987a; 1987b; Cairns et al.,1988; 1989). Results of these surveys have also become more important and have been incorporated in the most recent assessment of this stock (Chadwick et al.,1989). As evidenced above, although the history of herring acoustic biomass surveys is relatively short in Atlantic Canada, the results of these surveys now form an integral part of the annual assessment of all stocks in the region.

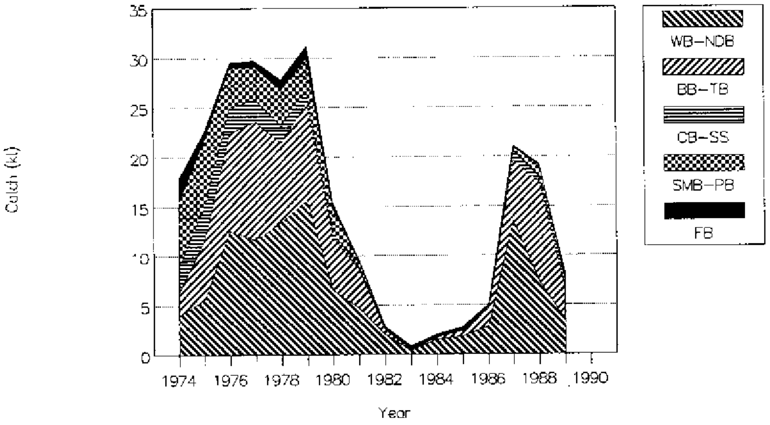

Fig. 2. Annual commercial herring catches (KT), by stock area, 1974 to 1989.

This paper will review the development of hydroacoustic research techniques utilized to empirically estimate herring stock sizes within the Newfoundland region during the past decade. As a review, it will concentrate on methodology rather than actual survey results. The paper is divided chronologically from: 1) 1982–1986, when a sonar and sounder technique was used to map the size of herring schools and to estimate biomass, and 2) 1987 to the present, when echo integration has been used to measure herring densities and to estimate biomass.

1982-1986 : DEVELOPMENT OF THE SONAR-SOUNDER TECHNIQUE

When it was decided in 1982 to conduct annual acoustic surveys for herring stock biomass estimation, two approaches were considered. Echo integration was already being used to estimate capelin biomass in offshore Newfoundland waters (Miller and Carscadden,1979). However, the system was not suited for inshore shallow water work from small vessels as would be required for herring surveys. Instead, it was decided to develop a technique to measure and estimate herring school sizes from sounder records and to extrapolate to stock biomass.

An exploratory survey was conducted during the fall of 1982 along the east coast of Newfoundland to determine both the distributional pattern of herring and the feasibility of such an approach. Two commercial purse seine vessels (<20 m LOA) were chartered to search for herring concentrations using sonar, to measure as many concentrations as possible on the sounder chart recorder, and to make purse seine sets in order to identify the ensonified species and to scale the chart recorder measurements. The results of this survey indicated that during October and November, most herring concentrations were in coastal areas in water depths of less than 90 m. This was consistent with the results of tagging studies (Wheeler and Winter,1984) which indicated that herring along the east coast of Newfoundland undertook coastal migrations during the fall to overwinter in the local coastal embayments.

Acoustic surveys were conducted each fall through east coast stock areas from 1983 to 1986 (Wheeler et al.,1984; 1985; 1986; Wheeler and Chaulk,1987). Similarly, surveys were conducted during the winter through southeast coast stock areas from 1984 to 1986 (Wheeler and Dalley,1984; 1985; 1986). An additional survey was conducted in 1986 along the southeast coast subsequent to the east coast fall survey (Wheeler and Chaulk,1987).

From 1983 to 1986, the surveys were designed so that each of two purse seine vessels covered a separate cruise track, at a predetermined fixed distance from and approximately parallel to the shoreline, within the 90 m depth contour. The cruise track width was estimated as the lateral distance swept by the sonar (0.304 km) while searching along the cruise track. From an estimate of cruise track length and width, it was possible to calculate the area (km^2) surveyed within each stock area. Each vessel used its sonar to locate herring schools within the cruise track. Single line transects through the widest lateral dimension of the school, as viewed by the sonar, were then recorded on the sounder chart paper. Horizontal and vertical dimensions of each school were subsequently measured, school depth directly from the sounder chart scale and the horizontal dimension by converting the sounder chart measurement to actual distance by relating chart paper speed to vessel speed. Not all schools observed by the sonar within the cruise track were recorded by the sounder. Purse seine sets were made whenever conditions permitted, to identify species and to obtain biological samples.

From data collected during the 1984, 1985, and 1986 acoustic surveys, the following relationship was calculated (Fig. 3) between the cross-sectional area of herring schools (m^2), as measured from the sounder chart, and school biomass (kg), as visually estimated from purse seine sets in shallow water (<30 m) where it was considered that the entire school had been caught (Wheeler et al.,1985; 1986; Wheeler and Chaulk,1987):

$$\text{Wgt (kg)} = 2.12 * \text{Area } (m^2)^{1.39} \qquad r^2 = 0.73$$

The relationship was applied to each of the measured schools to obtain a density estimate along the cruise track. Total biomass estimates were calculated within the 90 m contour, considered to be the stock area, by prorating density estimates by areal expansion.

Although the survey design did not change from 1983 to 1986, certain refinements were made to the biomass estimation technique. In 1985, each of the stock areas was divided into strata; population numbers at age were then calculated on a stratum by stratum basis to better account for intra-stock differences (Wheeler et al.,1986). In most years not all strata within a stock area could be surveyed. Extrapolations were made to non-surveyed areas assuming an equal distribution of fish between surveyed and non-surveyed areas (Wheeler et al.,1985; 1986). In 1986, a minimum estimate of stock abundance was calculated from only those core strata which had been consistently surveyed in each of the previous surveys (Wheeler and Chaulk,1987). However, there were still sources of uncertainty in the calculation of stock biomass from these acoustic surveys which could not be quantified (Anon.,1986; 1987). The cruise track width may have been underestimated as schools which were detected and measured at the outermost lateral edge of the track would have increased the effective width of the search pattern. The effect of changing vessel course to measure these schools was uncertain, as schools on the original course may have gone undetected. Biomass estimates were also particularly dependent upon the relationship between school size and the weight of fish in the school. This relationship could only be tested for small schools since these were the only ones that could be caught completely. However, approximately 60-80% of the estimated biomass (Wheeler and Chaulk,1987) was in larger schools and consequently, any change in the relationship could have a major effect on the estimated weight of the larger schools and hence the total biomass. Nevertheless, biomass levels estimated by this rather crude technique were generally consistent with expected levels based on the historical virtual population analyses.

Acknowledging these concerns, a BioSonics 120 kHz dual beam hydroacoustic system, capable of both echo integration and target strength measurement, was leased for a two week period during the 1986 fall purse seine survey to examine alternate biomass estimation techniques. Unlike the echo integration system used for capelin, the BioSonics system was portable, and the 1 m v-fin and transducer could easily be deployed from the 23 m research vessel used to conduct the

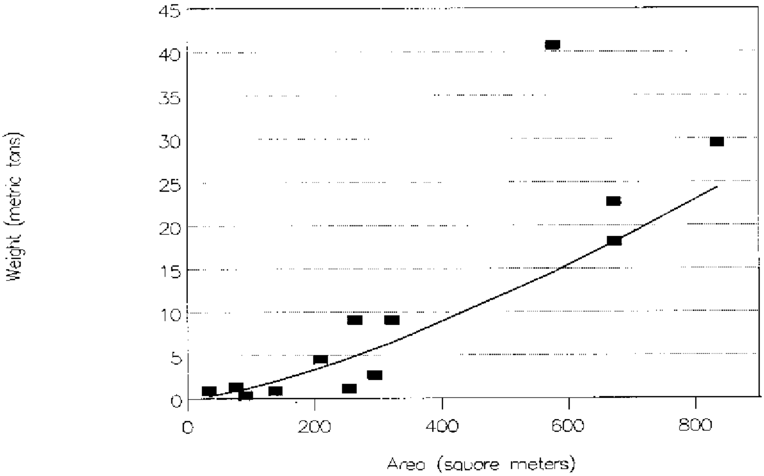

Fig. 3. The relationship between cross-sectional area of herring schools (m^2) and weight per school (kg) as derived from the 1984, 1985, and 1986 acoustic surveys.

survey. There were four objectives to the experiment: 1) to obtain density estimates of individual herring schools and to make comparisons between schools, 2) to determine in situ target strengths of herring and mackerel, to distinguish between each and to possibly distinguish size differentiation within herring, 3) given certain assumptions concerning school shape, to obtain school biomass estimates and to make comparisons with the sounder method, and 4) to determine the suitability of the system for future inshore quantitative herring acoustic surveys. The use of the BioSonics system proved very successful (Wheeler and Chaulk,1987). Differences in school densities were detected and quantified; herring and mackerel schools were differentiated based upon target strength measurements, and given certain assumptions, school biomass estimates were derived which were comparable in magnitude to sounder estimates.

1987-1990 : DEVELOPMENT OF ECHO INTEGRATION SURVEYS

Given the success of the experimental work conducted during the 1986 survey, it was decided to revise survey design in 1987 to utilize the echo integration technique. One survey only was conducted in 1987, a fall survey of east coast stock areas (Wheeler et al.,1988). The objectives of the survey were: 1) to derive unscaled density estimates through echo integration along transects in each of the stock areas, 2) to determine in situ target strength estimates from as many individual herring as possible to scale the integration outputs, 3) to derive population numbers and biomass estimates by areal expansion of the transect density estimates, 4) to compare density estimates between coastline (along shore) transects and zigzag (inshore - offshore) transects in a subsample of randomly selected strata to determine if herring densities were greater nearshore or offshore within the stock areas, and 5) to determine herring distribution patterns within the stock areas to aid in future survey design.

As in previous surveys, each of the stock areas was divided into strata, the outer stock boundary being determined by the 90 m depth contour (Wheeler et al.,1988). Integrated density estimates were derived along predetermined coastline transects (i.e. parallel to shore) through each of the strata. Sonar was not used to locate fish concentrations; the cruise track width was determined by the ensonified water volume. In situ target strengths were calculated by back-tracking over previously integrated fish concentrations. Due to the dense nature of the herring aggregations, less than 700 individual targets could be isolated from 28 herring schools. Population estimates within each stratum were then calculated by areal extrapalation from density estimates along the transect within the stratum.

The following relationship (Fig. 4) between fish numbers and water depth, adjusted to account for searching time, was calculated from the zigzag transect data:

$$Y = -0.0035X^2 + 0.42X - 0.37 \qquad r^2 = 0.94$$

This relationship suggested that the outer stock boundary should be approximately 120 m and that population estimates may be biased downward by surveying to 90 m only.

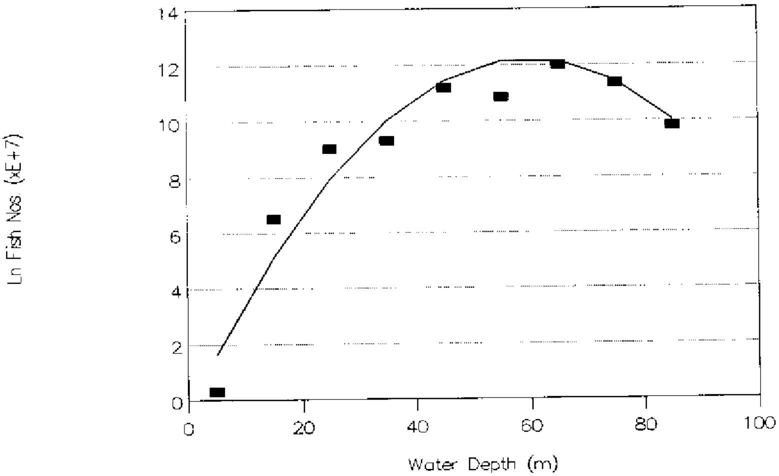

Fig. 4. Estimate of the number of herring by water depth, adjusted to account for searching time, as derived from the 1987 acoustic survey.

In 1988, the Canadian Atlantic Fisheries Scientific Advisory Committee (CAFSAC) held a special meeting of the Pelagic Subcommittee to discuss the issue of acoustic survey design for pelagic species within the Northwest Atlantic (O'Boyle and Atkinson,1989). It was recognized that a variety of survey designs were being used (Miller et al.,1983; Buerkle,1985; Shotten,1986; Wheeler et al.,1986) some of which lacked statistical information associated with survey results. As hydroacoustic estimates became more integrated into the assessments of both herring and capelin, unbiased estimates of both the mean biomass and the variance due to survey design were necessary. The concept of finite population sampling (Jolly and Hampton,1988) was presented as the most appropriate for this purpose where finite referred to identifiable and mutually exclusive sample units encompassing all possible sample units in the target population. For acoustic surveys, the most appropriate sampling frame consisted of contiguous parallel transects with the measurement of concern being the density of fish along the transect. The essence of a valid sample was the independent selection of random transects. It was therefore recommended by CAFSAC that random parallel transects form the basis of future acoustic biomass surveys in the Northwest Atlantic. The direction of the transects should be chosen across the density gradient of the target species to maximize the variation along the transect and hence minimize the variation between transects. Stratification of sample units and optimum allocation of sampling would increase the precision of the sample mean. With regard to the estimation and use of target strength information, it was recommended that in situ estimates of backscattering cross-section of sonified fish should be obtained on a stratum basis if possible. If not, then Foote's (1987) target strength - fish length relationship calculated

$$TS(dB) = 20 \log L\ (cm) - 71.9$$

for herring in European waters, should be used for all future herring work until in situ measurements become available for the Northwest Atlantic stocks.

The recommendations of CAFSAC were incorporated in the survey design prior to the 1988 survey of east coast stock areas (Wheeler et al.,1989). Each of the stock areas was divided into low, medium, and high density strata based upon distributional patterns observed during previous surveys. Sampling intensity (total transect length) was allocated on a 3:2:1 ratio between high, medium, and low density areas, respectively. Subsequent to the analysis of results of the 1987 acoustic survey, which indicated that there may have been herring outside the area surveyed (Wheeler et al.,1988), the outer boundary of each of the stock areas was extended from 90 m to 120 m. The survey design consisted of a series of randomly selected parallel transects from shore to the 120 m depth contour, with a minimum of three transects in each stratum to allow for the calculation of variance estimates. Due to the irregular nature of the coastline, transects within strata were of unequal length. Integrated density estimates were calculated along each transect; acoustic backscatter was converted to biomass using Foote's (1987) relationship between target strength and fish length.

A two-staged process was used to identify herring concentrations for inclusion in data analysis. All fish schools, regardless of species, were first identified from chart recorder tracings and acoustic logbook observations recorded during the survey. Detected voltages from all other sources were eliminated prior to further analysis. The shape of the echo trace of each of the fish schools was then viewed with an oscilloscope to distinguish between herring and other species. This method involved examination of peak voltage amplitudes, voltage peak to trough distances and distance between voltage peaks. The methodology is based on that described by Rose and Leggett (1988) who used discriminant functions for the identification of capelin, mackerel, and cod schools.

The effect of extending the outer stock boundary to 120 m was examined from the relationship between fish density and water depth (Fig. 5). All fish were detected within the 140 m depth contour and greater than 95% were detected within the 110 m contour suggesting that the 120 m depth contour be retained as the outer stock boundary in future surveys.

The most recent herring acoustic survey was conducted during the winter of 1990 in Fortune Bay, Placentia Bay, and St. Mary's Bay (Wheeler,1990). The same survey design was used as in 1988 (Wheeler et al.,1989). However, as distributional information from previous surveys was not as extensive as for east coast stocks, each of the stock areas was divided into only high and low density strata, with sampling intensity allocated on a 2:1 ratio between high and low density strata respectively. The results of this survey have been incorporated in the most recent assessment of these stocks (Wheeler et al.,1990).

Besides variance due to survey design and to target strength estimation, the variance in calibration parameters of the hydroacoustic system is another major source of variance which must be accounted for in deriving population estimates from acoustic surveys utilizing echo integration techniques. The system used during the 1988 and 1990 surveys was calibrated by BioSonics Inc. immediately prior to each survey. In addition, the system was tested for stability on a standard sphere at regular intervals during the surveys. Consistent results were derived during the fall survey in 1988 (Wheeler et al.,1989). However, during the winter survey in 1990 (Wheeler,1990), the results of the standard target calibrations during the survey were variable and highly dependent upon soak time (i.e. the amount of time that the transducer and standard target were suspended in the water column prior to measurements being made). For soak times of less than two hours, target strength estimates of the sphere ranged by as much as 10 dB. However, when soaked for greater than two hours, the range was 4 dB, with a mean estimate 2.5 dB greater than expected. It was hypothesized that this average difference was caused by the cold water temperatures in which the system was operating. Surface water temperatures ranged from -1.39°C to 0.93°C during the survey. BioSonics engineers have speculated that at such low temperatures, the physical properties of the transducer's ceramics may have changed enough to produce such a difference. It was further hypothesized that the greater variability of results for soak times less than two hours may have been caused by minute ice crystals forming on the face of the transducer when it was placed in such cold water temperatures. During the survey, the v-fin and transducer were stored outside on the vessel deck, subject to air temperatures ranging from -25°C to 0°C. An

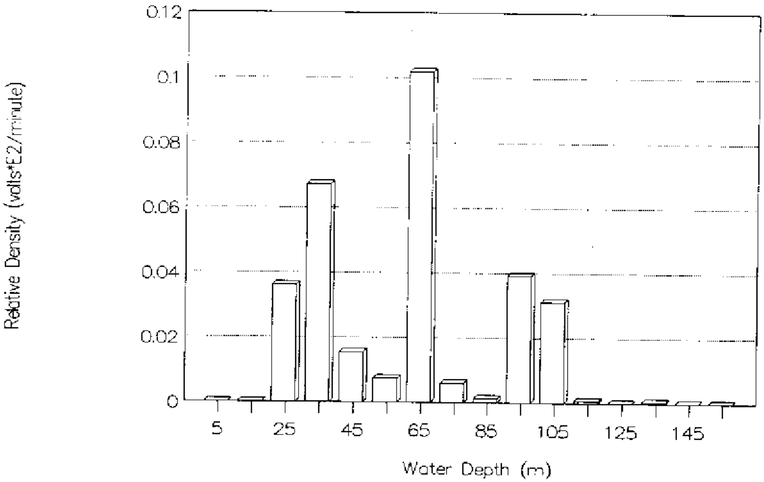

Fig. 5. Relative density of herring by water depth, as derived from the 1988 acoustic survey.

acclimation period was required for the transducer to equilibrate from the colder air to the warmer water. To ensure that the standard target calibration differences observed during the winter survey were environmentally induced and not a result of electronic instability within the hydroacoustic system, the system was recalibrated by BioSonics Inc. immediately after the survey. The source level for both pre and post survey system calibrations was identical, and receiving sensitivities for both receivers at 20 log R and 40 log R were within 0.3 dB. It was concluded that the 2.5 dB difference observed during the winter survey was a real change, regardless of the source, and that as the total backscatter of herring schools was also increased, this difference had to be accounted for in the conversion from backscatter to biomass.

CAFSAC has recommended the use of Foote's (1987) target strength - fish length relationship in the analysis of acoustic survey results until in situ measurements become available for Northwest Atlantic herring stocks (O'Boyle and Atkinson,1989). However, the applicability of Foote's results, derived at 38 kHz, to results derived from a 120 kHz hydroacoustic system, as used in the Newfoundland region, is questionable, as other comparative studies on herring and other species (Lassen and Staehr,1985; Everson et al.,1990), and modelling experiments (Foote,1985) have shown substantial differences in target strengths derived using different frequency systems. It was therefore decided, in the fall of 1989, to conduct a controlled field experiment to measure herring target strengths within a net enclosure. Although there are well documented concerns as to the effect of stress of capture and confinement on fish target strengths measured in enclosures (Foote,1986), this approach was chosen as there are also limitations to in situ measurements, such as how representative solitary fish target strengths may be for a schooling species and associated problems with the actual sampling of fish acoustically measured (MacLennan,1990). In addition, in previous acoustic surveys (Wheeler and Chaulk,1987; Wheeler et al.,1988), it has been very difficult to isolate sufficient single targets from dense herring schools for in situ target strength measurements. The results of the experimental target strength study indicated that for herring with a mean length of 25.8 cm, the average target strength, measured at 120 kHz and derived during the night, was 4.5 dB larger than that derived using Foote's (1987) in situ relationship for fish of the same length. These results were presented in the most recent assessment of the Newfoundland herring stocks (Wheeler,1990). Given the implications of calculating biomass estimates from an acoustic survey using Foote's (1987) relationship versus the experimental results, CAFSAC deferred the provision of scientific advice until the results of further experimental target strength research could be reviewed (Wheeler et al.,1990).

A second experimental target strength study was conducted in May, 1990, the objectives of which were: 1) to determine an experimental target strength - fish length relationship within the net enclosure by acoustically measuring different length ranges of herring, and 2) to compare herring target strength estimates at different frequencies by simultaneously measuring target strengths using a 38 kHz and 120 kHz system. Analysis of the results have not been completed; however, both objectives were achieved and initial observations suggest substantial differences in the target strength of the same fish measured at 38 kHz and 120 kHz.

FUTURE RESEARCH

Acoustic surveys of the three northern stock areas and the two southern stock areas will continue to be conducted on alternate fiscal years to empirically estimate biomass levels. Although finite sampling theory will continue to the basis for survey design, modifications will be made to minimize the variance due to survey design and to increase the precision of the mean biomass estimate. For example, for the two southern stocks, which are surveyed when the herring are in dense overwintering concentrations, a two phase sampling design, similar to that of Buerkle (1989), may be more appropriate. Random parallel transects would be surveyed through the stock area to determine the location of major fish concentrations. A more detailed survey of these areas would then be conducted during the second phase of the survey. However, for the three northern stock areas, which are surveyed during the fall when the herring are dispersed in smaller schools, such an approach may not be appropriate. Further consideration will be given to improving survey design for these areas.

To address the problem of species identification in acoustic survey analysis, a data base of school integrated data is being developed of herring concentrations for which groundtruthing information is available. Once sufficient information is available, the data will be analyzed to determine if a discriminant function exists to distinguish herring schools from capelin, mackerel, cod, and other species.

Further research will be conducted during the next winter survey to quantify the potential effect of cold water temperatures on transducer dynamics. This problem will not be as pronounced as transducers become available which are capable of operating effectively in a broader range of water temperatures.

The accurate estimation of fish target strength is critical for the conversion of acoustic backscatter to biomass. As MacLennan (1990) stresses, the target strength of similar fish may change with time for behavioral or physiological reasons and therefore, when surveying fish populations, target strength cannot be considered to be constant. Emphasis will be placed on research to examine all aspects of herring target strength estimation. Initial results from the experimental target strength studies conducted in the fall of 1989 and the spring of 1990 suggest there are changes in target strength which may be related to the fish maturity cycle. Seasonal changes in herring target strength estimates will be examined through further enclosure experiments. In situ target strength research will also be initiated to compare experimental results with results from naturally schooling fish. Target strength - fish length relationships will be established, by season if necessary, to convert acoustic backscatter to biomass. The necessity of such relationships will be overcome as transducer technology improves; in situ target strength and integrated data will then be collected simultaneously during acoustic surveys.

SUMMARY

Within the past decade, there have been substantial changes in biomass estimation methods for herring stocks within the Newfoundland region. Prior to 1983, all stocks were assessed analytically, using cohort analysis. Since then, acoustic methods have become increasingly important in assessing stock biomass. From 1983 to 1986, a sonar and sounder technique was used to map the size of herring schools and to estimate biomass. This method was based upon a relationship between the cross-sectional area of herring schools and the weight per school, derived from data where the entire school had been caught by purse seine. This relationship could only be tested for small schools which could be caught completely. However, as 60-80% of the estimated biomass was in larger schools, any change in the relationship could have a major effect on the estimated weight of the larger schools and hence the total biomass.

In acoustic surveys since 1987, herring density estimates have been derived through echo integration and scaled by target strength data from in situ experiments conducted in the northeast Atlantic (Foote,1987). Population numbers and biomass estimates have been calculated by areal expansion of transect densities. Random parallel transects have been used since 1988 to provide unbiased estimates of both the mean biomass and the variance due to survey design.

A data editing procedure has been developed to distinguish between fish species based upon characteristics of school echo traces. The method involves using an oscilloscope to examine peak voltage amplitudes, voltage peak to trough distances, and distance between voltage peaks.

Controlled field experiments have been conducted in 1989 and 1990 to measure herring target strengths within a net enclosure. The results have indicated that for herring of a specific length, the average target strength, measured at 120 kHz, is substantially larger (4.5 dB) than that derived using Foote's (1987) in situ relationship which itself was derived from measurements at 38 kHz.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

In Situ Target Strength Measurements of Pacific Herring (*Clupea harengus pallasi*) in the Eastern Strait of Georgia Using Dual-Beam and Split-Beam Sonar

G.A. Kautsky and N.A. Lemberg
Washington Department of Fisheries
Seattle, Washington

E. Ona
Institute of Marine Research
Bergen, Norway

ABSTRACT

Hydroacoustic assessment surveys of herring stocks within Washington State began in the early 1970s and have provided timely in-season abundance estimates for management of bait, sac-roe, and, more recently, spawn on kelp fisheries. Acoustic biomass estimates were initially based on a target strength of -33 dB/kg for adult herring which was estimated from regression analyses of net haul and catch with escapement estimates of abundance versus integrated acoustic density. As the mean length of surveyed stocks began to decline in the late 1970s, target strength adjustments were derived from models based on foreign herring stocks. Concern over the validity of the assumed target strength used for scaling contemporary echo-integration surveys of herring abundance in the Strait of Georgia prompted target strength investigations using direct in situ techniques. Dual-beam and split-beam echo sounders, operating at 120 and 38 kHz respectively, were used to acquire target strength data during standardized stock assessment surveys. A mean target strength of -37 dB/fish (-24 dB/kg) was estimated for 15 cm herring at both frequencies. The difference between the assumed and measured target strength was on the order of 6-9 dB. The unexpectedly high target strength value was perhaps a function of three factors, each of which tended to increase fish target strength; low fat content, large percentage of spent fish, and shallow depth of measured targets. An improved method for standard sphere calibration of dual-beam and split-beam echo sounders is also discussed.

INTRODUCTION

Fishery hydroacoustics using echo-integration provides managers with an instantaneous measure of pelagic fish abundance and is widely employed in the assessment of herring (Clupea harengus pallasi) biomass in Washington State and elsewhere (Hagstroem et al., 1986; Lemberg et al., 1988; Reilly et al., 1989). The accuracy of this assessment approach is largely dependent on unbiased estimates of the scaling factor (target strength) used to convert echo intensity to fish density. Several methods for identifying fish target strength have been used including controlled laboratory experiments and in situ sampling (Foote, 1988). Implementation of these methods has revealed the extremely dynamic nature of target strength within a species in response to fish size, behavior, and physiological state (Edwards and Armstrong, 1984; Foote, 1980a, 1981, Nakken and Olsen, 1977; Ona, 1990a; Traynor and Williamson, 1982). While models relating target strength to fish length have been proposed for herring (Degnbol et al., 1985; Johannesson and Losse, 1977; Halldorsson and Reynisson, 1982), the validity of applying these estimates over a broad range of herring populations may be in question. Concern focuses on potential geographic, year-to-year, and seasonal fluctuations in the parameters affecting target strength and the direct implications on the accuracy of biomass estimates. For example, the size distribution of an exploited herring population may shift through time, and seasonal or regional differences in fat content and gonadal volume may occur within as well as among discrete herring populations. Therefore, a systematic approach of in situ target strength measurement is recommended, when practicable, to develop a data base of length specific target strength estimates for discrete herring populations during population assessment periods.

The Washington Department of Fisheries (WDF) initiated hydroacoustic assessment of herring stocks throughout Puget Sound and the Strait of Georgia in 1972 in response to a rapidly developing sac-roe fishery with tremendous fleet harvest capacity (Trumble, 1983). From 1972-75 several spawning stocks were identified and in-season estimates of run size were obtained by annual hydroacoustic-midwater trawl surveys (Lemberg, 1978). Target strength estimates were initially calculated indirectly by regressing pelagic net haul and catch plus escapement estimates of abundance against integrated acoustic output (Thorne, 1977; Thorne and Drew, 1975). From these early studies a target strength value of -33 dB/kg was estimated which agreed with results from other herring target strength investigations (Halldorsson and Reynisson, 1982; Nakken and Olsen, 1977).

Abnormally low recruitment for most Washington State herring stocks began occurring in the late 1970s which resulted in a general shift from 3-5 year old to 2-4 year old herring as the predominate age group (Buchanan, 1985; Gonyea, 1985). Beginning in 1984 and continuing to the present, adjustments to the assumed target strength have been referenced to the Halldorsson and Reynisson (1982) model to compensate for changes in mean herring size on a survey by survey basis. However, the selected target strength model was possibly inappropriate since it was based on a foreign herring population whose biological characteristics could have differed from the Strait of Georgia stock. Recent in situ target strength measurements of the Strait of Georgia herring stock are used here to evaluate the validity of the assumed target strength and the selected model.

METHODS

Acoustic data and corresponding biological samples were acquired during two surveys conducted on 9 and 16 May 1990 in the eastern Strait of Georgia, Washington (Figure 1). Two vessels were used during each survey. The 16.5 m F/V CHASINA, powered by a 350 hp diesel engine, was used for midwater trawl biological sampling. Trawl effort was directed from aboard the 11.3 m R/V PASQUALE which was powered by a 200 hp diesel engine and served as the acoustic platform. Sampling procedures were restricted to hours of darkness when fish aggregations tended to disperse.

Biological samples were obtained in the same time and position strata as acoustic measurements. A rectangular mid-water rope-trawl (Nor-eastern Trawl, Bainbridge Island, Washington) with a vertical opening of approximately 12.2 m and a horizontal opening of 18.3 m was fished with 1.5 m^2 high-lift doors and 37 m bridles (2 per side). Leeward of the jibs, mesh size decreased from 810 mm in the first section to 38 mm in the cod end which was lined with a 10 mm mesh insert. Mesh sizes for the five intermediate sections of the trawl were 410, 203, 127, 89, and 38 mm.

Fishing depth of the trawl was determined by bathykymograph which was attached to the headrope of the trawl. Trawling speed was generally 3 knots but varied slightly to achieve desired fishing depth. Tow duration varied as a function of fish density as observed on a chart recorder. The objective was to capture a sample of between 50 and 100 kg which typically required less than 20 min. Total haul weights were obtained and net contents were sorted on deck. Incidental species were separated and weighed on deck while herring were randomly sub-sampled to provide about 200 fish per tow for later specimen examination.

Herring samples were stored on ice and transported to the laboratory where they were frozen. All samples were processed within three months of capture. Standard length (mm), weight (g), and sex were determined. Selected specimens were refrozen for fat content analysis at a later date. These specimens were representative of the overall range of fish sizes for a given sample and sexes were combined. Total lipid content of herring was determined by Soxlet extraction using methylene chloride as the solvent (Association of Official Analytical Chemists, 1975).

Research trawl data collected by WDF was used to estimate mean herring size for the Strait of Georgia stock during the spawning periods of 1976-1990. Each annual mean value was estimated from hauls which were individually weighted by the proportion of biomass they represented on a given survey week as determined by hydroacoustic density estimates.

Hydroacoustic data were obtained using dual-beam and split-beam echo sounders. The dual-beam system consisted of a 120 kHz BioSonics Model 101 echo sounder linked to a BioSonics

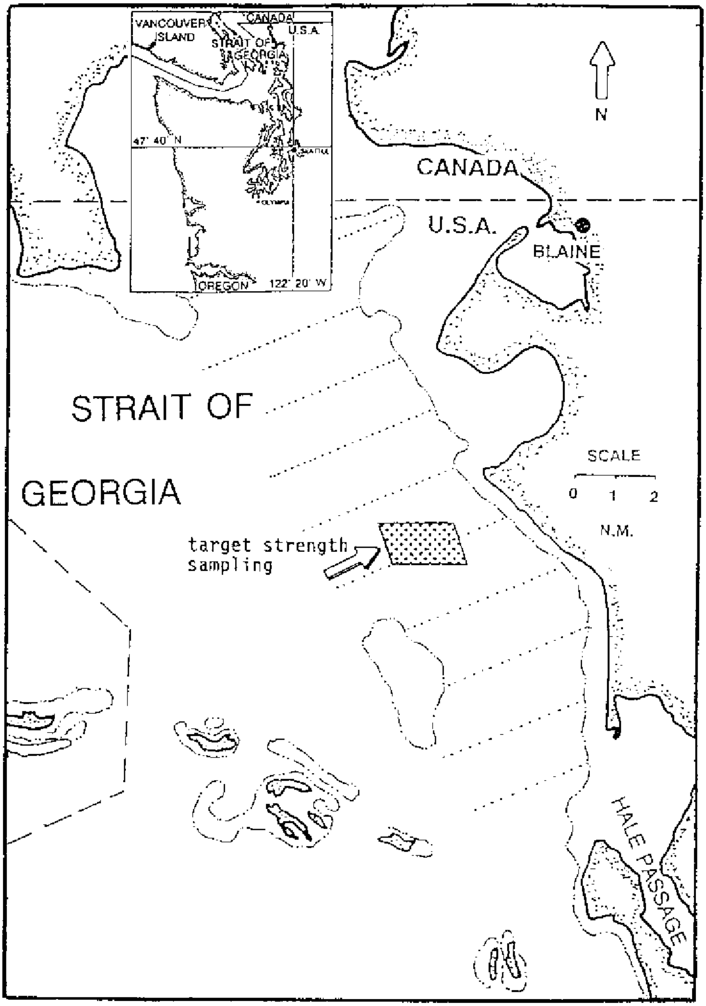

Figure 1. Map of study site and target strength sampling location in the eastern Strait of Georgia. Broken 30 meter contour (broken line) and transect pattern (dotted line) for echo-integration surveys are also shown.

Model 281 Echo Signal Processor which was installed in a microcomputer for logging of pulse width, depth, and raw echo voltages at a sampling frequency of 25 kHz. The split-beam system was a 38 kHz Simrad Model ES-380\400 which was modified for parallel data logging to a portable computer via a parallel interface (Ona and Hansen, 1989). The Simrad system was operated using a 1.0 msec pulse length and parallel output raw data provided a 7.5 kHz data stream containing 10 cm samples of depth, amplitude, and transverse and longitudinal angles all at a rate of 60 bytes/meter. During data logging the acoustic vessel followed a straight line course at a speed of between 1 and 3 nautical miles per hour. The dual-beam and split-beam systems were operated independently of each other to avoid acoustical interference between systems by alternately disabling one and enabling the other over 10 min intervals.

Acoustic System Calibrations

The two acoustic systems were calibrated on 9 May 1990 from on board the R/V PASQUALE in Hale Passage using a 38.1 mm diameter tungsten-carbide reference sphere which was suspended by 13 kg-test monofilament line. Details on the procedures used and assumptions made during standard sphere calibrations of scientific echo sounders have been described in several papers (Foote, 1989; Foote et al., 1987; Foote et al., 1982; Kautsky, 1989). Calibration of the 120 kHz dual-beam system also included correction for system time-varied-gain (TVG) error. Split-beam TVG was digitally controlled and required no correction.

Dual-beam calibration. For calibration of the dual-beam system, the suspended sphere was moved fore and aft and from side to side to obtain on axis alignment. Axial alignment of the calibration sphere was assumed once maximum peak amplitudes were observed in the narrow beam channel. The narrow to wide ratio of the TVG corrected peak amplitudes squared, of the axially aligned sphere, described the on-axis sensitivity difference between the two channels (K_1):

$$K_1 = V_N^2(0)/V_W^2(0) \tag{1}$$

where $V_N^2(0)$ = squared voltage (intensity) in the narrow channel and $V_W^2(0)$ = squared voltage in the wide channel at a beam angle of 0° (i.e. on-axis).

Transducer directivity plots of the two channels revealed that the sensitivity of the wide beam decreased within the beam angle defined by the half-amplitude sensitivity points (main lobe) of the narrow beam. The rate of sensitivity decrease of the wide beam within the main lobe of the narrow was estimated as the slope of the linear regression of the actual narrow beam directivity function versus the apparent directivity function relative to the wide beam:

$$B_N(\theta) = K2(B_N(\theta)-B_W(\theta)) \tag{2}$$

where K2 = the slope, and $B_N(\theta)$ and $B_W(\theta)$ are the values of the beam pattern function in decibels at the angular coordinate θ measured from the acoustic axis for the narrow and wide beams respectively.

While theoretical aspects of dual-beam applications in fishery hydroacoustics have been discussed in several papers (Ehrenberg, 1974, Ehrenberg, 1978, Traynor, 1984, Traynor and Ehrenberg, 1979), an overview of dual-beam theory is presented here in order to introduce an approach for dual-beam data processing based solely on standard sphere calibration. For completeness, an analogous description of standard sphere calibration of the split-beam system is provided later.

In the absence of noise, the received intensity in the narrow and wide beams of the dual-beam transducer for a single-fish target with a scattering cross-section of σ_i and at angular coordinate θ_i may be expressed as:

$$I_N = K_3(10^{-2\alpha R}/R^4)b_N^2(\theta_i)\sigma_i \tag{3}$$

$$I_W = K_4(10^{-2\alpha R}/R^4)b_N(\theta_i)b_W(\theta_i)\sigma_i \tag{4}$$

respectively, where I_N and I_W are the received echo intensities for the narrow and wide beams respectively, K_3 and K_4 are constants which match the on-axis sensitivities of the two channels, $(10^{-2\alpha R}/R^4)$ is the two-way propagation loss due to absorption and spreading of acoustic energy, and $b_N(\theta_i)$ and $b_W(\theta_i)$ are the directivity functions of the narrow and wide beams respectively. Time-varied-gain amplifiers correct for range dependent propagation loss. Then the ratio of equations (3) and (4) gives:

$$\frac{I_N}{I_W} = \frac{K_3 b_N(\theta_i)}{K_4 b_W(\theta_i)} \tag{5}$$

The constants K_3 and K_4 are replaced by K_1 (Eq. 1) which simultaneously compensates for on-axis sensitivity differences between the two channels and (5) is expressed in logarithmic form as:

$$ESN-ESW = K1+B_N(\theta_i)-B_W(\theta_i) \tag{6}$$

where $ESN = 10\log(I_N)$, $ESW = 10\log(I_W)$, and $K1 = 10\log(K_1)$. Replacing the last two terms in (6) with the equivalent from (2) and rearranging yields:

$$\widehat{BN(\theta)} = K2(ESN-ESW-K1). \tag{7}$$

The target strength (TS) for echoes meeting noise and pulse width threshold criteria (presented later) was estimated as:

$$\widehat{TS} = 20\log(V_{N\,f}/V_{N\,s})+TS_s-2BN(\theta) \tag{8}$$

where $V_{N\,f}$ = detected voltage in the narrow channel of a fish target, $V_{N\,s}$ = detected voltage in the narrow channel of the on-axis calibration sphere, TS_s = theoretical target strength of the calibration sphere (Foote, 1989).

Split-beam calibration. From the sonar equation, Urick (1975), we have:

(9) $$I = I_0 \, \sigma \, (10^{-2\alpha R}/R^4) \, b^2(\alpha,\beta).$$

The two-way propagation loss (within first parentheses) due to geometrical spreading and absorption, is compensated for digitally by the echo sounder with α = 10.5 dB/km. At the depths sampled, this term is effectively equal to 1.00 which is well within a precision of 0.1 dB.
At the acoustic axis, $b^2(\alpha,\beta) = 1$, I_0, the source intensity, is estimated relatively as:

(10) $$I_0 = I_s/\sigma_s \quad ,$$

where I_s is the returned intensity, measured from a standard sphere with back scattering cross section σ_s, located at the acoustic axis.

Combining Eqs. 9 and 10 yields an expression for the back scattering cross section of other targets, such as fish:

(11) $$\sigma_f = (I_f/I_s) \; (\sigma_s/b^2(\alpha,\beta)) \quad ,$$

or, in logarithmic terms:

(12) $$TS_f = 20\log(u_f/u_s) + TS_s - 2B(\alpha,\beta) \quad ,$$

where the intensities are replaced by the squared detected voltages, u.

The beam pattern correction, $2B(\alpha,\beta)$, was computed according to Ona (1990b), where a modified Bessel function is fitted to the measured and mapped acoustic beam.

A matrix of beam data was obtained by lowering a standard 38.1 mm tungsten-carbide sphere to a depth of 20 m and moving the transducer mounting platform fore and aft and from side to side. A module of the logging software displayed the angular position of the target relative to the acoustic axis while recording the data.

The function:

(13) $$b(\alpha,\beta) = 2^{-\left[\left(\frac{\alpha-\Delta\alpha}{\phi_A}\right)^2 + \left(\frac{\beta-\Delta\beta}{\phi_B}\right)^2\right]^E}$$

where:

α - transverse electrical angle
β - longitudinal electrical angle
$\Delta\alpha$ - transverse offset
$\Delta\beta$ - longitudinal offset
ϕ_A - transverse half power angle
ϕ_B - longitudinal half power angle
E - shape parameter

was fitted to the data using nonlinear regression methods to obtain estimates of $\Delta\alpha$, $\Delta\beta$, ϕ_A, ϕ_B, and E.

The split-beam transducer showed nearly perfect symmetry with only slight angular offsets (Figure 2, Table 1). The residual target strength of the sphere, i.e. the difference between the estimated target strength and the theoretical value of -42.2 dB, was minimal with a mean of -0.016 dB (SD = 0.287 dB) and -0.014 dB (SD = 0.182) for the entire beam and within the θ = 2.5° limit used for target strength measurements respectively. This was about twice the ping to ping variance observed on a stationary target. For the dual-beam system the residual was greater with a mean of -0.257 dB (SD = 1.458 dB).

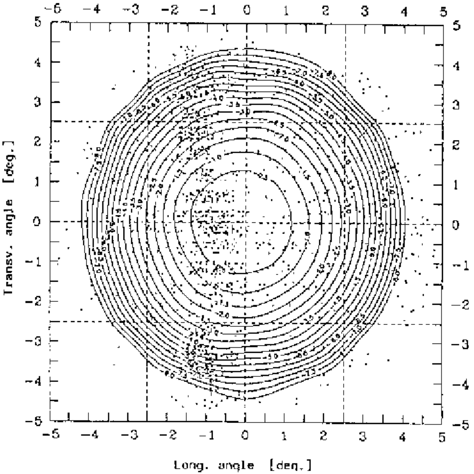

Figure 2. Contour plot of two-way beam pattern for the ES-400 split-beam transducer. Dots represent the actual measured matrix and contours range down to -8.0 dB by estimated 0.5 dB intervals.

Table 1. Estimated parameters of the beam pattern function (Eq. 13) for the ES-400 split-beam transducer using a 38.1 mm diameter tungsten-carbide sphere. Angles and offsets are given in degrees, ϕ_A and ϕ_B are the -3 dB half angles.

Date	ϕ_A	ϕ_B	$\Delta\alpha$	$\Delta\beta$	E	N
3/27/90	3.61	3.75	-0.09	0.01	1.10	1386
95% C.I.	(3.60)	(3.74)	(-0.08)	(0.00)	(1.09)	
	(3.62)	(3.77)	(-0.09)	(0.02)	(1.11)	

Acoustic Data Processing

Specifically designed thresholds were applied in the analysis of average target strength to avoid accepting multiple targets as valid single-fish targets. These were, for the dual-beam:

A. A pulse peak amplitude threshold of twice the RMS noise level at the sampled depth (-74.8 dB referenced to the acoustic axis);

B. Pulse length threshold of 0.2 ms centered on the nominal transmitted pulse length of 0.5 ms;

C. A -3 dB (5°) narrow beam pattern threshold.

And for the split-beam:

A. A pulse peak amplitude threshold of 50 A/D units, about 8 times the RMS noise level at the sampled depths (-65.1 dB referenced to the acoustic axis);

B. Pulse length limits of +10% and -25% of the measured average effective pulse length:

$$\tau_e = (u_{\max}^2)^{-1} \int_{t-1}^{t-n} u_i^2 \, dt$$

C. An angle jitter threshold was applied to remove close to horizontally overlapping echoes. In the split-beam echo sounder, the angular position of the target is estimated from the electrical phase measurements along the pulse. For each 10 cm sample, a set of angles was given and the mean and standard deviation was calculated. Targets where the standard deviation of the jitter exceeded 0.26° were rejected;

D. A beam threshold of $\theta = 2.5°$ was chosen to improve the signal to noise ratio of small targets.

E. Vertical distance threshold of 30 cm between accepted pulses over which the amplitude could not exceed twice the RMS noise level.

Split-beam criteria A, B, and C were also applied during sphere measurements and beam mapping.

RESULTS

Biological Results

A decline in average fish length was revealed for the Strait of Georgia herring stock over the survey years of 1976-1990 (Figure 3). The overall mean length herring during the 1990 survey period was 161 mm.

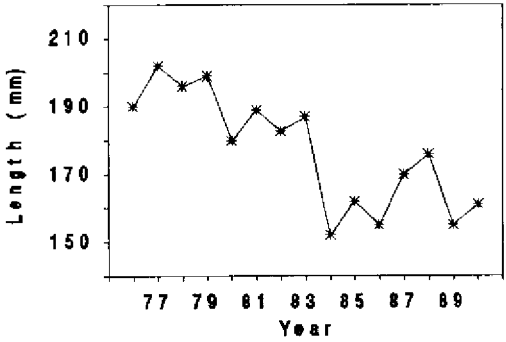

Figure 3. Mean standard length of Strait of Georgia herring for survey years 1976-90. Each point represents a pooled and weighted mean for all surveys conducted in the given year.

For the 9 and 16 May target strength surveys, 10 trawl hauls were made. Based on the species composition and size distribution of captured herring, only three samples were acceptable for herring target strength analyses (Table 2). The percent by weight of herring in these three samples was 87% or greater with dogfish (Squalus acanthius) being the only incidental

Table 2. Summary of catch data obtained at target strength data collection sites.

Haul	Date	Time (PDST)	Average headrope depth (m)	Catch				
				Herring			Dogfish	
				Weight (Kg)	n	% by weight	Weight (Kg)	n
1	5/16/90	2324-2330	18	81.7	1571	94	5.4	8
2	5/17/90	0018-0031	17	82.4	1716	92	6.7	7
3	5/17/90	0151-0214	26	116.0	1945	87	17.0	18

Note: All trawl stations were located within ± 0.1' of 48° 52.2'N 122° 49.2'W.

Table 3. Summary of dual-beam (120 kHz) and split-beam (38 kHz) data and processed results obtained.

Sample	Date	Time (PDST)	Depth range sampled (m)		Herring		Target strength			Echo sample size		
			120 kHz	38 kHz	$\overline{L}$ (mm)	$\overline{W}$ (g)	120	38_A	38_B	120	38_A	38_B
1	5/16/90	2318-2359	16-24	5-75	154	52	-36.4	-37.1	-37.0	2086	2594	1115
2	5/17/90	0006-0111	15-22	7-85	149	48	-38.5	-37.3	-37.4	2478	2212	1025
3	5/17/90	0203-0213	24-31	----	147	43	-35.9	----	----	1309	----	----

A--Measurements made over entire beam width of 38 kHz split-beam transducer (± 5°).
B--Measurements made within an angular limit of 2.5° from the axis of the 38 kHz split-beam transducer.

species. The length frequencies observed in these samples were unimodal with means of 154, 149, and 147 mm for hauls 1, 2, and 3 respectively (Figure 4). Weight frequencies were also unimodal with means of 52, 48, and 43 g for hauls 1, 2, and 3 respectively. Lipid content for herring from tows 1, 2, and 3 ranged between 4.37 and 8.31% of the wet sample weight with a mean of 6% (SD = 1.16%).

Acoustic results

Target strength estimates from dual-beam data collected at the three trawl sites ranged between -65.0 and -24.5 dB/fish and average target strengths were -36.4, -38.5, and -35.9 dB/fish for samples 1, 2, and 3 respectively (Figure 5, Table 3). Split-beam data collected at trawl sites 1 and 2 ranged between -61.6 to -28.3 dB/fish with average target strengths at the $\theta = 2.5^{\circ}$ beam threshold of -37.0 and -37.4 dB/fish for samples 1 and 2 respectively. From these data a target strength of -37 dB per fish was estimated for eastern Strait of Georgia herring ranging in size from 147 to 154 mm. The target strength distributions for dual-beam data from samples 1 and 2 were more dispersed than the split-beam data for the same samples. This was probably a function of slightly higher directivity of herring swimbladders at 120 kHz over the 38 kHz split-beam system.

DISCUSSION

Several factors, both technical and biological, may influence the accuracy of direct in situ measurements of fish target strength and are not always properly addressed in reports on the subject. We address five areas of concern: system calibration, single-fish recognition criteria, fish behavior, biological sampling by trawl, and physical condition of the fish.

System calibration will lead to first order bias in the estimates of fish target strength and directly impacts the accuracy of echo-integration biomass estimates. Calibration of hydroacoustic systems has traditionally been carried out in laboratory environments where transducer beam directivity, and system receive and transmit sensitivities have been measured with a reference hydrophone. However, calibration accuracy may be significantly improved by conducting field calibrations using reference spheres to obtain receiving and transmitting sensitivity in a combined term (Foote, 1989; Foote et al., 1987). In this paper, we have introduced improved calibration methods for both dual- and split-beam echo sounders. The overall system error, i.e. the sum of TVG compensating errors, center sensitivity, and beam compensation are estimated to be within ± 0.2 dB for both systems.

Dual-beam data revealed instances where the received narrow channel intensity exceeded the corresponding wide channel intensity for a given echo after correction for gain imbalances. While contrary to dual-beam theory, this result has been observed in other studies and has generally been attributed to noise (Dickie et al., 1983; Traynor, 1984). For the purposes of this study, echoes exhibiting this phenomenon

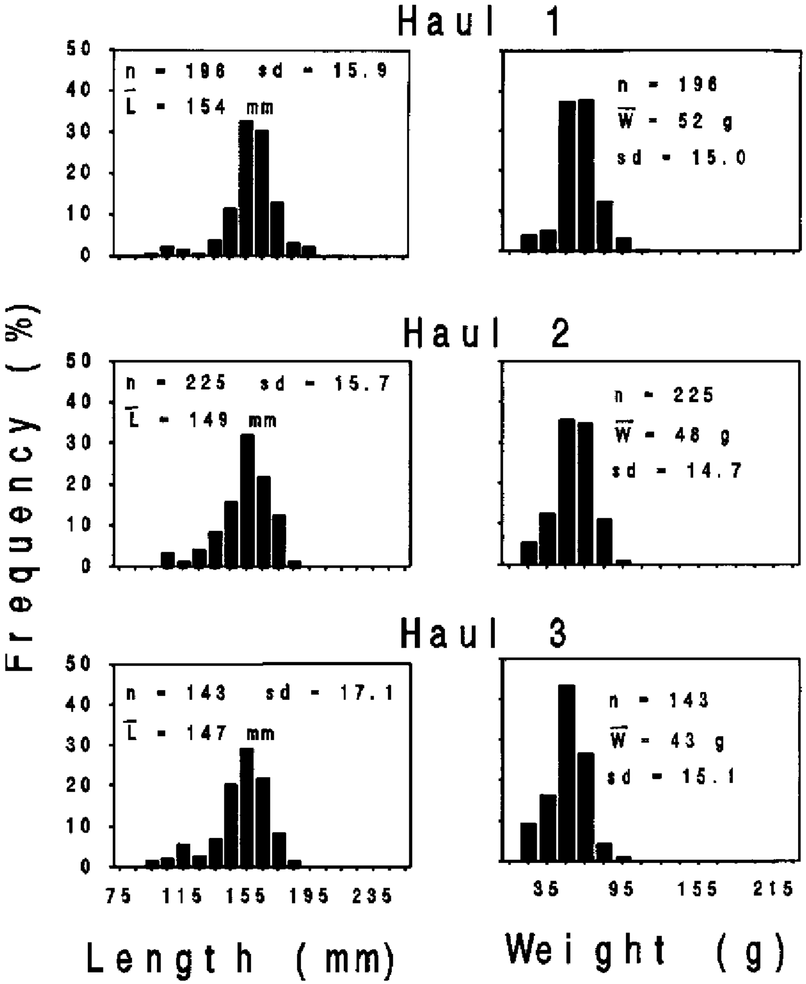

Figure 4. Length (mm) and weight (g) frequency distributions of herring sampled in hauls 1, 2, and 3 set in the Strait of Georgia on 16-17 May 1990. Sample size, mean length, mean weight, and standard deviations are indicated.

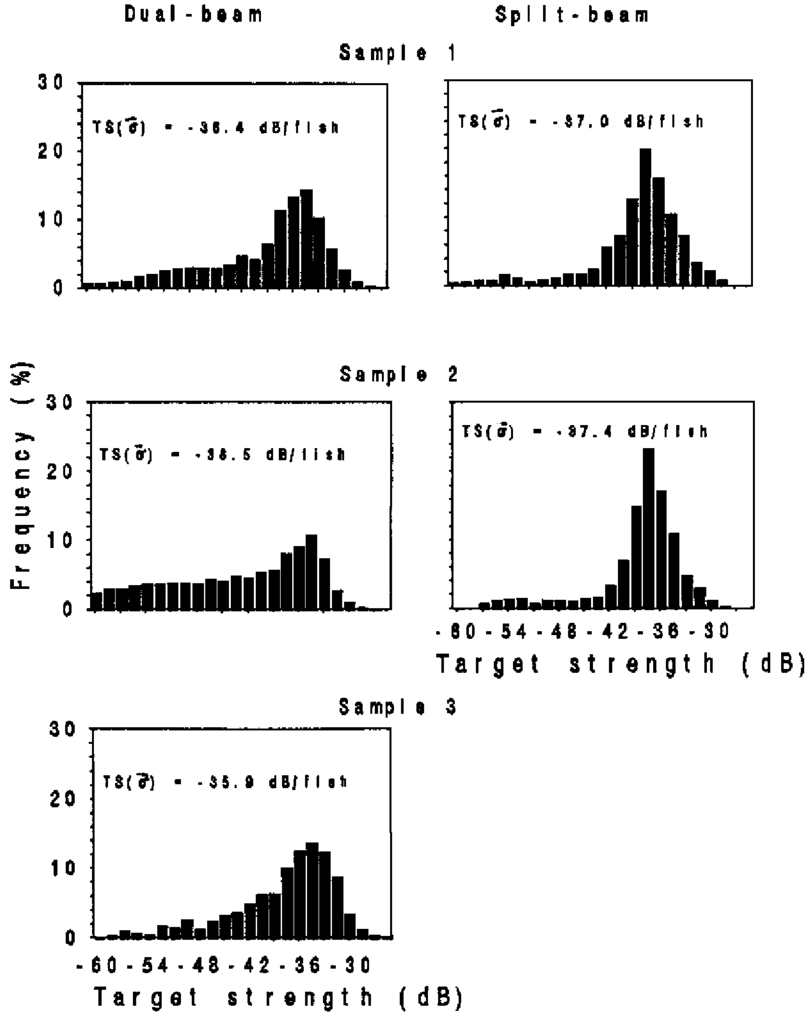

Figure 5. Target strength distributions for dual-beam (left) and split-beam (right) data from trawl sites in the Strait of Georgia on 16-17 May 1990. Mean target strengths (dB/fish) are indicated. Split-beam data were unavailabel for sample 3.

were deleted from target strength analyses if the resultant narrow beam pattern estimate was greater than 1 dB. This resulted in the exclusion of less than 10% of the data and caused an increase in the estimated target strength of the mean back scattering cross section of less than 0.5 dB. Removal of these data may have created a slight bias against small targets since the influence of noise on smaller echo strength targets is greater in this respect than on larger targets.

Because this study compares results obtained at several echo sounder frequencies the influence of frequency on target strength should be noted. Nakken and Olsen (1977) observed that the maximum dorsal aspect target strength for Atlantic cod (Gadus morhua) could vary by 2.4 dB when comparing results from 120 and 105 kHz systems. However, since the directivity of swimbladders in small herring is low at the measured frequencies, this effect is reduced for the averaged values in our study. Direct comparison of the average target strengths obtained at 38 and 120 kHz was not possible as only serially recorded data were available. While data suggested slightly higher directivity at 120 kHz (Figure 5), a larger data set would be necessary to study this difference statistically since serial variance within a system is generally larger than the observed difference between systems. This is probably a result of fish behavior and size variation along a track.

Direct techniques for target strength measurement require that individual targets be resolved. To meet this requirement, selection criteria must be employed to accept valid single-fish targets and to reject multiple or overlapping targets. However, proposed single-fish recognition criteria and thresholds may bias target strength distributions. Criteria which are too loose may not sufficiently guard against multiple targets (Ona and Røttingen, 1986) affecting the upper portion of the distribution. On the other hand, overly restrictive selection criteria will always discriminate against small targets (Weimer and Ehrenberg, 1975). Adaptive processing of raw data, using several independent threshold limits, is perhaps the only contemporary solution to this problem and permits detailed evaluation of threshold effects on target strength distributions. The selection criteria used in processing split-beam data were evaluated using this technique on smaller sized fish. The dual-beam selection criteria were similarly evaluated by comparison with results obtained for a very low density layer of 17 cm herring. When empirically justified, over a large volume of data, stringent selection criteria ensure the acceptance of high quality echoes from both systems.

Fish behavior may easily be affected by the vessel from which acoustic measurements are carried out (Olsen, 1981). However, if care is taken with regard to light level and engine noise, shallow swimming herring may exhibit little or no reaction to the surveying vessel (Ona and Toresen, 1988a). The difference we observed in target strength of Puget Sound herring between samples obtained at night from a darkened vessel with the engine off and a darkened vessel under way was insignificant.

In most assessment work, it is generally assumed that the biological samples obtained are representative of the "acoustical population" or the true fish community. This is a gross oversimplification of both trawl sampling and fish behavior in response to trawling vessels (Ona and Godø, 1987; Ona and Toresen, 1988b). Experience using our mid-water trawl has shown that catches of herring may at times contain a wide distribution of fish sizes. However, assuming trawl avoidance by herring is a function of fish size, our samples may under represent the true ratio of larger fish within a school. If so, this would bias the estimated target strength scaling factor (dB/kg) upwards. Direct in situ target strength measurements should only be attempted where unimodal size distributions of the target species occur and minimal incidental species contamination are found. Several samples were rejected from analysis during this study based on their failure to meet these assumptions. In our results, dogfish shark represented the only incidental species and contaminated trawl hauls by as high as 13%. The absence of a swimbladder in dogfish implies that its target strength should be about 10 dB lower than herring of the same length. As the mean dogfish length was 50 cm, a slight negative bias in the herring target strength estimate may have resulted.

The physical condition of the fish and also the gas exchange system in the swimbladder are as important, or even more so, than the previously mentioned sources of variability (Ona, 1990a). The high target strengths observed for herring in this investigation may have been caused in part by a combination of two factors, each of which serve to increase swimbladder volume; shallow depths and low body fat. Considering that the swimbladder accounts for 90-95% of the total reflected acoustic energy in fishes (Foote, 1980), varying swimbladder volume should dramatically influence target strength. The herring swimbladder is physostomatous, open, and has no documented system for gas production (Fahlén, 1967). Herring are therefore unable to compensate their buoyancy by gas secretion at depth. Under this strategy, the target strength is expected to be depth dependent, decreasing quickly over the first 10 to 20 m where the pressure gradient is sharp, and then more gradually with depth. The influence of fat content is difficult to assess in comparison with other herring stocks as this parameter is seldom reported in literature dealing with herring target strength. However, Ona (1990a) reports that fat content in the Skogsvaag, Norway herring stock ranged from 8% to 27% with a mean of 16.8% for a sample of 60 herring. This value exceeds the mean fat content for Strait of Georgia herring presented in this paper three fold which implies a potential doubling of swimbladder volume over the Skogsvaag stock. Large swimbladder volumes in low fat herring have also been observed in the Baltic stock (Ona and Palmen, unpublished data). The effective acoustic implications of increased swimbladder volume have yet to be documented by in situ measurements. However, based on the increased dorsal area of the swimbladder, the expected increase in target strength of the Strait of Georgia herring over other stocks with three times the fat content would be on the order of 2-4 dB. Gonadal maturation and stomach fullness may further contribute to target strength variation in herring by deformation of the swimbladder. Although these parameters were not directly measured, observations of the analyzed fish suggested that more than 60% of the fish were spent.

Historic records on the mean length for herring in Strait of Georgia clearly demonstrate a progressive decrease in size from 1976 through the present (Figure 3). This evidence alone suggests that the scaling factor of -33 dB/kg derived indirectly in the mid 1970s for the Puget Sound population is currently invalid since target strength relative to a kilogram of biomass is inversely related to fish size. Support for the early target strength estimate was gained by its agreement to the target strength on length model developed by Halldorsson and Reynisson (1982) and, as the mean size of individuals of the surveyed populations began to decline in response to intense exploitation, it seemed reasonable to reference new scaling factors to this model. Results presented in this study have suggested that the model was inappropriate for the Strait of Georgia herring stock. The -37 dB/fish (-23.7 dB/kg) target strength estimated at 120 and 38 kHz in this study was 9 dB greater than that predicted for 150 mm herring by the 38 kHz model (Figure 6). Some of this difference may be attributed to the fact that our target strength measurements were at shallow depths. Hence, the difference between the measured and the assumed target strength, used for scaling echo-integrated data collected throughout the water column, may actually be on the order of 6 dB. If this difference is representative of the Strait of Georgia herring population in general, using the model may have overestimated true herring biomass by as much as 300%. It should also be noted that the -33 dB/kg scaling factor initially estimated for the Puget Sound and Strait of Georgia herring stocks may have been inaccurate as it was based on regression analyses of catch versus integrated acoustic density and as such combined two sources of error. Drew (1980), using a 105 kHz prototype dual-beam system, reported in situ measurements for herring in the Strait Georgia and estimated a target strength of -25.7 dB/kg for 18.6 cm fish which more closely agrees with our result of -23.7 dB/kg (Figure 6).

To ensure the accuracy of echo-integration surveys of fish abundance, a high priority must be placed on obtaining unbiased estimates of the target strength scaling factor. The dynamic nature of herring target strength in response to biological factors further requires that target strength research be conducted at a time and place which corresponds to the hydroacoustic stock assessment surveys. The availability of dual-beam and split-beam echo sounders for in situ measurement of fish target strength permit fishery management agencies to carry out such work and to develop appropriate models of target strength for surveyed populations. It is premature to conclude on the appropriate scaling factor for echo-integration surveys of Strait of Georgia herring since the data are on smaller herring only. However, this investigation has strongly suggested that target strength assumptions made in previous years for the Strait of Georgia herring stock were erroneous. The estimates presented in this paper were the product of a systematic procedure now implemented to develop a target strength data base for Washington State herring stocks. This data base will need to include measurements over a wide range of fish sizes and be stratified by season so that the potential for gross variation in target strength due to seasonal variation in biological factors may be minimized. Biological sampling to identify species composition, size, fat content, gonadal and stomach volumes of insonified fish shall also be an integral part of the research.

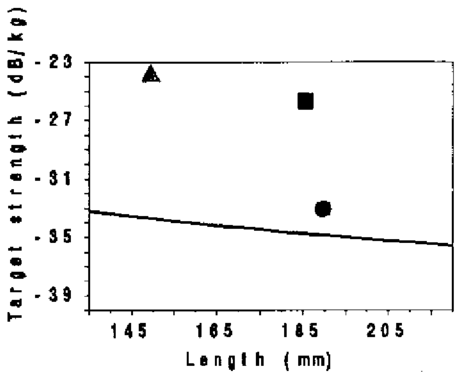

Figure 6. The target strength model of Halldorsson and Reynisson (1982) is compared with the historic scaling factor of -33 dB/kg (●), Drew's (1980) estimate (■), and the -23.7 dB/kg estimate from this study (▲).

CONCLUSIONS

1) Published models relating herring size to target strength, while useful as an approximation, should be verified for specific populations prior to adoption as scaling factors for echo-integration surveys of absolute herring abundance.

2) Direct target strength measurements should be carried out routinely, concurrent with assessment surveys, to account for the influence of dynamic biological factors (eg. fat content, gonad and stomach volume) affecting herring target strength.

3) The unexpected high target strength reported here may have been caused by three conditions working in concert: low fat content, shallow depth, and a high ratio of spent fish.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support provided by Simrad, Inc. of Seattle, Washington for providing the ES-380/400 split-beam echo sounder used in this study. We also thank Dr. Ronald W. Hardy, Research Chemist at the NMFS Laboratory at Montlake in Seattle, for analyzing fat content of herring samples. Mr. Dwayne Day of WDF is graciously thanked for his analyses of historic biological data on the Strait of Georgia herring.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Herring School Dynamics and Its Impact on Acoustic Abundance Estimates

U. Buerkle and R.L. Stephenson
Department of Fisheries and Oceans
St. Andrews, New Brunswick, Canada

ABSTRACT

The NAFO Division 4WX Atlantic herring stock spawns in area 4X off southwest Nova Scotia and overwinters in area 4W about 750 km to the northeast. Acoustic abundance surveys have been carried out in winter in area 4W since 1981. The 1981 to 1983 surveys attempted to survey the entire area of the historical winter fishery by surveying day and night, but were successful in locating the herring only in 1981. From 1984 to 1987, the surveys have been done at night and have focused on a smaller area in Chedabucto Bay where the purse seine fleet was fishing.

The aim of these surveys was to quantify the herring by determining the size and acoustic scattering in herring schools. The 1984, 1986 and 1987 surveys mapped and quantified large concentrations of herring and showed the dynamic nature of herring aggregation. In 1989, the survey design was changed to a statistical sampling of parallel transects. The 1989 and 1990 surveys estimated fewer herring than in previous years and indicated that parallel transect sampling of schooled fish can produce very high variance estimates.

The acoustic results and the trawl catch results of the surveys also indicate that there are diel effects in herring behavior. The herring appear to be more densely aggregated and in closer association with the sea floor during the day than during the night. Daytime herring surveys are shown to be potentially biased.

The close association of herring with the sea floor is not restricted to daytime. At night, also, the bottom of herring schools is often in contact with the sea floor. This creates a problem in separating herring echoes from sea floor

echoes and raises the possibility that the high variability in nighttime acoustic abundance is due in part to undetected herring near the sea floor.

INTRODUCTION

In recent years, there has been increased emphasis on acoustic estimation of fish abundance for stock assessment. In Atlantic herring assessments, for example, acoustic biomass estimates - or at least indices of abundance based upon acoustic surveys - have now been used by both ICES (Anon. 1988) and CAFSAC (Wheeler, 1990; Stephenson et al., 1990a). This increase in emphasis on acoustics has been brought about in part by improvements in acoustic technology (and availability of this technology) but also by the recent realization that there are weaknesses in traditional analytical assessment methods and standard tuning procedures (see, for example, Anon., 1988; Stephenson et al., 1990b). This tendency is not limited to herring or even to pelagic assessments, but is also true of groundfish and has led to a high expectation for acoustics in stock assessments.

Acoustic surveys of Atlantic herring in the waters around Nova Scotia (Fig. 1) have been undertaken for a number of years (Shotton and Randall, 1982; Buerkle, 1985, 1987, 1989, 1990). These surveys have evolved to become an

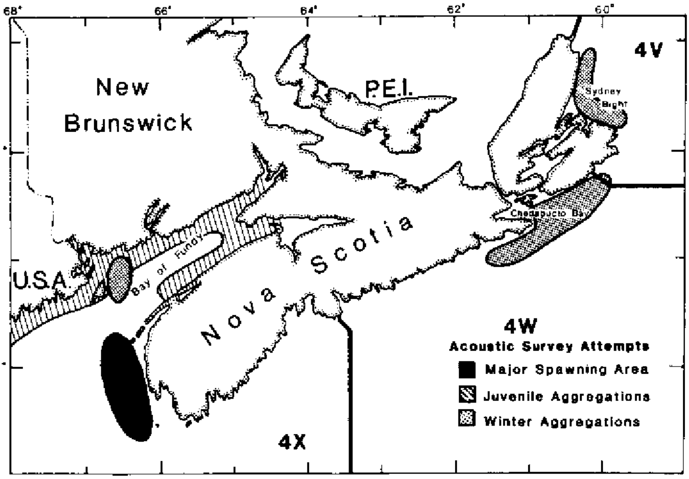

Fig. 1. Map of the generalized distribution of herring in the waters around Nova Scotia which have been the subject of acoustic survey attempts.

integral part of the assessment for the large NAFO Div. 4WX herring stock, and in 1989 formed the basis for scientific advice for this stock (Stephenson et al., 1989). Recent surveys have been relatively intensive and have included repetitive observations and changes in survey design which provide a unique chance to test several aspects of the application of acoustic survey techniques to Atlantic herring. In this paper, we touch on several aspects - pointing out what we have learned, some improvements which have been made and some questions which remain to be resolved.

SURVEY DEVELOPMENT

The NAFO Div. 4WX herring stock complex is currently the largest in the northwest Atlantic, supporting a fishery of over 100,000 t (Stephenson et al., 1990a). Tagging has linked major concentrations of these fish which occur in two areas. In summer, they occur in the major fishery area off southwest Nova Scotia where purse seine and gillnet fleets catch about 80,000 t of spawning and pre-spawning herring. In winter, they are found in a major winter aggregation off northeast Nova Scotia where purse seiners catch about 20,000 t.

In the late 1970s and early 1980s, several attempts were made to do acoustic surveys in summer off southwest Nova Scotia. The surveys were not successful because the herring aggregated in very mobile schools in small areas at different locations every night. During daytime, they disappeared. The pattern of the commercial fleet was to leave port at dusk, fan out over a large area searching for the herring with acoustic gear and to converge when fish were found. During surveys, as many as 128 boats (gillnets and purse seines) have been seen fishing in an area of less than 3 km^2, and no herring could be detected around the outside of that area. Acoustic surveys could not be done under such conditions. Traditionally, the commercial fleet did not fish on Saturday night because the processing plants were closed on Sunday. Attempts to locate and survey the herring with a single boat on Saturday nights, however, were not successful, and summer surveys were given up.

In the winter aggregations off northeast Nova Scotia, the herring are less mobile and are fished by only a few purse seiners. The major catches are made in January-February and the quantitative observations reported here were made on acoustic surveys during that time period in 1984, 1986, 1987, 1989 and 1990. The 1985 and 1988 surveys are missing from the series because ice cover interfered with the 1985 survey, and because of acoustic equipment malfunction in 1988.

ACOUSTIC EQUIPMENT AND DATA PROCESSING (Fig. 2, 3)

The surveys were done with Simrad EK50 echo sounders and Ametek Straza single-beam transducers in Fathom towed bodies. The analog (50 kHz) output from the sounder in the early surveys was demodulated, digitized by a 12-bit A-D at a 10-kHz rate and stored on 9-track magnetic tapes by equipment developed by the Department of Fisheries and Oceans at the Bedford Institute of Oceanography. For the 1989 and 1990 surveys, the sounder output was digitized at a 15-kHz rate by a Simrad QX525 preprocessor and was formatted and stored on Bernoulli disks by a Femto Model 8618 data acquisition card in an IBM compatible XT computer. This system also recorded boat position (latitude and longitude), from a Loran C receiver, with the acoustic data every 20 sec.

Calibration of sounder and transducer source level, receiver sensitivity, and beam pattern was done by standard hydrophone at the Defence Research Establishment calibration barge in Bedford Basin, N.S. Calibration of sounder receivers was done by measured input/output signals to determine gains and TVG functions (Buerkle, 1984).

Data processing consisted of editing the acoustic data and integrating fish echoes in fish schools. The data editing was done by examination of echo sounder echograms to identify the time windows during which herring occurred in the acoustic data. Echo integration was done only in these time windows to reduce the effect of integrating noise over large stretches of water devoid of fish. The processing software was developed at St. Andrews. It removes the analog TVG applied by the sounder receiver, as determined by calibration, and replaces it digitally with an accurate TVG function. Bottom echoes are removed by rejecting all echo samples that are less than 0.5 m above the Simrad white line bottom pulse. Echo integration was done between sequential navigation records and average area scattering was weighted by the distance so that the overall area scattering coefficients for transects were not biased by variation in boat speed. This is especially advantageous in surveys where fish are close to shore, so that the boat can slow down for safety reasons.

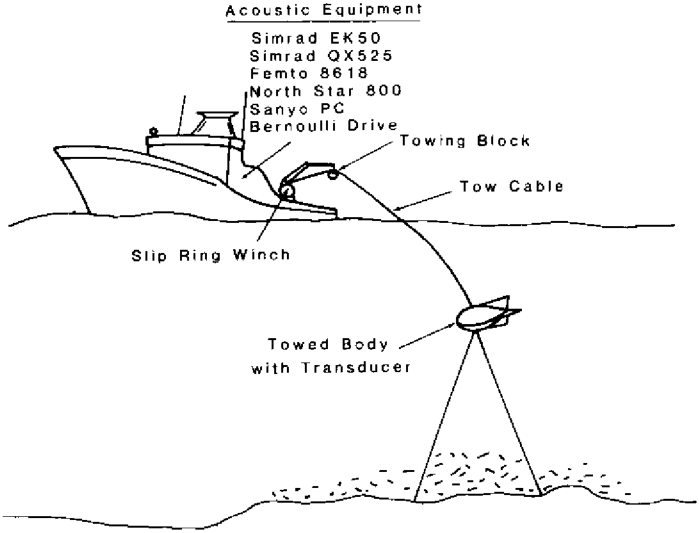

Fig. 2. Conceptual diagram of the "St. Andrews" acoustic system.

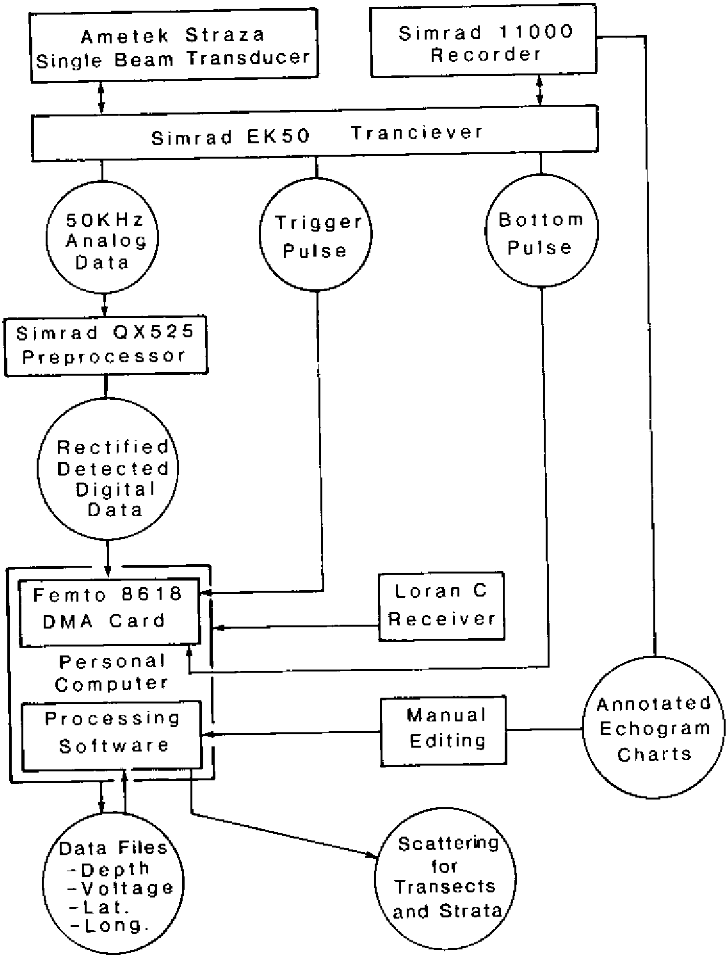

Fig. 3. Schematic diagram of the data processing for St. Andrews acoustic surveys.

EVOLUTION OF SURVEY DESIGNS

The first acoustic survey off northeast Nova Scotia was done in 1981; it covered the 8000 km^2 area of the historical winter fishery and resulted in the first acoustic abundance estimate of the southwest Nova Scotia herring stock. The survey design was replicate random zig-zag tracks in seven strata (Fig. 4). The survey was run day and night and 93% of the total biomass of 400,000 t was located in one small 30-km^2 area southwest of Canso (Shotton and Randall, 1982).

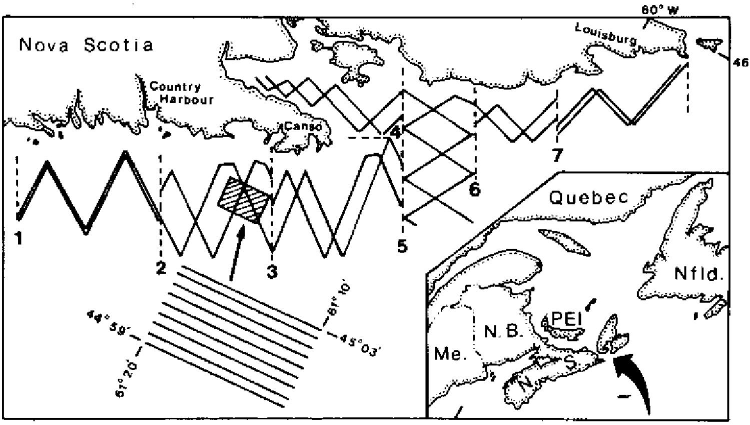

Fig. 4. Map of northeast Nova Scotia showing the location of the seven strata and the survey track. Inset shows the area in stratum 2 where a more detailed survey track was searched (from Shotton and Randall 1982).

The second survey, in 1982, never really took place because the survey boat could not leave the wharf long enough during a whole month of continuous bad weather. To minimize risk of similar occurrence in 1983, the survey design was changed so that the area could be surveyed piece-meal during short periods of good weather without a great loss of time in steaming to and from starting positions (Fig. 5). The aim of this design was simply to locate areas of herring concentrations which could then be surveyed in detail. As in 1981, surveying was done day and night when weather permitted, but this time no herring were found. Purse seiners, however, made good catches at night in a small area where the survey had detected no herring during the day. This led to the suspicion that herring are not reliably detected by acoustics during the day.

In 1984, the design was changed from surveying the whole area, to include replicate nighttime surveys in the small areas of herring aggregation as identified by purse seiner fishing effort. The aim of the replicate surveys was to map the size and shape of the herring schools fished by the seiners. This was done by running transects through the schools in different directions. When the schools were more or less stable, it resulted in relatively simple zig-zag patterns (Fig. 6) from which the school shape could be estimated. Often,

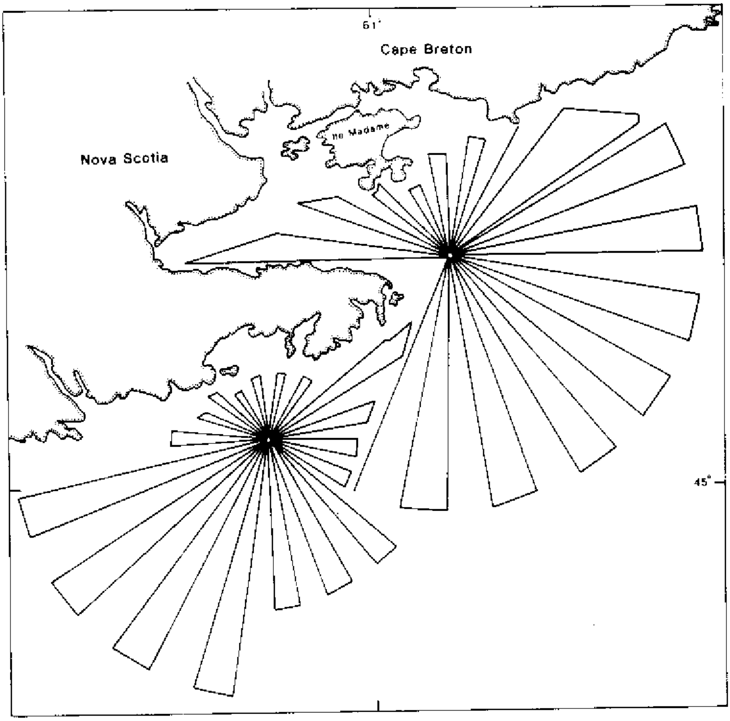

Fig. 5. 1985 survey cruise track for searching the whole area of the winter purse seine fishery.

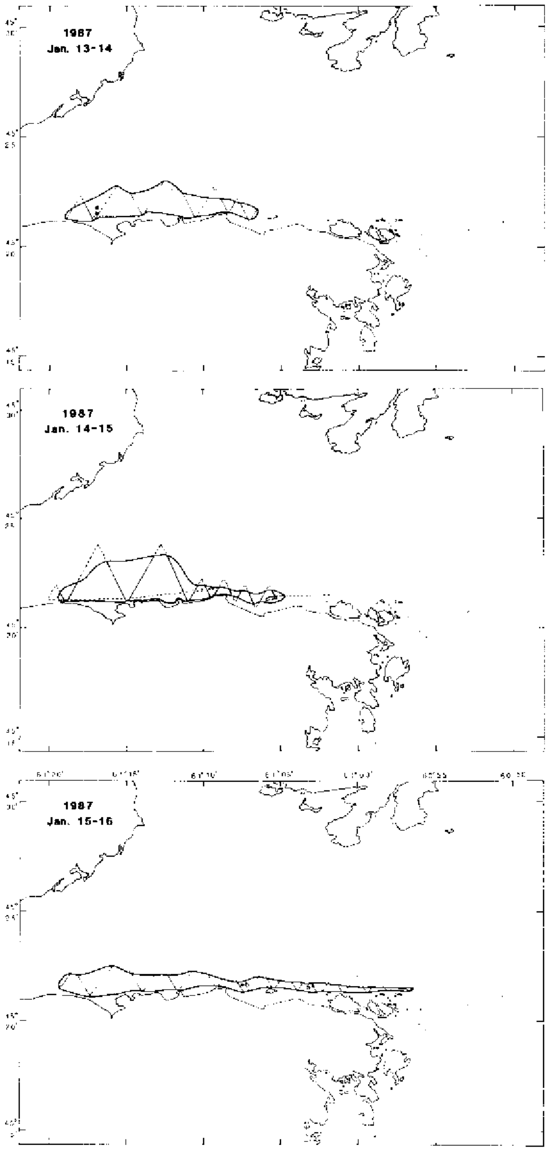

Fig. 6. Three samples of herring school mapping surveys showing the change in size and shape of a single large herring school on three consecutive nights.

the schools changed shape, split up, recombined and moved during the night. This made the mapping difficult but it provided a very good insight into the dynamic nature of herring schools. Each night's work resulted in an estimate of the number, shape, size and acoustic scattering of the herring schools in the area (Buerkle, 1987).

In 1984 and 1985, the surveys were successful in mapping large concentrations of herring in one 340-km^2 area in Chedabucto Bay. No herring were found in the larger, 8000-km^2 area of the historical fishery. Beginning in 1986, the star pattern surveys (Fig. 5) were discontinued and survey effort was confined to the 340-km^2 area in Chedabucto Bay.

The weaknesses of the mapping surveys were that they were not a statistical sampling design and that no variance estimates could be produced.

In response to a CAFSAC recommendation (O'Boyle and Atkinson, 1989) to run random parallel transects in acoustic surveys, the survey method was changed again for the 1989 and 1990 surveys. The survey effort was still concentrated in the 340-km^2 area in Chedabucto Bay, but separate replicate surveys of the area were done during days and during nights. Each survey consisted of a set of equidistant parallel transects placed randomly in the survey area (Fig. 7). These surveys were also successful in quantifying major concentrations of herring, but the approach has a major weakness also. The herring may be aggregated in a single school that is small in relation to transect spacing. The herring will then be sampled along one, or very few, transects, or the major concentration may be missed altogether. This happened several times during the 1990 survey and led to very high variance estimates of abundance. To date, however, no better survey method has been devised for these conditions.

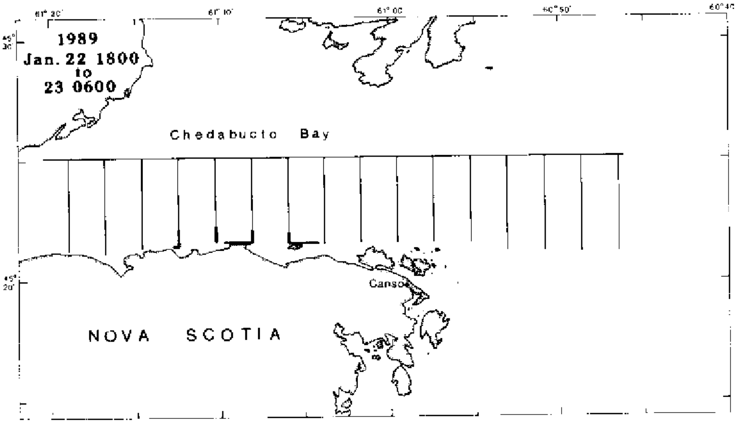

Fig. 7. A parallel transect survey track showing one night's work in 1989. Thick lines indicate the location of herring.

HERRING DISTRIBUTION AND ABUNDANCE

a) Within- and between-year variation

The nighttime mapping surveys (1984-87) showed the herring to be aggregated in schools. Most of the time they were within an area of 7.5 km in the north-south direction and 45 km in the east-west direction along the south shore of Chedabucto Bay. The schools changed shape and moved around in the area continuously. The largest movements were in the east-west directions along the shore. During 12 nights of the 17 nights surveyed, the herring were aggregated in a single large school. During 4 nights they were divided into two or three schools, and during one night, they were broken up into eight schools.

The area occupied by individual schools varied from a small fraction of 1 km^2 to about 56 km^2. The total school area per night varied between about 10 km^2 and 56 km^2 (Fig. 8). The largest school areas were associated with aggregations in one or two schools. Herring aggregated in one or two large schools, of course, are better suited to acoustic mapping than when they are dispersed in a number of smaller schools.

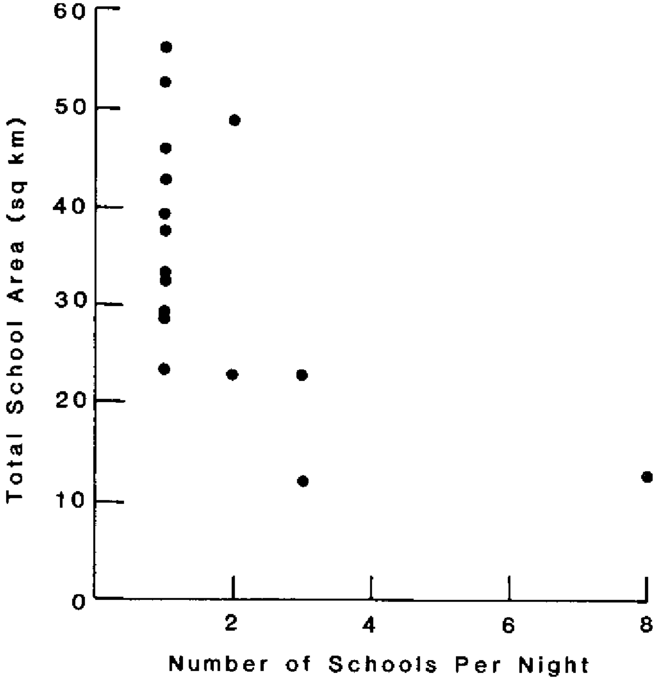

Fig. 8. Total school area and number of schools found per nightly survey during the mapping surveys 1984-87.

The number of schools cannot be determined in the parallel line surveys (1989, 1990) but total school area can be calculated. Total school area and average area scattering for all surveys are shown in Fig. 9. Total school area in the parallel line surveys (1989, 1990) was much smaller than in the previous years and the average area scattering was higher. This indicates that the herring were more densely aggregated into smaller schools in 1989 and 1990. The average area scattering does not vary greatly in the 1984, 1986 and 1987 surveys, but varies a great deal in the 1989 and 1990 surveys. One explanation for that is that scattering in the herring schools is patchy and variation in scattering among transects is large. In the 1984 survey, for example, where 71 transects were run across a single school during several nights (Fig. 10), the coefficient of variation of area scattering among transects was about 60%. Assuming a normal distribution, that means that 32% of transects varied in area scattering by a factor of more than 4. In the mapping surveys (1984, 1986, 1987), an average of 23 transects were run over the schools to obtain the nightly average. In the parallel line surveys in 1989, an average of only four transects run over the herring, and in 1990, 10 of the 11

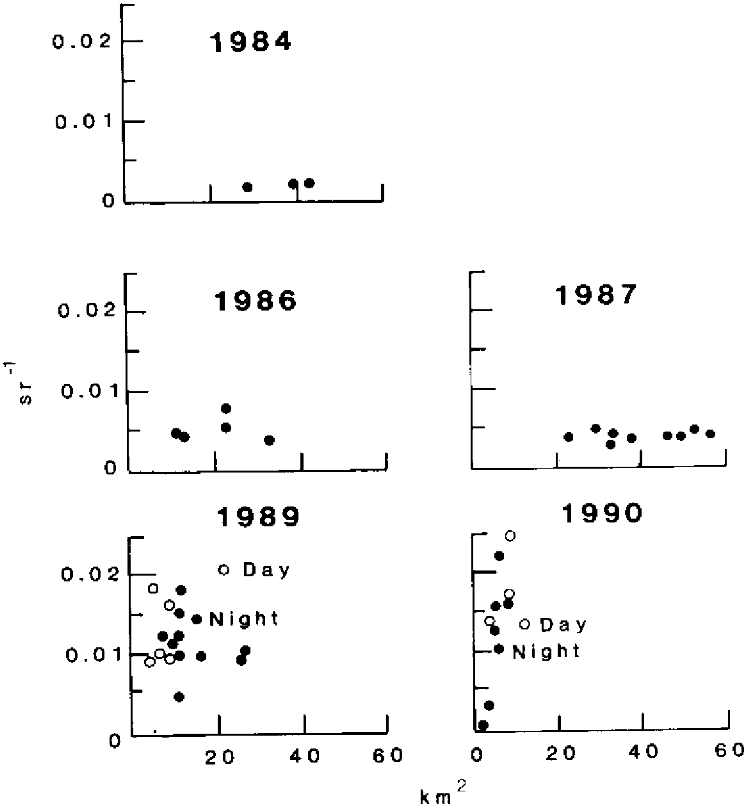

Fig. 9. Average area scattering coefficients (sr^{-1}) and total area scattering for 45 nightly surveys in 5 years.

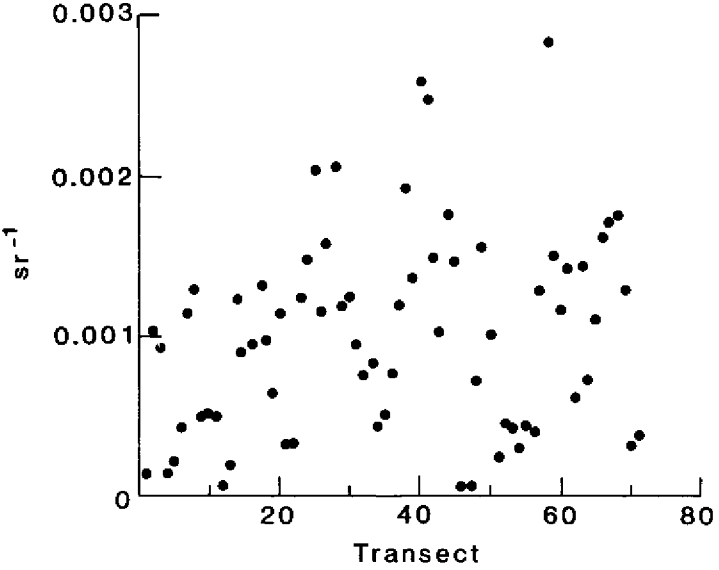

Fig. 10. Average area scattering (sr^{-1}) in 71 transects through one herring aggregation in 1984.

estimates are based on a single transect over the fish. When only a few transects in each survey cross the fish, as happened in 1989 and 1990, large variation in average area scattering must be expected.

The biomass of herring estimated in all surveys is shown in Fig. 11. The horizontal areas show the 40 days from Dec. 31 to Feb. 9. It can be seen that survey results over the years were not obtained at the same time of year. In 1984, the herring were found late and indicate a low biomass. From 1986 to 1990, the surveys were begun increasingly early and indicated higher biomass until 1990 when there was a decline. The 1990 survey results are cut off on Jan. 11 because the towed body was lost and the remaining surveys were done with an uncalibrated transducer. There is no relationship between biomass and date in any of the years except 1989 when there was a significant decline in biomass between Jan. 7 and 23. To monitor the buildup and decline of the winter herring population in Chedabucto Bay would require more protracted survey periods than available until now.

The most notable feature about the estimates is the great variation, not so much from year to year, but between individual surveys in the same year. The coefficients of variation range from 31% in 1984 to 68% in 1990. One possible explanation for this is sampling errors due to the patchiness of herring densities in the aggregations. Another is variability in the availability of herring for acoustic detection.

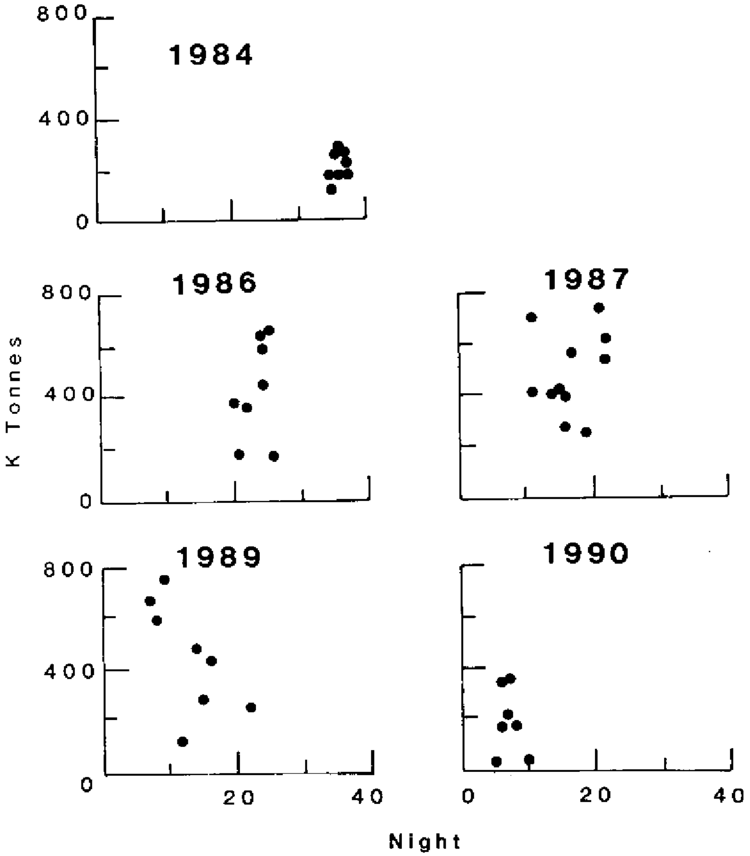

Fig. 11. Nighttime herring biomass estimates (1000 tonnes) in Chedabucto Bay by time of year from Dec. 31 to Feb. 9.

b) Diel effects - i) acoustic data

Nighttime distributions of herring in Chedabucto Bay appear on the echo sounder as dispersed in the water column. The lower edge of the aggregations is sometimes separated from the sea floor. In daytime, the herring appear more densely packed and the lower edge of the aggregations is almost always in contact with the sea floor. Figure 12 shows typical day and night echograms. The difference between daytime and nighttime scattering is also shown by 1-m depth intervals in Fig. 13. The nighttime herring (transect 63) are fairly well separated from the sea floor with very little scattering in the bottom most depth layer. The highest scattering occurs at about 12 m above the sea floor and it decreases gradually to about 50 m above the sea floor. In daytime herring (transect 85), the scattering is spread more evenly at higher

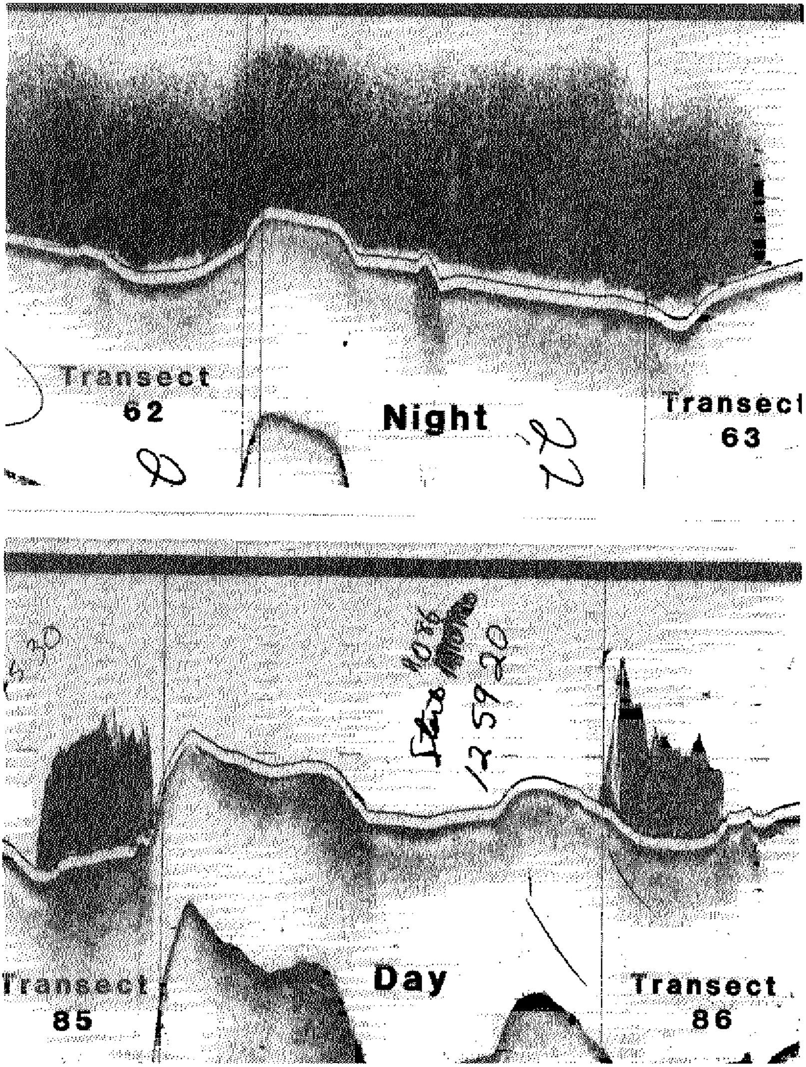

Fig. 12. Echograms from four transects through herring schools in the 1989 parallel line survey. Transects 62 and 86 show the herring along one line by night and by day, respectively. Transects 63 and 85 show the same thing along another line 2.8 km to the east. The middle portions of the echograms (between the vertical lines) show the boat's path connecting the survey lines.

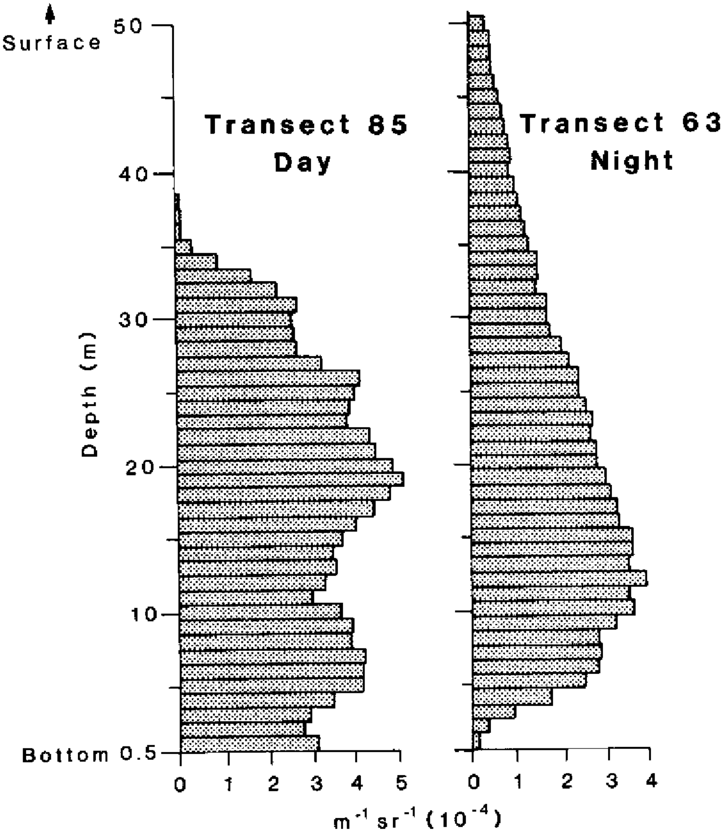

Fig. 13. Average volume scattering (m^{-1} sr^{-1}) of herring by night and by day in 1-m depth layers.

levels from the sea floor to a sharp decrease at about 35 m. Observations of herring in midwater at night and near the sea floor during day have also been reported from Iceland (Jakobsson, 1983).

In addition to these differences in day and night vertical distribution of herring and acoustic scattering, day and night scattering can also be expected to differ because of the tilt angle distribution of the herring. Spawning and pre-spawning herring photographed at night off southwest Nova Scotia in summer were oriented at all tilt angles, from horizontal to belly up and from head straight up to head down (Buerkle, 1983). Wide ranges of tilt angles have also been photographed at night in Chedabucto Bay during the winter (Fig. 14). During daytime, herring are more uniformly horizontal and swim in the same direction. This difference in tilt angle distribution was estimated

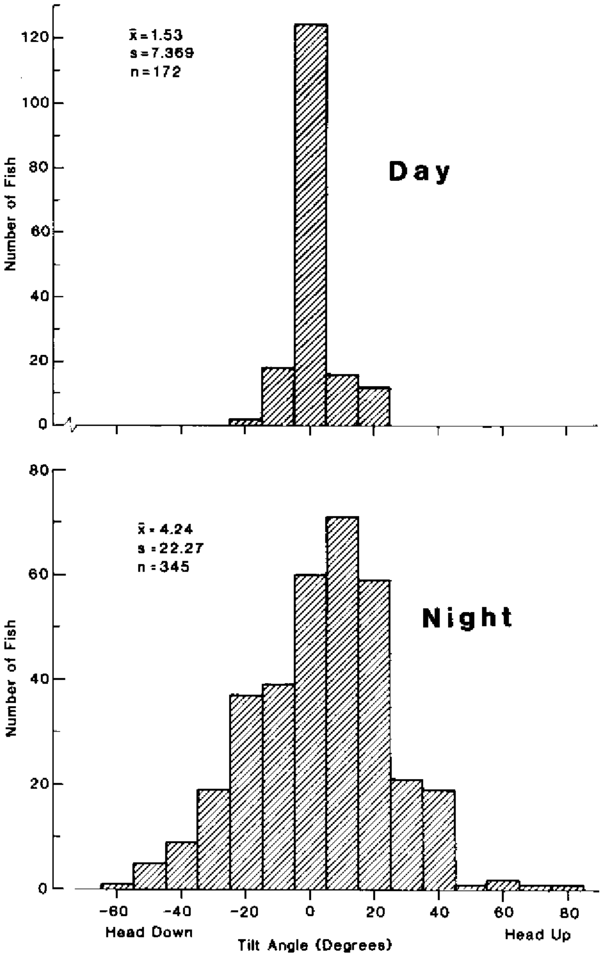

Fig. 14. Tilt angle distributions of herring in Chedabucto Bay in 1984 during day and during night.

by Buerkle (1983) to result in target strengths that should be about four times higher during the day than during the night. Higher daytime target strengths, due to differences in tilt angle distribution, have also been reported for walleye pollack (Traynor and Williamson, 1983).

The daytime surveys in Chedabucto Bay in 1989 showed that herring schools occupied less area than during the night and that average area scattering was only slightly higher (Fig. 9). The 1990 surveys also showed slightly higher scattering during the day but the areas occupied both day and night were not different. In light of the much higher expected daytime target strength, the small increases in area scattering indicate that fewer herring were detected in daytime surveys than in night surveys.

The Chedabucto Bay surveys were done with single beam acoustic equipment and direct estimates of *in situ* target strength were not possible. Single herring are difficult to resolve in the acoustic data so *in situ* target strengths cannot be calculated by removing the beam pattern effect statistically. Conversion of acoustic measurement to biomass therefore relies on published target strength/length relationships. A compilation of *in situ* measurements of herring target strengths by different workers in Europe has been made by Foote (1987). These were all nighttime measurements, so daytime abundances cannot be calculated.

In the light of other facts also, however, it is reasonable to expect lower acoustic abundance during daytime. Purse seiners fish mainly at night when the herring come off bottom and are more accessible to seines. Herring are often caught at night in areas where they are not detectable by echo sounders during the day. When herring are seen on echo sounders during the day, they are in close association with the sea floor.

The association of herring with the sea floor may cause acoustic detection problems, not only during daytime, but also at night. There is no information that indicates that all herring in an area come off bottom at night to where they can be detected acoustically. Some proportion, and maybe a proportion that varies with time, may remain undetected near the sea floor and that may be a contributing factor to the high variability of acoustic abundance estimates.

b) Diel effects - ii) biological data

Every acoustic survey must be accompanied by biological sampling to identify the species and size composition of the acoustic targets. In the Chedabucto Bay surveys, sampling was done on the acoustic targets in the water column throughout the survey periods by midwater trawl. In the 1989 and 1990 surveys, fish echo traces were also observed on the sea floor in the western half of the survey area. A bottom trawl tow aimed at sampling these fish in 1989 caught juvenile herring (13.5 cm). During the attempt to sample the traces in 1990, no fish were seen on the sounder during the tow, but the trawl caught 3 1/2 baskets of 22.1-cm herring. Ten other bottom trawl tows were made over a 24-hour period in areas where no fish were seen on the sounder. All but two of these caught herring. That indicates that there were herring close to the sea floor all over the western half of the survey area. The size of the catches, generally a fraction of a basket per 20-min tow, indicated few fish near bottom compared to the numbers in the midwater concentrations in the eastern half of the survey area.

The length-frequency distributions of all trawl samples in 1989 (Fig. 15) show remarkable differences between daytime and nighttime samples and between bottom trawl and midwater trawl samples. There are three main length modes, one around 15 cm, one around 22 cm, and one around 27 cm. The midwater samples show the 27-cm herring during day and night, but the 22-cm herring are not well represented during the day. Bottom night samples are mostly 15-cm herring and bottom day samples include 15-cm herring and a much higher proportion of 22-cm herring. It seems that large herring appear only in mid-water, small herring appear mostly near bottom, and the mid-sized herring appear in mid-water at night and in bottom during the day.

Such differences, of course, affect the target strength of the fish and, where no *in situ* target strength estimates can be made, the appropriate length-frequency distribution must be used with the appropriate target strength length relationship to calculate the ensemble average target strength.

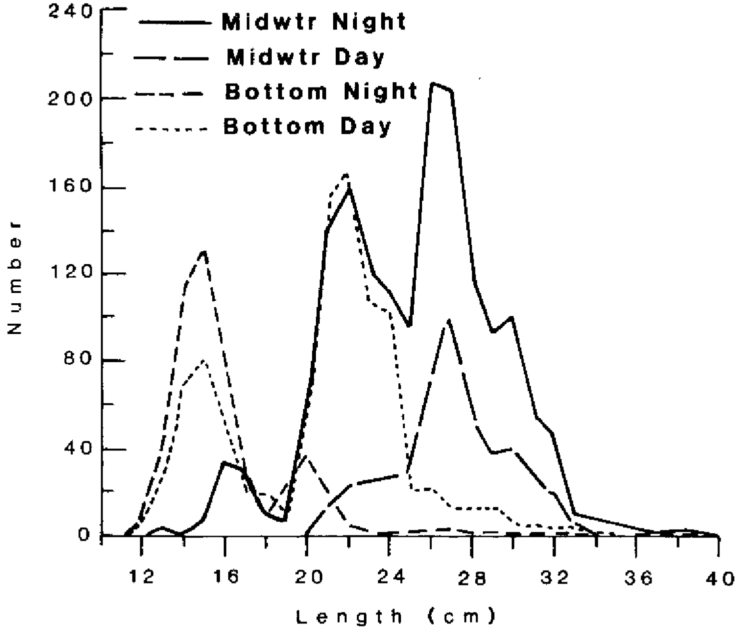

Fig. 15. Herring length frequencies in midwater and bottom trawl samples by day and by night from the 1989 survey.

BOTTOM DISCRIMINATION

The acoustic data recording equipment recorded all echo voltage samples in each echo ping that were above a 0.015 volt detection threshold, down through the water column to the sea floor. The bottom was detected by a threshold in the Simrad receiver and the bottom threshold level is adjustable by the discriminator switch. When an echo level reaches the bottom threshold, a bottom pulse is generated. The bottom pulse produces the white line on the echograms and stops the recording of further voltage samples from the echo ping. In the surveys, the bottom echo levels were generally much higher than herring echo levels and the discriminator could be adjusted so that bottom pulses were generated by bottom echoes and not by herring echoes. Sometimes, however, the bottom pulse was not produced. These occurrences were called 'missed bottoms' and can be seen on the echograms as vertical black lines through the horizontal bottom white line. When a missed bottom occurs, the whole bottom echo is recorded in the acoustic data. Echo pings with missed bottoms were identified in the digital data and were discarded.

In normal echo pings where a bottom pulse is generated, bottom echoes were digitized and recorded until the bottom echo level reached the bottom threshold level. The number of bottom echo samples recorded depends on the pulse length, the bottom threshold level, and the beam angle of the acoustic equipment. It also depends on the consistency and slope of the sea floor itself. Figure 16 shows the bottom echoes recorded under the herring aggregations shown in Fig. 12. The scattering decreases from very high levels at the bottom threshold to low levels at an altitude of 0.4 m to 0.5 m above the bottom threshold. If these bottom samples are integrated with the fish echoes, they increase abundance estimates by as much as 146% in these four transects. Deciding how much echo to reject as bottom echo, however, is not as simple as it would appear. The very high scattering in the bottom echo dictates a scale in Fig. 16 that shows very little of the scattering from the herring. To show the transition between bottom echoes and fish echoes, the scattering in two transects is plotted from 0.25 m to 2.75 m above the bottom in Fig. 17. In transect 63 where the herring are separated from the bottom on the echogram, the bottom echo scattering can be seen to begin at an altitude of about 0.5 m above the bottom threshold. In situations like transect 85, there is no separation between bottom echoes and herring echoes but bottom echoes must be excluded nonetheless. The approach adopted in the Chedabucto Bay surveys was to reject all echoes that were less than 0.5 m above the bottom threshold level. More work to establish guidelines for bottom rejection is needed.

CONCLUSION

Acoustic technology is improving and there is a high expectation of/for the contribution of acoustics to stock assessment. In this paper, we have shown that there are problems with the application of acoustics for herring (and likely for other fish species) caused by fish dynamics. The intensive surveying and sampling in Chedabucto Bay has shown problems with temporal and spatial distributions of fish (within and between years), survey design and

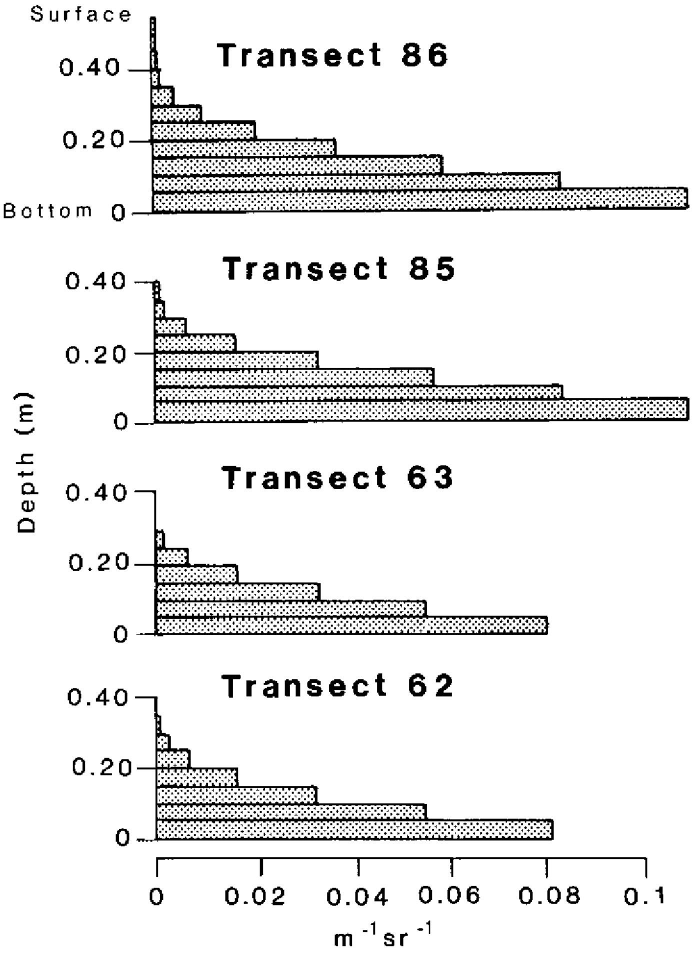

Fig. 16. Volume scattering (m^{-1} sr^{-1}) in 5-cm layers of bottom echoes under herring in Fig. 8.

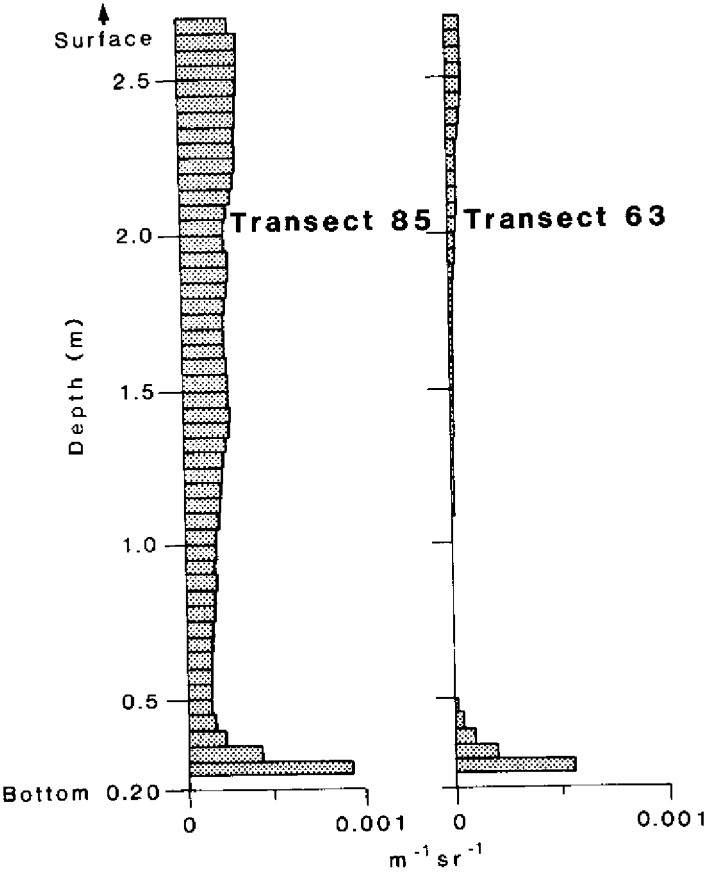

Fig. 17. Volume scattering (m^{-1} sr^{-1}) in 5-cm layers to show relation of herring and bottom echoes.

bottom detection, which have major indications for implementation of acoustic surveys. How could one now, for example, justify a continuous single survey coverage (day and night) for herring? Acoustics offers great potential (and indeed will be necessary for future stock assessments) but must be implemented with knowledge of, and matched to, fish behavior and local conditions.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Comparison of Pacific Spawner Herring Biomass Estimates from Hydroacoustic-Trawl and Spawning Ground Escapement Surveys in Puget Sound, Washington

S.F. Burton
Washington Department of Fisheries
Seattle, Washington

ABSTRACT

Pacific herring (Clupea harengus pallasi) stock assessment estimates in Puget Sound are acquired through both hydroacoustic and spawning ground escapement techniques. Herring resource managers use the hydroacoustic results to determine in-season run size and prespawning biomass, and the spawn surveys to monitor corresponding escapement and establish the end-of-season run size. Results for spawner herring assessment of Strait of Georgia, Discovery Bay, northern Hood Canal, and Port Orchard indicate estimates from the two methods differed by less than 20% nearly half the time. A discussion of potential biases of each method includes outdated conversion factors, survey frequency and other inherent sources of variability.

INTRODUCTION

Pacific herring (Clupea harengus pallasi) are harvested by four different fisheries in Washington state, sport-bait, general purpose, sac-roe, and more recently, impounded spawn-on-kelp (Trumble, 1983). Fisheries directed towards juvenile herring, such as the sport-bait fishery in Puget Sound, have been passively managed -- catches limited primarily by market conditions. However, fisheries that target on spawning herring, such as the sac-roe and impounded spawn-on-kelp fisheries in the lower Strait of Georgia, require rapid response and active management to prevent potential over-harvest. In the early 1970's, the Washington Department of Fisheries (WDF), began employing two independent methods to assess spawner herring abundance throughout Puget Sound. One technique employed hydroacoustic sampling combined with pelagic trawling to determine the abundance of spawner herring adjacent to their spawning grounds. The other technique consisted of spawning ground egg deposition surveys to estimate escapement. Typically, herring move into Puget Sound in October to January, gradually move to their spawning grounds and spawn in February and March. Hydroacoustic surveys are conducted in February to assess the herring just prior to spawning. The acoustic estimate, combined with catch, and spawn on the beach gives resource managers an estimate of run size at this time. The spawn surveys normally begin in January and continue through March to encompass the complete cycle from beginning to end. The cumulative spawn, plus the cumulative catch gives an end-of-season run size.

The purpose of this paper is to present comparable estimates of peak spawner abundance of the acoustic and spawn survey methodologies for herring stocks found in the Strait of Georgia, Discovery Bay, northern Hood Canal, and Port Orchard (Figure 1). This paper also presents sources of variability associated with the two methodologies. It is hoped that understanding and evaluation of these problems will benefit future survey design.

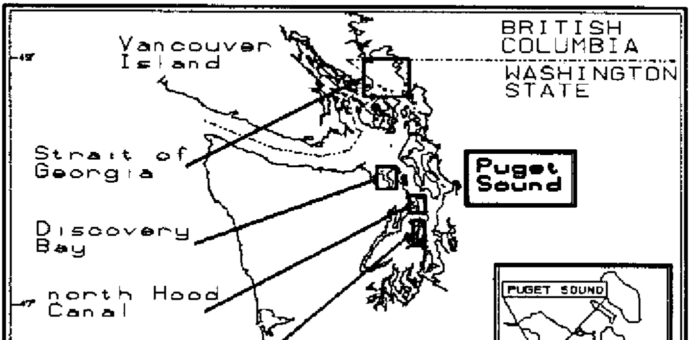

Figure 1. Map of Puget Sound area, northwestern corner of Washington state, showing location of Strait of Georgia, Discovery Bay, northern Hood Canal, and Port Orchard.

METHODS AND MATERIALS

Hydroacoustic/Trawl

Hydroacoustic midwater trawl surveys were conducted to obtain point in time estimates of abundance and distribution. Usually the maturing herring begin arriving in the vicinity of the spawning grounds over a 2 to 3 week span and sequential assessment surveys were conducted to monitor distribution and establish when the population peaked.

Two vessels were employed for the stock assessment surveys (Lemberg, et al., 1988). The acoustic vessel sampled along standard trackline patterns and directed the trawler to specific trawl locations (Loran C referenced) chosen on the basis of fish density and distribution. Trawl duration was varied to assure catches of 100-200 kg for biological sampling purposes. All surveys were conducted at night when the schools moved upward in the water column, and dispersed to form fairly widespread but vertically discrete layers approximately 10m thick and between 10m and 30m in depth. This nighttime distribution makes herring more accessible to hydroacoustic sampling and also more vulnerable to midwater trawl gear. Acoustic vessel speed during transects averaged about 8 knots. All deck lighting was eliminated to circumvent potential fish avoidance.

Prior to 1978, the hydroacoustic data acquisition system consisted of a modified commercial echosounder (Ross 200A, 105kHz), a Sony TC-377 tape deck which recorded the data on magnetic tape, and a Ross 10^0 narrow beam transducer. Integration of the data was done at the Applied Physics Laboratory, University of Washington. The hydroacoustic data acquisition system from 1978 on, has consisted of a scientific echosounder (Biosonics 101, 105kHz) coupled to the same Ross narrow beam transducer. Since 1980, all data has been processed "real time" on board with a Biosonics 120/121 echo integrator. A complete system calibration including measurement of source levels, receiver gain, and transducer receive and transmit sensitivities have been conducted before every survey season at the Applied Physics Laboratory, University of Washington.

The target strength scaling value used to scale acoustic data to abundance estimates was -33 dB/kg for herring 18 to 24 cm (Thorne, et al., 1975; Trumble, et al., 1982). From 1984 on, target strength correction factors were applied for mixed age stocks. The fish length thresholds for separating adults from juveniles in mixed age stocks was 17 cm for herring (Buchanan, 1985).

Prior to 1979, midwater trawl samples were taken using a tapered four panel trawl (6.1m x 6.1m opening) with a 1.27 cm stretch measure codend liner (Lemberg, 1978). From 1980 on, trawl samples were taken with Nor'Eastern Trawl Systems pelagic trawl, with a 1 cm knotless (mesh to mesh) codend-liner. Towing speed was 2.5 to 3.0 knots. Telemetry measurements indicated a nominal net mouth opening of 10 by 15 m. Head rope depth was determined by a net sounding system or bathykymograph (Lemberg, et al. 1988). On-deck samples were taken for species composition, herring spawner and size percentages, and biological samples of herring were taken for further lab analysis of length, weight, sexual maturity stage, and scale aging.

Nekton biomass was estimated using the echo integration method (Thorne, 1977), by calculating mean surface referenced density (kg/m^2) for transects within regions and extrapolating the value over the region's surface area (Nunnalle, 1974). Spawner herring abundance was then obtained by apportioning the nekton biomass with species compositions and spawner percentages (by weight), from on-deck samples from the appropriate trawl. Spawner and non-spawner categories were referenced to sexual maturity stages (Parrish and Seville, 1965). Immature and recovering spent adult herring were considered non-spawners, and mature (unspawned) herring as spawners (Lemberg, 1978).

Peak acoustic spawner biomass for this method was defined as the highest, acoustic spawner biomass, plus escapement at the time of the acoustic peak (determined from the spawn surveys), plus catch at the time of the acoustic peak (from the computerized catch record system).

Spawning Ground Surveys

Pacific herring in Puget Sound are assumed to be a mixture of several spawning stocks, all with unique population dynamics and associated spawning grounds (Trumble, 1983). This situation has lent itself to discrete stock assessment by surveying the herring egg deposition on nearshore marine vegetation of a specific spawning ground.

Timing of documented herring spawning in Puget Sound has typically been in February and March, but the lower Strait of Georgia also receives spawning in April, May and June. Although spawning in a given area may extend over a fairly long period, peak spawning usually occurs at similar time each year for a particular ground.

Herring spawn surveys were regularly conducted (weekly or twice weekly), for many grounds in Puget Sound to encompass the spawning season (January to June). From small, open boats, two person crews grappled marine vegetation at non-fixed sites, 30 to 150 m along the shoreline of the spawning ground, at depths from +.5 to -20 m tidal elevation (MLLW = 0 m).

Basically, procedures were followed as outlined by Hourston et al. (1972). The sampled sites were plotted on field charts, grappled vegetation types noted, and herring spawn deposition, if present, was assigned an intensity (number of egg layers), which represented a conversion factor of spawner herring biomass per distance.

Biomass of spawner herring was then estimated from the distance of each spawn deposition along the beach and the conversion factor. Spawn dates were determined from the embryonic stages of herring egg samples taken and preserved in Stockard's solution (Trumble et al., 1977; Meyer and Adair, 1978).

Peak spawner biomass for this method was defined as the end-of-season, cumulative spawning escapement from the spawning ground surveys, plus the end-of-season, cumulative catch from the catch records.

RESULTS AND DISCUSSION

Strait Of Georgia

Herring stock assessment efforts were most intensive for the Strait of Georgia, sac-roe/spawn-on-kelp fishery, in which abundance estimates had to be made available within a day after the data collection to set and maintain catch quotas. Hydroacoustic/trawl work was conducted weekly, and spawn surveys twice weekly. As the peak spawner abundance was approached, acoustic surveys were conducted twice weekly to confirm the peak. This data, compiled from 1977 to 1990, was the most comprehensive set for comparing results between the hydroacoustic and spawning ground stock assessment methods (Table 1, Figure 2).

Table 1. Herring peak spawner biomass for hydroacoustic/trawl (ACSTIC/TRAWL) and spawning ground escapement surveys (SPWNING GROUND); and percent difference (PERCENT DIFFERENCE) from the acoustic to the spawning ground estimates for the Puget Sound areas of Strait of Georgia, Discovery Bay, northern Hood Canal, and Port Orchard, 1976 to 1990.

	STRAIT OF GEORGIA			DISCOVERY BAY		
	Peak Spawner Biomass in Metric Tons			Peak Spawner Biomass in Metric Tons		
YEAR	ACSTIC/ TRAWL	SPWNING GROUND	PERCENT DIFFERENCE	ACSTIC/ TRAWL	SPWNING GROUND	PERCENT DIFFERENCE
1976	13832	10689	29%	3550	697*	409%
1977	10270	10073	2%	1350	110*	1127%
1978	14314	9939	44%	690	1155	-40%
1979	8684	9033	-4%	800		
1980	9589	8459	13%	2230	2921	-24%
1981	8637	5642	53%	2460	3392	-27%
1982	11562	4846	139%		2137	
1983	10142	7315	39%		2339	
1984	7347	5353	37%		2852	
1985	5519	5825	-5%		1313	
1986	3528	5145	-31%		1421	
1987	2775	2761	1%		1445	
1988	3236	3999	-19%	622	774	-20%
1989	3983	3765	6%		1111	
1990	4215	4538	-7%		776	

	NORTHERN HOOD CANAL			PORT ORCHARD		
	Peak Spawner Biomass in Metric Tons			Peak Spawner Biomass in Metric Tons		
YEAR	ACSTIC/ TRAWL	SPWNING GROUND	PERCENT DIFFERENCE	ACSTIC/ TRAWL	SPWNING GROUND	PERCENT DIFFERENCE
1976	3280	1036*	217%			
1977	2397	2291	5%			
1978	2590	1800	44%			
1979	700	1624	-57%			
1980	1884	2095	-10%		1941	
1981	690	1590	-57%		807	
1982		1327			1101	
1983		2184			1498	
1984		2436			1173	
1985		2165			1284	
1986		1860			1747	
1987		1846			2302	
1988	1440	1237	16%	1429	1547	-8%
1989	2673	2160	24%	1291	1498	-14%
1990	998	2869	-65%	417	1628	-74%

* Incomplete spawn surveys, data not used.

Table 1 also shows a percent difference between the acoustic and spawning ground results. I arbitrarily designated > 20% difference as the threshold for non-agreement, that results in 7 out of 8 years (47%) being in agreement. For the Strait of Georgia, the widest spread occurred in 1982 (139%), and the closest in 1987 (1%).

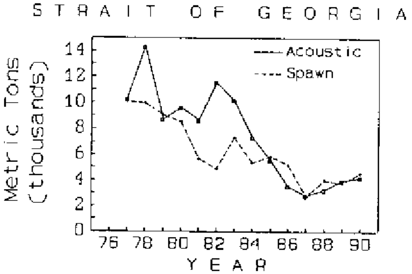

Figure 2. Peak spawner biomass for hydroacoustic/trawl (ACOUSTIC), and spawning ground surveys (SPAWN), for the Strait of Georgia, 1976-90.

In 1984 the mean length for the Strait of Georgia herring, decreased from an average of 191 mm (1976 to 1983), to 162 mm (1984 to 1990). The 1984 drop in mean length raised the issue of measuring the effects of fish size on the acoustic scaling factor. The -33 dB/kg was based on predominately larger fish, and if applied to a smaller sized population would cause an overestimation. So visible was the decrease in herring mean length in 1984 (152 mm), that correction factors were incorporated into the acoustic calculations that year to compensate for the smaller fish (Johannesson and Losse, 1977). I removed these correction factors and recalculated the spawner biomass and found very little change, if any, in the results. Generally, the corrections were applied in areas that contained low biomass, hence the overall effect was minimal. To confuse the issue, 1990 analysis by the WDF hydroacoustic unit, suggested that the original target strength scaling value may not have been applicable to all Puget Sound spawning stocks. Although, the correction factors were a step in the right direction they appeared to be insufficient. The scaling factor, combined with decreased fish size, should have caused significant overestimation. However, the acoustic estimates, in relation to the spawn escapement from 1984 to 1990, does not suggest this.

Although, the need for corrections to the spawn survey conversions were not addressed, theoretically, the spawning ground escapement estimates would likewise be affected by the mean length of the population. Egg deposition intensity factors were based on fecundities of a population dominated by larger herring (Meyer and Adair, 1978). It was unclear how the shift towards a smaller, younger population affected the spawning ground escapement estimates. It can be argued that the range for number of egg layers for any given intensity was so great (Humphreys and Haegele, 1976), that the inherent variability of the technique overshadowed the error caused by the slightly reduced fecundity of a smaller sized, younger population.

Regardless of the percent differences, both results show the decline in the Strait of Georgia herring population from 1976 to 1987 (Figure 2). The 1976 average of the two results was

12,260 metric tons; dropping to a low of 2,768 metric tons in 1987. The biomass for 1988, 1989 and 1990, seemed to show this trend slowly reversing. In 1990, the averaged biomass was 4,376 metric tons.

Discovery Bay, Northern Hood Canal, Port Orchard

Discovery Bay, northern Hood Canal and Port Orchard were surveyed much less intensively than the Strait of Georgia. Discovery Bay was not supporting any commercial herring fishery, and the latter two areas had limited spawn-on-kelp fisheries. Acoustic work consisted of 1 or 2 scheduled surveys per season while spawn surveys were conducted weekly.

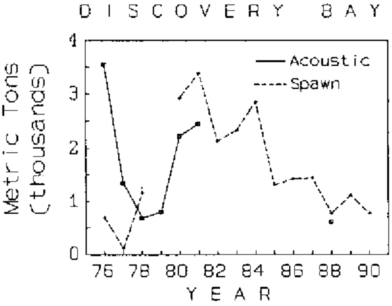

Figure 3. Peak spawner biomass for hydroacoustic/trawl (ACOUSTIC), and spawning ground surveys (SPAWN), for Discovery Bay, 1976-90.

For Discovery Bay, percent differences between the two results ranged from -40% (1978) to -20% (1988). The spawn estimates are shown for 1976 and 1977, but the data was incomplete and not used for comparison purposes. Spawn survey effort was shared between WDF and the U.S. Fish & Wildlife Service until 1978. During this time, surveys were conducted biweekly, which would explain the low spawning ground escapement estimates that occurred in 1976 (Figure 3). In 1977, only 3 spawn surveys were conducted for the entire season. From 1979 on, WDF surveyed Discovery Bay on a weekly basis.

The hydroacoustic/trawl surveys were conducted only once per season in 1976, 1978, 1979, 1981 and 1988; and twice per season in 1977 and 1980.

Generally, the spawn surveys showed a trend of declining biomass from 1981 (3392 metric tons), to 1990 (776 metric tons). This trend was confirmed by the most recent acoustic survey conducted in 1988 (622 metric tons).

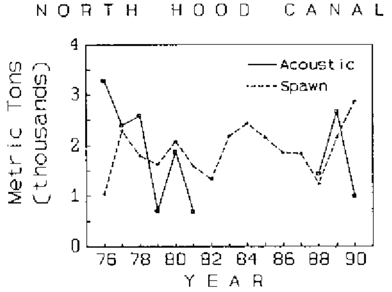

Figure 4. Peak spawner biomass for hydroacoustic/trawl (ACOUSTIC), and spawning ground surveys (SPAWN), for northern Hood Canal, 1976-90.

Northern Hood Canal (Figure 4), results ranged in percent difference from -65% (1990) to 5% (1977), and likewise was surveyed cooperatively with the U.S. Fish & Wildlife Service until 1978. In 1976 there were no spawn surveys conducted in February, the time of peak spawning for this ground, hence, the comparison between the two techniques is not valid for this year. A weekly survey schedule by the WDF was maintained for this area after 1978.

Overall, the spawner biomass estimates for northern Hood Canal were quite variable from year to year. The spawn surveys did not indicate a decline in the abundance of spawner herring.

The percent difference for Port Orchard (Figure 5), ranged from -74% (1990) to -8% (1988). Hydroacoustic/ trawl surveys were first conducted for this area in 1988, and for so few points to compare, the spawn survey data was only presented from 1980 on. Two acoustic surveys per season have been conducted.

For these three areas agreement in the two spawner biomass estimates were observed for 40% of the data. Poor comparisons were primarily caused by acoustic survey timing, which missed the peak spawner biomass (Gonyea, 1985). The acoustic survey schedules were based on previous years spawning dates but the window for this peak was limited in time and may have varied by as much as two weeks. From the hydroacoustic/trawl standpoint, the survey timing probably obscured any other inherent sources of error.

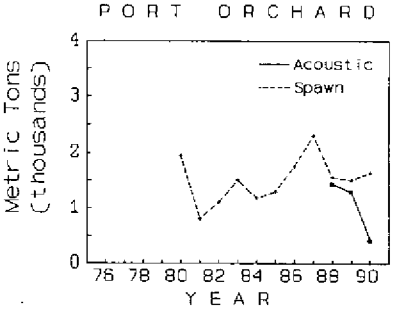

Figure 5. Peak spawner biomass for hydroacoustic/trawl (ACOUSTIC), and spawning ground surveys (SPAWN), for Port Orchard, 1980-90.

Weekly spawn surveys, compared to twice weekly in the Strait of Georgia, may have caused a tendency towards underestimation for this method. The frequency of spawning ground surveys was shown to be significant, in the Strait of Georgia and other areas of Puget Sound, due primarily to bird predation on the deposited eggs (Palsson, 1984; O'Toole, 1989). However, egg deposition intensities for Discovery Bay, northern Hood Canal and Port Orchard tended to be in the lower range of the "very light" category. It is thought that applying a conversion factor that encompasses such a wide range of egg layers may inflate spawner escapement estimates for these areas, and therefore, balance out the potential underestimation caused by survey frequency.

While the overall trend displayed a declining biomass in the Strait of Georgia, and Discovery Bay, the areas of northern Hood Canal, and Port Orchard showed high variations in their herring population sizes,with no overall trends.

Sources Of Error

Heretofore, this paper has addressed only two possible sources of error that were common to both assessment techniques, conversion factors and survey frequency. However, inherent in each method was a myriad of forces all acting perturbedly on the biomass estimations. To give some examples, prior to 1979, the acoustics unit used a modified commercial sounder with a "non-linear" receiver function, thus low and high density signals were not equally represented. Data before 1979 could not be corrected because the nonlinearity was not constant. Sometime, between 1981 - 1983, an undetected change in the calibration oscillator preamplifier took place which resulted in approximately 20% overestimation of the biomass. Unfortunately, the timing of the change could not be accurately determined. In many of the spawn surveys through the years, bad weather caused major delays, hence decreasing escapement estimates. Spawning ground surveys conducted by other agencies tended to not be consistent with WDF standards. These are some of the significant occurrences I found in the data "archives". Unfortunately, the data was unable to be adjusted or the variance measured. Below is a compilation of what I perceived to be the inherent problems that contributed the most variability to each of the methods, listing those already discussed. They are not presented in any order of significance.

Hydroacoustic/trawl

> Calibration errors. The acoustic accuracy of the 1981 to 1983 data was in question because of calibration inconsistencies discovered at the end of the 1983 season. These errors, if constant, would have resulted in approximately 20% overestimation of the biomass. The data for 1981, 1982 and 1983 seasons was not adjusted however, since it was unknown exactly when the inconsistencies arose and to what magnitude. Very rigid standards for system calibrations were implemented after this occurrence.

> The target strength scaling factor. The -33 dB/kg that was used to convert echo signal returns to nekton biomass was determined by trawl work in the early 1970's. This value may not have been correct and the effect may have been exacerbated by the decrease in herring mean length. Target strength analysis was incorporated into the regular stock assessment surveys in 1990.

> Survey timing in areas such as Discovery Bay, northern Hood Canal, Port Orchard, and others not covered in this paper, may miss the peak, prespawner buildup when only 1 or 2 surveys are scheduled for the entire season (Gonyea, 1985).

> Fish distribution. Patchiness or non-contiguous distribution of herring schools may have been missed entirely (Lemberg, 1978). Sometimes, the herring patches formed such small, densely packed schools that they saturated acoustic gear and avoided midwater trawl sampling. There was always a potential for species composition to be skewed by non-clupeids on the perimeter of herring schools

> There was a potential bias in the apportionment of the trawl data due to selectivity of the net, sample size, and the number of samples needed to accurately estimate age, maturity, and species composition (Kimura, 1984; Schweigert and Sibert, 1983). Significant sampling changes were made in 1979 from the four panel trawl net with a 6.1m x 6.1m mouth opening, to the much faster Nor'Eastern rope trawl with a 10m x 15m mouth opening. Bigger, more efficient trawl doors were used from

1986 on. Changes in chartered fishing vessels, towing at different speeds have also added to the potential for variability from year to year. To address some of the biases, the acoustic unit has standardized the net, the vessel requirements and adopted 5 year vessel contracts in efforts to reduce sample variabilities due to trawl gear.

Spawning ground escapement surveys:

> Spawn deposition that was patchy or small in area had the potential to be missed entirely during the survey. Spawn depositions that were not homogeneous in intensity (number of egg layers) may have had the wrong intensity applied over an area (Meyers and Adair, 1978, Haegele et al., 1979, Hourston et al., 1972, Humphreys and Haegele, 1976).

> There was a subjective evaluation of egg deposition intensities. Although definitive guidelines were provided for determining egg deposition intensities, it was still a subjective decision to the "overall" intensity, i.e. taking into account the different intensities on the various substrates (Humphreys and Haegele, 1976).

> The conversion factors used to convert lineal distance of an egg deposition intensity to biomass, were based on populations predominately composed of larger sized individuals (Meyer and Adair, 1978). When the mean length decreased in these populations, the conversion factors may have affected the escapement. These factors have also been shown to be different for different areas of Puget Sound (Palsson, 1984).

> The frequency of surveys in a given area was shown to affect cumulative biomass (O'Toole, 1989). It has been documented that 34% to 52% egg loss per day can occur due to bird predation in the Strait of Georgia area (Palsson, 1984). Ideally, surveys would have been conducted twice weekly in all areas to reduce the possibility of severe egg loss, and hence decreased intensity factors. Weather, aside from delaying or hampering surveys, affected intensity by ripping up egg laden, nearshore vegetation, thus reducing or even eliminating spawn deposition (Meyer and Adair, 1978).

> For each of the intensity conversion factors there was an extremely high variability associated with the wide range for number of egg layers within a given intensity (Humphreys and Haegele, 1976, O'Toole, pers. comm., 1990). For example, "very light" deposition was defined as 1 to 50 eggs per square inch (Stick, 1990). "Heavy" deposition was equivalent to 500 to 1000 eggs per square inch.

> Variability of vegetation areas throughout Washington state. Different spawning grounds had denser or wider bands of marine vegetation, however, the conversion factors were based on a lineal distance only, and were without regard to vegetation density or width (Hourston et al., 1972; O'Toole, pers. comm., 1990).

CONCLUSION

The preceding data have been presented to compare the herring spawner biomass estimates of two vastly different methods of herring stock assessment, conducted by different divisions within Washington Department of Fisheries. Hydroacoustic/trawl and spawning ground escapement estimates have been used separately and in conjunction with one another by WDF since the mid 1970's for herring stock assessment in several areas throughout Puget Sound. In the Strait of Georgia, Discovery Bay, northern Hood Canal and Port Orchard, both methods of stock assessment were employed. In all but Discovery Bay, the two assessment methods were combined with catch records for in season management of sac-roe and/or impounded spawn-on-kelp fisheries. While the peak spawner abundance determined from the acoustic/trawl was an instantaneous view in time of the population in its peak prespawning holding area, the spawning ground escapement surveys were the end-of-the-season, cumulative totals for the abundance of herring that spawned on the beaches.

The formidable list of sources of error for each of the methods, and the changes in methodology inherent in the evolution of hydroacoustics, made direct comparisons of the data subjective. Percent differences from acoustic to spawning ground estimates were given in Table 1 to aid in comparing the data. I have arbitrarily assigned a difference of 20% as the threshold of agreement versus non-agreement between the two methods. Using this guideline for 30 comparable data points, 53% were in non-agreement and 47% in agreement.

To improve accuracy and further the advancement towards absolute values for herring stock assessment, the hydroacoustic/trawl could increase its precision with focus on target strength evaluation to provide updated scaling factors. Very rigid guidelines for system calibrations were implemented after inconsistencies were found in 1983 that affected all areas. Standardization of trawl gear and vessels was incorporated in 1986 to reduce trawl variabilities. In areas where the need for absolute values is shown, an increase in survey effort is required.

To improve the spawning ground escapement estimates, end-of-season adjustments for shifts in fecundity ratios may be required, however, refining the intensity categories and taking vegetation widths into account would be much more significant. As in the acoustic/trawl method, where the need is shown for more accuracy, an increase in survey effort is also required.

For analysis such as this one, and for the resource managers that must predict the stock sizes and quotas based on past years data, comparable variance of the two techniques would be extremely useful.

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Proc. Int. Herring Symposium
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Stock Structure and Classification of Herring (*Clupea harengus* L.) in the North Sea, Skagerrak/Kattegat and Western Baltic Based on a Multivariate Analysis of Morphometric and Meristic Characters

A. Johannessen
University of Bergen
Bergen, Norway
T. Jørgensen
Institute of Marine Research
Bergen, Norway

ABSTRACT

Samples of spawning herring were collected from spawning sites in the western Baltic, Skagerrak-Kattegat, the North Sea and the west coast of Norway. For each specimen a total of 15 morphometric and 4 meristic characters were measured. The morphometric measurements were corrected for differences in fish length using a linear relationship.

Mahalanobis D^2 was used as a measure of phenetic distance between spawning aggregations, and the phenetic relationship between them was analysed using UPGMA clustering of the phenetic distances. Four main clusters were formed: Baltic spring spawners, Skagerrak-Kattegat spring spawners, North Sea autumn spawners, and Norwegian spring spawners (Atlanto-scandian herring). These clusters correspond to the presently used management units.

From a management point of view a method is needed to distinguish between North Sea autumn spawners and Baltic spring spawners in catches from the north-eastern North Sea and Skagerrak/Kattegat. A linear discriminant analysis based on the measured characters showed a classification success of 90-95%. The characters were rated according to their separating power, and classification functions were constructed. The constructed classification functions were then applied to samples of unknown composition, caught in areas of mixed distribution. Mean vertebrae numbers (VS) were calculated for each subgroup and corresponded well with the characteristic values for the two management units. An attempt to distinguish on an individual basis between herring from all four clusters was unsuccessful.

INTRODUCTION

A number of different techniques have been used in an effort to establish the stock structure of herring. Analyses based on morphometric and meristic characters, supported by information on spawning areas, distribution patterns and tag return data, have generally shown a great complexity in population (racial) structure, and generally it is concluded that several stocks exist (Blaxter and Holliday, 1963; Parrish and Saville, 1965; Harden Jones, 1970, Saville and Bailey, 1980). The present division of herring in the north-eastern Atlantic into management units are largely based on the stock structure derived from morpometric and meristic studies. Length frequency analysis combined with mean vertebrae counts (VS) are used to separate the components of spring and autumn spawners in catches from the North Sea, Skagerrak and Kattegat (Anon., 1988, 1989).

Biochemical studies based on analyses of protein polymorphism have, however, shown herring to be relatively homogeneous over large geographic areas (Grant, 1984; Grant and Utter, 1984; Ryman et al., 1984; King et al., 1987) and do not support the conclusions from the meristic studies. This result has been interpreted as an indication that genetic studies are not well suited for analysing stock structure of herring (Blaxter and Hunter, 1982; Cushing 1985). Smith and Jamieson (1986) on the other hand question the concept of discrete stocks. Herring from different management units are often harvested in non-reproductive areas where they intermingle, thus making the allocation of catches to the various management units difficult for the management bodies. Under such circumstances the smaller groups may become overexploited. Methods to separate catches of mixed origin are therefore needed.

Although it is usually possible to show statistically significant differences between spawning groups for mean values of most morphometric and meristic characters, the variation within groups is generally of the same order as that between groups (Ryman et al.,1984). This fact makes it impossible to classify a specimen in a mixed sample as belonging to a specific spawning group on the basis of individual characters. Success has, however, been reported on the use of multivariate analysis of morphometric and meristic characters, both to establish the stock structure of fish (Meng and Stocker, 1984; Sharp et al., 1978; Misra and Carscadden, 1987) and for the classification of mixed samples (Reddin, 1986; Reddin et al., 1988). Meristic characters may be modified by environmental factors (Hempel and Blaxter, 1961; Lindsey, 1988), and some morphometric characters are likely to vary with the condition of the fish.

This paper gives the preliminary results of a study of stock structure of herring in the Skagerrak/Kattegat and adjacent waters, based on a multivariate analysis of 15 morphometric and 4 meristic characters. Linear discriminant analysis was used in an effort to distinguish on an individual basis between herring from the different management units. The measured characters were also rated according to their separating power and classification functions were constructed and applied to samples of unknown origin.

MATERIAL AND METHODS

Data

Samples were collected from spawning aggregations of herring from from 4 management units; the western Baltic spring spawners, spring spawners in the Skagerrak/Kattegat (including two samples of coastal spring spawners from the west coast of Norway), North Sea autumn spawners and Norwegian spring spawners (Atlanto-Scandian herring). Sampling locations and times are listed in Table 1 (see also Fig. 1). The fish were frozen and later thawed prior to examination in the laboratory. For each of the 2653 herring measured, wet weight (in grams), standard length, sex and maturity stage were recorded as well as the values of 15 morphometric and 4 meristic characters (Table 2). Measurements of morphometric characters (including standard length) were made with calipers to the nearest 0.1 mm. Counts of vertebrae included the urostyle. All fish included in the analysis were in maturity stages 4 to 6 (running or close to spawning).

Statistical Analysis

Analyses of morphometric data have frequently been unsatisfactory due to the confounding effect of the varying size of specimens and also due to the large overlapping of measurements (Misra 1985). The morphometric characters in this study were generally linearly related to the standard length (r^2=0.7-0.9). A linear regression was consequently used to correct for length effects (Meng and Stocker, 1984). The morphometric measurements were then standardized to the overall mean length of the fish used in the study (Thorpe, 1976). None of the meristic characters were correlated with standard length.

Similarity of samples was quantified using the generalized distance of Mahalanobis (Mahalanobis D^2), a distance coefficient with the characteristic that each character adds to the statistic only to the extent that it is uncorrelated with characters previously considered in the analysis (Blackith and Reyment, 1971). Mahalanobis D^2 was subsequently converted to percentage overlap, a measure of the extent to which groups share identical characters (Mais 1972, Royce 1963). The matrix of D^2-values was used to construct a phenogram illustrating the relationship between samples, using the unweighted pair group method with arithmetic mean averages (UPGMA) (Sneath and Sokal, 1973).

A nested ANOVA was used to identify characters with a comparatively large variance component between spawning groups and thus potentially useful for discriminating between them. Two-way ANOVAs were used to study variance between year classes and between readers. Linear discriminant function analysis (LDF) was used to construct a function of the measured characters that best separate the spawning groups. Only characters with at least 10% of the total variance between spawning groups were included in the LDF. The characters were also rated according to their separating power. Population membership

Table 1. Details of samples.

	Position	Date	Gear	No. fish
Reference samples				
Warnemünde	N 54°15′ E 12°00′	2 March 1989	Trawl	98
Darsser Ort	N 54°30′ E 12°20′	31 March 1989	Trawl	100
Faxebugt	N 55°09′ E 12°02′	Spring 1988	Gill net	100
Kattegat-I	N 58°16′ E 10°57′	20 Mar 1989	Gill net	23
Kattegat-II	N 56°22′ E 12°18′	4 Apr 1989	Trawl	98
Limfjord	N 56°34′ E 08°32′	4 May 1988	Trap net	100
Skjeberg	N 59°09′ E 11°07′	21 Feb 1989	Gill net	100
Horten	N 59°26′ E 10°30′	20 Mar 1989	Gill net	86
Langesund	N 59°00′ E 11°15′	4 Apr 1989	Gill net	78
Risør	N 58°44′ E 09°12′	3 June 1989	Gill net	79
Arendal	N 58°28′ E 08°52′	3 June 1989	Gill net	60
Kristiansand-I	N 58°06′ E 08°13′	24 Mar 1988	Gill net	78
Kristiansand-II	N 58°06′ E 08°13′	3 June 1989	Gill net	67
Kristiansand-III	N 58°06′ E 08°13′	14 Mar 1990	Gill net	71
Karmøy	N 59°19′ E 05°40′	30 Mar 1989	Gill net	100
Bjoroy	N 60°18′ E 05°15′	12 Nov 1989	Gill net	61
Skogsvågen	N 60°17′ E 05°15′	27 Mar 1990	Gill net	56
Runde	N 62°24′ E 05°38′	14.Mar 1989	Pelagic trawl	83
South Bank	N 57°48′ W 01°37′	24 Aug 1988	Purse seine	100
Troup Head	N 57°44′ W 02°16′	4 Sept 1988	Purse seine	100
Turbot Bank	N 57°26′ W 00°27′	18 Aug 1988	Purse seine	98
Whitby	N 54°27′ W 00°23′	30 Aug 1988	Purse seine	100
Scarborough	N 54°18′ W 00°15′	Sept 1988	Purse seine	100
Channel	N 50°08′ W 00°28′	Dec 1988	Trawl	100
Samples of unknown composition				
St. 20469	N 58°36′ E 05°10′	17 July 1989	Pelagic trawl	100
St. 20475	N 59°40′ E 04°05′	18 July 1989	Pelagic trawl	63
St. 20476	N 59°39′ E 03°23′	18 July 1989	Pelagic trawl	87
St. 20121	N 58°45′ E 02°30′	2 Sept 1989	Purse seine	70
St. 20122	N 59°15′ E 03°30′	23 Sept 1989	Purse seine	100

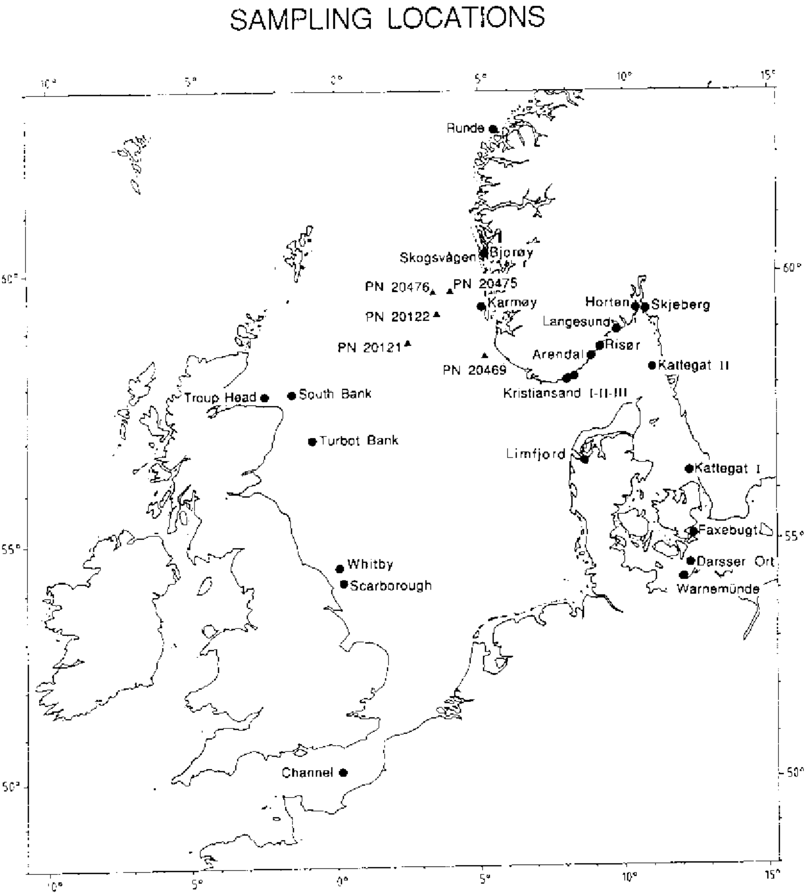

Figure 1. Geographic location of the sampling sites for the reference samples and for the samples of unknown composition.

Table 2. The morphometric and meristic characters measured and the acronyms used in the analysis (as defined by Meng and Stocker (1984)).

morphometric		
1	CHEEKL	Distance between orbit and preopercle
2	DORCAUD	Insertion of dorsal fin to CMP*
3	HEADL	Head length
4	HEADW	Head width
5	WINORB	Inorbital width
6	WMAX	Maxillary width
7	OCCIPL	Occipital length
8	PECCAUD	Insertion of pectoral fin to CMP*
9	PECDOR	Insertion of pectoral to insertion of dorsal fin
10	PECTW	Distance between pectoral fin insertion
11	PEDUNC	Peduncle height
12	PELCAUD	Insertion of pelvic fin to CMP*
13	SNOUTDOR	Tip of snout to insertion of dorsal fin
14	SNOUTL	Snout length
15	SNOUTM	Maxillary length
meristic		
1	ANALFIN	Number of anal fin rays
2	GILL	Number og lower gill rakers
3	PECTFIN	Number of pectoral fin rays
4	VERT	Vertebral count

* CMP = caudal measuring point

probabilities were calculated from the results of the LDF and used to estimate classification success applying the jackknife procedure (Lachenbruch, 1975). Program P7M of the BMDP statistical software package (Dixon, 1985) was used for the linear discriminant function analysis.

RESULTS

Relationship between Spawning Groups.

The multivariate analysis based on Mahalanobis D^2 showed significant pairwise differences between all samples ($p < 0.01$), but percentage overlap varied considerably between samples, from less than 1% to almost 70% (Table 3). The phenotypic relationship between the samples is illustrated by the dendrogram derived from the cluster analysis of the Mahalanobis D^2 values (Fig. 2). Four main clusters were formed, closely corresponding to the present management units: western Baltic spring spawners, Skagerrak-Kattegat spring spawners (including the Bjorøy and Skogsvaag samples), North Sea autumn spawners, and Norwegian spring spawners. Within each cluster phenetic distances generally increased with increasing geographic distance. The phenogram also indicated that both the Baltic and central North Sea groups are relatively homogeneous, compared to the phenetic distance between them. The Skagerrak - Kattegat group is phenetically more similar to the Baltic spring spawners, than to the North Sea autumn spawners. Although the two samples of Norwegian spring spawners formed one cluster, they are phenetically very dissimilar (approximately 5% overlap) compared to the other groups.

Sources of Variation in The Measured Characters.

A nested ANOVA based on the three samples from the Baltic and the five samples from the central North Sea, demonstrated that although there are significant differences between spawning groups for the measured characters, the larger part of the variance is within samples (Table 4). Partition of the variance also showed that less than 10% of the variance is between samples from the same spawning group (with the exception of PECTFIN for which it was 12%). Only three characters (PEDUNC, PECDOR, and SNOUTDOR) had more than 50% of the total variance between spawning groups. The variance between fish within the same sample accounted for between 38% and 98% (average 70.8%) of the total variance.

Variances in the measured characters between year classes were analysed with a two-way ANOVA, using the data from the central North Sea for which the 1983 and 1984 year classes were represented by a sufficient large number of specimens. With the exception of the vertebrae count, no significant differences between year classes were found for any of the measured characters (Table 5).

To assess how well defined the characters are, two tests were designed; one to study the variance between readers, and one to study repeated measurements by the same reader. The 15 morphometric characters of 5 fish were read by three different readers. Two of the readers measured

Table 3. Statistical separation between samples as estimated by the Mahalanobis D^2 . Percentage overlap is given in parenthesis.

	Warnemünde	Darsser Ort	Faxebugt	Kattegat I	Kattegat II	Limfjorden	Skjeberg
Warnemünde	-						
Darsser Ort	1.590 (52.9)	-					
Faxebugt	5.396 (26.6)	2.937 (39.1)					
Kattegat I	6.157 (21.5)	7.756 (16.4)	11.185 (9.5)	-			
Kattegat II	6.758 (19.4)	9.231 (12.8)	14.165 (9.5)	2.081 (47.1)			
Limfjorden	7.521 (17.0)	9.252 (12.8)	11.270 (9.3)	2.630 (41.1)	2.360 (44.2)	-	
Skjeberg	7.847 (16.1)	10.890 (9.9)	14.848 (5.6)	2.839 (40.0)	1.182 (58.6)	2.639 (41.7)	-
Horten	7.139 (18.2)	10.978 (9.8)	14.434 (5.7)	1.426 (55.1)	767 (66.6)	2.821 (40.2)	1.086 (60.2)
Langesund	6.484 (20.3)	7.826 (17.8)	13.495 (6.6)	3.539 (34.7)	1.549 (53.4)	4.393 (29.5)	1.960 (48.4)
Riser	*2.249 (45.3)	2.074 (47.2)	5.729 (23.1)	2.676 (41.3)	1.959 (48.4)	3.217 (37.0)	4.063 (31.6)
Arendal	*3.883 (32.5)	4.633 (28.2)	10.371 (10.7)	2.356 (44.3)	3.468 (35.2)	5.015 (26.3)	5.149 (25.6)
Kr.sand 1	5.456 (24.4)	7.271 (17.8)	11.494 (9.0)	1.658 (52.0)	1.575 (53.1)	3.602 (34.3)	2.280 (45.0)
Kr.sand 2	13.879 (6.2)	18.451 (3.2)	23.260 (1.6)	13.142 (7.0)	4.930 (27.1)	16.524 (4.4)	5.946 (22.3)
Karmøy	24.268 (1.4)	27.462 (0.9)	33.308 (0.4)	31.406 (0.5)	14.691 (5.3)	25.307 (1.2)	10.573 (10.4)
Bjorøy	15.719 (4.8)	18.735 (3.0)	20.071 (2.5)	17.196 (3.8)	11.875 (8.5)	17.475 (3.7)	5.558 (23.8)
Skogsvåg	11.725 (8.7)	11.680 (8.7)	14.703 (5.5)	13.223 (6.9)	5.128 (25.8)	14.054 (5.4)	6.807 (19.2)
Runde	38.297 (0.2)	33.005 (0.4)	35.250 (0.3)	34.955 (0.3)	22.539 (1.8)	46.813 (0.1)	24.715 (1.4)
South Bank	11.858 (8.5)	16.177 (4.4)	17.324 (3.8)	25.241 (1.2)	11.545 (8.9)	14.409 (5.8)	6.659 (19.7)
Troup Head	17.212 (3.8)	22.727 (1.7)	18.892 (3.0)	27.817 (0.8)	14.753 (5.5)	18.346 (4.3)	8.310 (15.0)
Turbot Bank	15.185 (5.1)	18.957 (2.9)	17.860 (3.5)	24.263 (1.4)	9.468 (12.4)	14.881 (5.4)	7.467 (17.2)
Whitby	15.103 (5.2)	20.627 (2.3)	19.252 (2.8)	21.988 (1.9)	10.806 (10.0)	16.493 (4.2)	7.896 (16.0)
Scarbor	14.075 (6.1)	21.173 (2.1)	20.179 (2.5)	21.799 (2.0)	12.620 (7.6)	16.495 (4.2)	10.080 (11.3)
Channel	17.281 (3.8)	17.347 (3.7)	21.860 (1.9)	26.896 (1.0)	15.434 (5.0)	24.130 (1.4)	13.323 (6.8)

Table 3. Continued

	Horten	Langesund	Riser	Arendal	Kr.sand 1	Kr.sand 2	Karmøy
Horten	-						
Langesund	1.258 (57.5)	-					
Riser	*3.545 (34.7)	3.409 (35.6)	-				
Arendal	*3.406 (35.6)	3.736 (33.4)	961 (62.4)	-			
Kr.sand 1	1.406 (55.4)	1.928 (48.8)	1.670 (51.8)	1.366 (55.9)	-		
Kr.sand 2	4.895 (26.9)	7.387 (17.4)	2.797 (40.3)	5.738 (23.1)	4.104 (31.1)		
Karmøy	10.452 (10.6)	14.317 (6.3)	14.334 (5.8)	16.816 (4.0)	7.387 (17.4)	12.056 (8.1)	-
Bjorøy	5.600 (23.7)	7.155 (18.1)	7.653 (16.7)	8.602 (14.1)	5.198 (25.4)	5.281 (25.3)	11.363 (9.2)
Skogsvåg	5.135 (25.7)	7.082 (18.3)	3.980 (31.9)	6.646 (19.7)	5.163 (25.6)	3.309 (36.3)	8.167 (15.3)
Runde	19.428 (2.8)	29.530 (0.7)	24.503 (1.3)	28.051 (0.8)	19.890 (2.6)	20.179 (2.5)	15.639 (4.8)
South Bank	5.521 (24.0)	7.241 (17.9)	11.019 (9.7)	15.756 (4.7)	6.446 (20.4)	10.747 (10.1)	12.365 (7.9)
Troup Head	6.720 (19.5)	10.564 (10.4)	12.988 (7.1)	21.097 (2.2)	8.147 (15.4)	11.674 (8.5)	17.513 (3.6)
Turbot Bank	5.039 (26.2)	7.567 (16.9)	11.073 (9.6)	19.170 (2.9)	8.751 (13.9)	11.814 (8.6)	14.975 (5.3)
Whitby	5.983 (22.0)	8.670 (14.1)	12.480 (7.7)	20.927 (2.2)	8.740 (13.9)	12.159 (8.1)	13.137 (7.0)
Scarbor.	7.025 (18.5)	10.284 (10.9)	12.342 (7.9)	17.488 (3.7)	7.595 (16.8)	9.666 (12.0)	13.504 (6.6)
Channel	10.475 (10.6)	13.860 (6.3)	16.598 (4.2)	25.136 (1.2)	11.318 (9.3)	15.016 (5.3)	19.815 (2.6)

Table 3. Continued

	Bjorøy	Skogsvåg	Runde	South Bank	Troup Head	Turbot Bank	Whitby	Scarbor.	Channel
Bjorøy									
Skogsvåg	4.175 (30.7)	-							
Runde	17.358 (3.7)	17.435 (3.7)	-						
South Bank	8.296 (15.0)	11.696 (8.7)	25.821 (1.1)	-					
Troup Head	7.453 (17.2)	14.787 (5.4)	24.302 (1.4)	3.176 (37.3)	-				
Turbot Bank	7.699 (16.6)	10.352 (10.7)	22.994 (1.6)	3.121 (37.7)	1.719 (51.2)	-			
Whitby	7.321 (17.6)	10.810 (10.0)	20.271 (2.4)	3.164 (37.5)	2.438 (43.5)	886 (63.8)	-		
Scarbor.	7.167 (18.1)	9.849 (11.7)	18.212 (3.3)	1.183 (58.6)	2.782 (40.4)	2.579 (42.6)	1.874 (49.4)	-	
Channel	11.603 (8.9)	15.442 (4.9)	26.946 (1.0)	6.175 (21.4)	7.470 (17.2)	5.879 (22.5)	4.499 (28.9)	5.508 (24.1)	

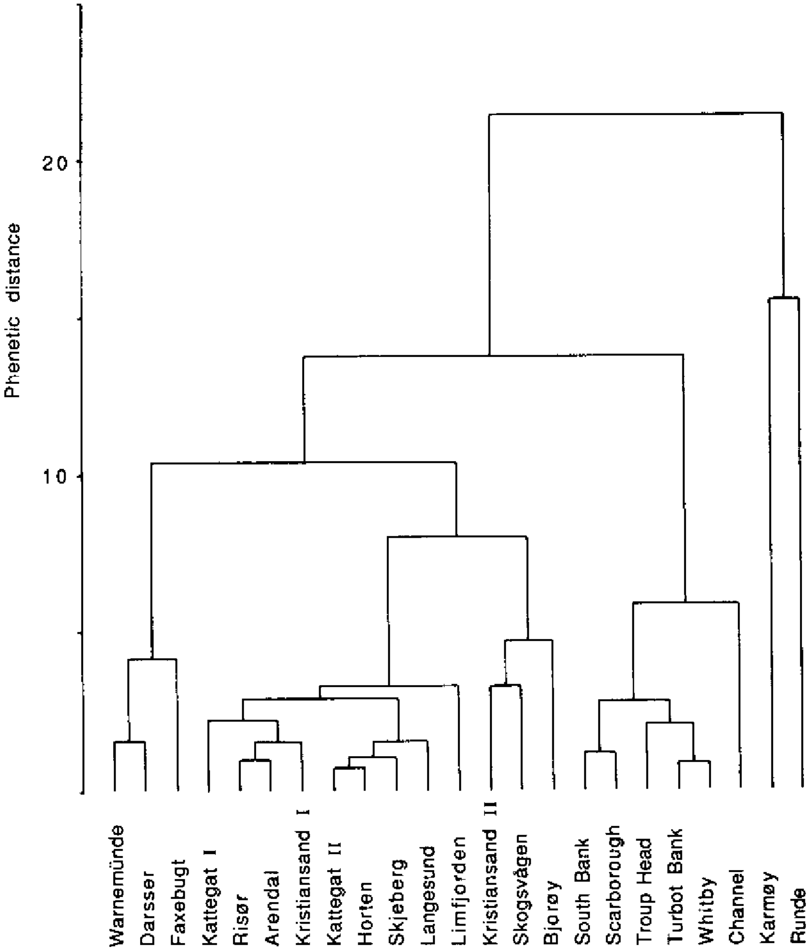

Figure 2. Dendrogram constructed using Mahalanobis D^2 as a measure of the phenetic distance.

Table 4. The partition of variation in each measured character as estimated by a nested ANOVA for the three levels: spawning group, sample within spawning group and individual fish within sample. The calculations are based on the 3 samples from the Baltic and the 6 from the North Sea.

	Variance component		
Character	Among spawning group	Samples within spawning group	Within samples
Pectw	19.4	1.8	78.8
Snoutmax	27.4	2.1	70.5
Wmax	0.0	8.6	91.4
Headw	13.4	2.8	83.7
Pedunc	56.6	5.2	38.2
Dorcaud	32.8	1.9	65.3
Peccaud	0.0	1.8	98.1
Pecdor	55.4	3.4	41.1
Pelcaud	1.9	1.3	96.8
winorb	15.9	10.0	74.0
Snoutdor	56.7	1.5	41.8
Cheekl	24.1	6.6	69.2
Headl	29.0	2.1	68.9
Occidl	21.0	7.3	71.7
Snoutl	25.0	9.7	65.3
Gill	7.3	7.0	85.7
Vertebrae	29.3	1.0	69.7
Pectfin	12.5	12.1	75.4
Analfin	34.7	6.4	59.0

Table 5. Results of a two-way ANOVA of measured characters with respect to sample and yearclass. The analysis was based on the samples from Scarborough, Whitby, and Turbot Bank for each of which two yearclasses only (1983 and 1984) were represented by a sufficient number of specimen. Morphometric measurements had been corrected for differences in fish length before the analysis was run.

Character	Source of variation	df	Mean square	F
PECTW	Sample(S)	2	440.21	3.98 *
	Yearclass(Y)	1	3.11	0.03
	SxY	2	122.45	1.11
	Error	220	110.48	
SNOUTM	Sample(S)	2	47.01	0.13
	Yearclass(Y)	1	93.77	0.26
	SxY	2	225.35	0.62
	Error	220	362.32	
WMAX	Sample(S)	2	122.02	12.59 **
	Yearclass(Y)	1	1.31	0.14
	SxY	2	11.83	1.22
	Error	220	9.69	
HEADW	Sample(S)	2	462.65	2.26
	Yearclass(Y)	1	134.93	0.66
	SxY	2	76.37	0.37
	Error	220	205.03	
PEDUNC	Sample(S)	2	51.50	2.03
	Yearclass(Y)	1	0.09	<0.01
	SxY	2	6.13	0.24
	Error	220	25.42	
DORCAUD	Sample(S)	2	587.02	1.17
	Yearclass(Y)	1	288.08	0.58
	SxY	2	1849.32	3.69 *
	Error	220	500.60	
PECCAUD	Sample(S)	2	6070.51	2.85
	Yearclass(Y)	1	1027.88	0.48
	SxY	2	623.46	0.29
	Error	220	2129.22	
PECDOR	Sample(S)	2	3283.80	7.88 **
	Yearclass(Y)	1	4.04	0.01
	SxY	2	470.06	1.13
	Error	220	416.63	
PELCAUD	Sample(S)	2	482.89	0.77
	Yearclass(Y)	1	810.12	1.29
	SxY	2	411.85	0.66
	Error	220	627.65	
WINORB	Sample(S)	2	82.26	5.94 **
	Yearclass(Y)	1	13.53	0.98
	SxY	2	19.06	1.38
	Error	220	13.85	

Table 5. Continued.

SNOUTDOR	Sample(S)	2	730.35	1.20	
	Yearclass(Y)	1	109.16	0.18	
	SxY	2	799.23	1.31	
	Error	220	609.84		
CHEEKL	Sample(S)	2	41.95	0.98	
	Yearclass(Y)	1	4.26	0.10	
	SxY	2	50.06	1.17	
	Error	220	42.95		
HEADL	Sample(S)	2	14.31	0.16	
	Yearclass(Y)	1	43.72	0.49	
	SxY	2	212.48	2.37	
	Error	220	89.82		
OCCIDL	Sample(S)	2	183.55	2.51	
	Yearclass(Y)	1	134.67	1.84	
	SxY	2	67.62	0.92	
	Error	220	73.24		
SNOUTL	Sample(S)	2	802.61	13.93	**
	Yearclass(Y)	1	0.99	0.02	
	SxY	2	30.80	0.53	
	Error	220	57.61		
GILLRAKERS	Sample(S)	2	0.99	0.47	
	Yearclass(Y)	1	<0.01	<0.01	
	SxY	2	4.36	2.09	
	Error	220	2.09		
VERTEBRAE	Sample(S)	2	1.22	2.52	
	Yearclass(Y)	1	3.09	6.40	*
	SxY	2	0.06	0.13	
	Error	220	0.48		
PECTFIN	Sample(S)	2	0.04	0.08	
	Yearclass(Y)	1	0.03	0.07	
	SxY	2	1.07	2.27	
	Error	220	0.47		
ANALFIN	Sample(S)	2	0.24	0.38	
	Fish(F)	1	0.64	1.00	
	SxY	2	0.13	0.20	
	Error	220	0.64		

each character three times and the third reader measured them twice. The individual measurements were independent. The results showed significant differences between readers for 10 of the 15 morphometric characters (Table 6). One reader also measured each of the 15 morphometric characters 37 times for the same specimen. The coefficient of variation (CV) between the repeated measurements was large, ranging between 35% and 220% (Table 7).

Classification of Samples.

A linear discriminant analysis was performed to see whether a linear function of the measured characters could be used to discriminate between herring from the central North Sea and the southwestern Baltic. Only the 15 characters in Table 4 for which at least 10% of the variance was between spawning groups, were used. The jackknife verification procedure showed that 95% of the Baltic and 96% of the central North Sea herring were correctly grouped (Table 8). Of the herring sample from the Channel 94% was classified as North Sea herring. The ranking of characters in decreasing order of separating power is shown in Fig. 3. The three best characters were SNOUTDOR, PEDUNC, and ANALFIN.

When the Skagerrak-Kattegat group were introduced as a third group in the analysis, the classification success dropped to approximately 65%. An attempt to classify herring from the North Sea, Baltic and Norwegian spring spawners indicated a success of 80 - 90%.

The classification functions established to separate the central North Sea and the Baltic groups were also applied to five samples of herring of unknown composition collected from the northeastern North Sea in late summer - early autumn (Table 8). Two samples (PN20469 and PN20475) were found to be mainly Baltic spring spawners (87% and 70% respectively). For the remaining samples, North Sea autumn spawners made up the bulk of the samples (70%, 86% and 63%). The estimated mean VS for each sample showed values characteristic for each of the management units, thus indicating successful separation (Table 9).

DISCUSSION

Quality of Data.

The repeated measurements of the morphometric characters showed large values for the coefficients of variation (up to 220%). The CV's are, however, probably overestimated, because the extensive handling and softening of the specimen likely increased the variance of these measurements, compared to those used in the main study. This assumption is supported by the low values of CV given by Meng and Stocker (1984) for the same set of characters. The same effect may have contributed to the observed significant differences between measurements of the same fish by different readers. Nevertheless, it is indicated that the added variance due to these factors may be important, and that care must be taken when defining and measuring characters.

Table 6. Summary results of a two-way ANOVA for repeated measurements of the morphometric characters with respect to fish and reader Morphometric measurements had been corrected for differences in fish length.

Character	Source of variation	df	Mean square	F
PECTW	Reader(R)	2	0.66	0.03
	Fish(F)	4	277.84	10.57 **
	RxF	8	38.58	1.47
	Error	25	26.28	
SNOUTM	Reader(R)	2	23.15	5.46 *
	Fish(F)	4	76.76	18.10 **
	RxF	8	3.79	0.89
	Error	25	4.24	
WMAX	Reader(R)	2	43.77	1.97
	Fish(F)	4	6.47	0.29
	RxF	8	6.41	0.29
	Error	25	22.24	
HEADW	Reader(R)	2	101.22	5.93 **
	Fish(F)	4	32.09	1.88
	RxF	8	34.77	2.04
	Error	25	2.04	
PEDUNC	Reader(R)	2	312.48	19.89 **
	Fish(F)	4	79.24	5.04 **
	RxF	8	22.49	1.43
	Error	25	15.71	
DORCAUD	Reader(R)	2	513.02	8.28 **
	Fish(F)	4	2175.51	35.10 **
	RxF	8	117.36	1.89
	Error	25	61.98	
PECCAUD	Reader(R)	2	513.02	8.28 **
	Fish(F)	4	2175.51	35.10 **
	RxF	8	117.36	1.89
	Error	25	61.99	
PECDOR	Reader (R)	2	2811.63	7.80 **
	Fish(F)	4	783.75	2.17
	RxF	8	83.41	0.23
	Error	25	360.65	
PELCAUD	Reader(R)	2	863.63	2.05
	Fish(F)	4	6535.32	15.48 **
	RxF	8	437.87	1.04
	Error	25	422.22	
WINORB	Reader(R)	2	108.08	12.64 **
	Fish(F)	4	115.74	13.53 **
	RxF	8	23.91	2.79 *
	Error	25	8.55	

Table 6. Continued.

SNOUTDOR	Reader(R)	2	1223.08	11.67 **
	Fish(F)	4	2736.58	26.10 **
	RxF	8	126.76	1.21
	Error	25	104.84	
CHEEKL	Reader(R)	2	1188.22	43.72 **
	Fish(F)	4	546.01	20.09 **
	RxF	8	95.98	3.53 **
	Error	25	27.18	
HEADL	Reader(R)	2	186.61	8.58 **
	Fish(F)	4	771.83	35.50 **
	RxF	8	55.38	2.55 *
	Error	25	21.74	
OCCIDL	Reader(R)	2	6.76	3.04
	Fish(F)	4	502.82	2.26
	RxF	8	344.73	1.55
	Error	25	222.30	
SNOUTL	Reader(R)	2	20.17	0.22
	Fish(F)	4	147.38	1.61
	RxF	8	79.67	0.87
	Error	25	91.51	

Table 7. Repeated measurements of individual morphometric characters of the same fish (standard length=26.6 cm) and by the same reader. Mean and coefficient of variation(100 SE/Mean) are shown.

Morphometric character	Mean value (mm)	Coefficient of variation (CV) (%)
SNOUTDOR	141.0	73,8
PEDUNCLE	19.1	123,2
SNOUTMAX	30.9	38,4
PECDOR	90.0	135,8
SNOUTL	14.6	212,5
DORCAUD	128.4	79,1
HEADL	59.3	35,3
PECTW	13.8	162,3
WMAX	7.3	191,3
HEADW	20.9	131,3
PECCAUD	205.6	80,1
PELCAUD	116.5	77,8
WINORB	9.9	220,8
CHEEKL	22.8	93,0
OCCIDL	38.0	62,5

Table 8. Predicted group membership. The results of classification using the 15 characters listed in Table 4. for the two "learning groups" used in the discrimination analysis (the central North Sea autumn spawners and the Baltic spring spawners).

Actual group	Predicted group membership		
	Baltic	North Sea	Total
<u>Reference spawning groups:</u>			
North Sea (5 groups)	17 (3,4%)	477 (96,4%)	495
Baltic (3 groups)	278 (95,5%)	13 (4,5%)	291
Channel	6 (6,1%)	93 (93,9%)	99
<u>Samples of unknown origin:</u>			
PN 20121	21 (30,0%)	49 (70,0%)	70
PN 20122	7 (14,3%)	42 (85,7%)	49
PN 20469	87 (87,0%)	13 (13,0%)	100
PN 20475	44 (69,8%)	19 (30,2%)	63
PN 20476	32 (36,8%)	55 (63,2 %)	87

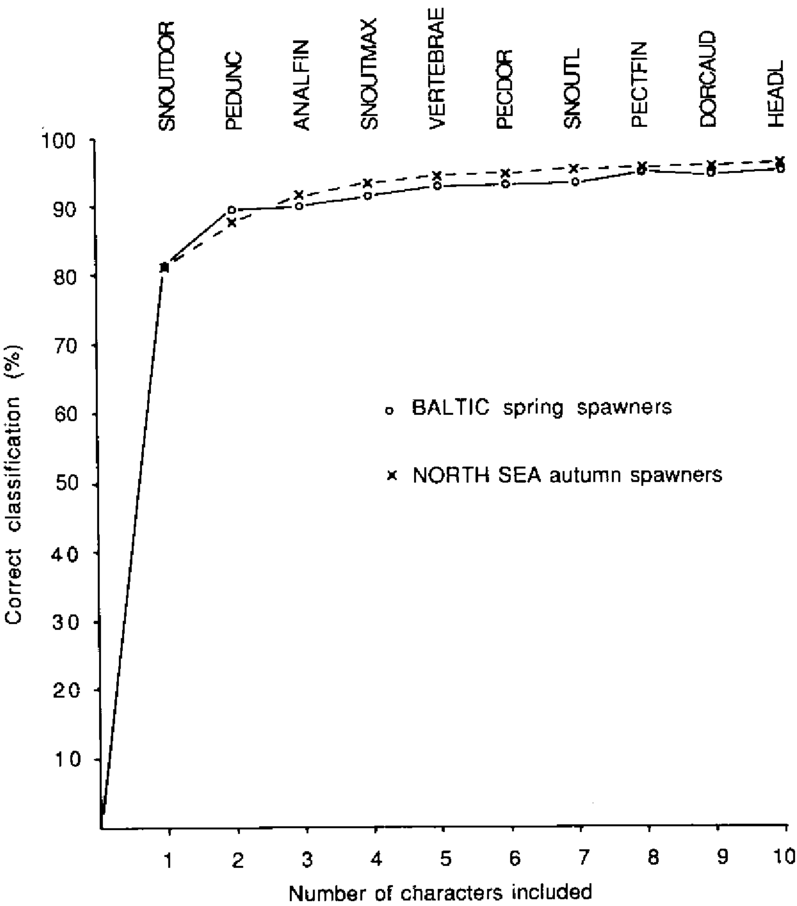

Figure 3. Percentage of each of the two selected groups (the North Sea and the Baltic samples) that were classified correctly using the jackknifed classification as a function of the nubmer of characters included in the discriminant functions. Characters were included in decreasing order of separating power.

Table 9. Estimated percentage of spring spawners and mean vertebral count for the subgroups of spring and autumn spawners.

Station no.	Sample size	Predicted proportion spring spawners	Mean vertebral count (VS)	
			spring sp.	autumn sp.
PN20121	70	30.0%	55.9	56.4
PN20122	49	14.3%	55.3	56.6
PN20469	100	87.0%	55.5	56.2
PN20475	63	69.8%	55.9	56.3
PN20476	87	36.8%	55.7	56.6

Stock Structure.

The results of the clustering of phenetic distances basically supports the present division into management units: Baltic spring spawners, North Sea autumn spawners and Norwegian spring spawners. The Skagerrak-Kattegat herring is included in the assessment of Baltic spring spawners (Anon., 1990). The phenogram also indicated some difference between the central North Sea and the Channel spawning groups (Corten, 1986). The large phenetic difference between the samples of Norwegian spring spawners from Runde and the newly recolonized spawning ground at Karmøy, suggests the substock status of these groups, but needs further investigations.

This result also indicated that the Skagerrak-Kattegat group can be divided into 3 subgroups on a regional basis: the Kattegat and the eastern Skagerrak, the western Norwegian coast of Skagerrak, and the west coast of Norway. The small Limfjord spawning group also forms a separate subgroup. The clustering of the samples "Kattegat I" and "Kristiansand II" does, however, not adhere to this general picture. Few recent studies have been made of the stock structure of herring in the Skagerrak-Kattegat. Rosenberg and Palmen (1982) identified 5 stocks of herring in the area, four of spring spawners and one of autumn spawners. The autumn spawners are now virtually extinct.

Because many morphometric and meristic characters may be environmentally modified, som authors emphazise the importance of molecular methods (Ihssen et al., 1981). Previous studies of herring in the area (Ryman et al., 1984), and analyses of mitochondrial DNA (Dahle and Eriksen, 1990) and fatty acid profiles (Grahl-Nielsen, pers.comm.) for most of the samples that were used in the phenetic analysis in the present study, have not given conclusive evidence of genetically distinct stocks.

Although modified by the environment, morphometric and meristic characters indicate reproductive isolation (and consequently stock unit identity) if the characters show differences between spawning aggregations, but not between different year classes of the same spawning group. No difference was found between two consequtive year classes from the North Sea, but more data are needed before any firm conclusion can be made regarding the stability of characters within a spawning group. The clustering in two different subgroups of the samples from Kristiansand (Krs I and II) questions the biological significance of the subgroups of Skagerrak-Kattegat spring spawners.

Separation of Groups.

With only 30% of the total variation in mean vertebrae counts between groups, this traditionally used character is not well suited to distinguish on an individual basis between herring from the North Sea autumn spawners and the Baltic spring spawners. The results from the discriminant function analysis, however, suggested that such an approach is potentially useful as a tool for separating mixtures of the two groups. With only 4-5 characters included in the discriminant function, close to 95% correct classification was achieved. The presence of herring from other groups than the two for which the discriminant functions were established, may severely bias the classification. But the abundance of Skagerrak-Kattegat spring spawners is comparatively insignificant, and Norwegian spring spawners are not present in the area of mixed distribution at the time when the Baltic spawners feed there.The classification of samples of unknown composition collected in the northeastern North Sea in late summer-early autumn, confirms the presence of appreciable quantities of Baltic spring spawners in the North Sea at that time of the year.

The use of linear discriminant analysis is based on two main assumptions; that the data are multinormal and that the variance-covariance matrixes of the groups included in the analysis are equal. This method is not robust to violations of those assumptions (Krzanowski, 1977). The validity of these assumptions therefore has to be confirmed.

ACKNOWLEDGEMENTS

The authors are grateful for financial support from the Norwegian Fisheries Research Council, no. I.501.016 and to the Nordic Council, no. 66.55.01. Greatly appreciated are also the efforts of Drs. V. Christensen, A. Corten, O. Hagstrøm, P. Johnson, E. Moksness, J. Morrison, P. Munk and O. Rechlin who provided spawning herring samples. The authors are also indebted to Mr. S. Lemvig for laboratory measurements and to Mr. H. Ullebust for assistance in data processing.

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Biological Tags for Stock Separation in Pacific Herring (*Clupea harengus pallasi* Valenciennes) and the Possible Effect of "El Niño" Currents on Parasitism

M. Moser
University of California
Santa Cruz, California

ABSTRACT

A ten-year study of Pacific herring off northern California showed that parasites could be used to separate the spawning stocks of San Francisco Bay and Tomales Bay. The distribution of the definitive hosts of the respective parasites suggest that the Tomales Bay fish are offshore and the San Francisco Bay fish onshore. The similarity in parasitism between San Francisco Bay and the nonspawning population in Monterey Bay suggests that these two populations represent a single stock. However, more samples are needed to confirm this suggestion.

Periodic warm-water "El Niño" currents occur off the California coast. Some diet-related parasites increased during the 1983-84 event. This increase may have been related to the influx of large numbers of marine mammals escaping the warm southern California waters.

INTRODUCTION

The Pacific herring (Clupea harengus pallasi Valenciennes) is an important roe fishery in central California. The fish enter San Francisco and Tomales Bays from December to March to spawn. They remain in the bays one to three weeks without feeding, spawn and leave the bay within days. The eggs hatch in approximately two weeks. The juveniles stay in the bays throughout the summer and into October. They remain offshore for two years, mature and then return to spawn for the first time. The spawning population in San Francisco Bay (50,000-70,000 tons) is approximately 10 times that of Tomales Bay (500-5,000 tons) (Jerome Spratt, Calif. Dept. Fish and Game, personal communication). Herring are caught in Monterey Bay in the summer. There is no significant spawning in Monterey Bay and this is a small, incidental fishery.

Currently, the California Department of Fish and Game does not have sufficient information to determine whether the two spawning areas represent separate or one breeding stock. If the two areas could be shown to be a single breeding stock, the quotas for the two areas could be combined. Commercial anglers would be free to fish both bays until this combined quota was met. However, to prevent potential overfishing in either bay, the two areas must be regulated separately. Presently, anglers are assigned to one of the two bays and are restricted to that bay regardless of the abundance of herring there that season. During the 1989-1990 season the San Francisco Bay fishery was valued at approximately $11 million and the Tomales Bay fishery at only $150 thousand. The purpose of this study was to use parasites to determine whether San Francisco and Tomales Bays represent separate breeding stocks and if these stocks remain separate while at sea.

During this ten-year survey, central California experienced a significant "El Niño" event. The data was examined to determine possible relationships between increased water temperatures and fish parasitism.

METHODS AND MATERIALS

Pacific herring (<u>Clupea</u> <u>harengus</u> <u>pallasi</u>) were collected from 1980-81 to the 1989-90 in San Francisco, Tomales and Monterey Bays (Monterey Bay 1982-83, 1987-88 and Tomales Bay 1989-90 excepted) and frozen (Figure 1). Fish were aged using a growth curve (Spratt 1981). All fish were two year olds. In the 1980-81 season, approximately 100 fish from both San Francisco and Tomales Bays and 20 from Monterey Bay were surveyed for parasites as potential candidates as biological tags. Thereafter, 30 fish were sampled from each bay per season.

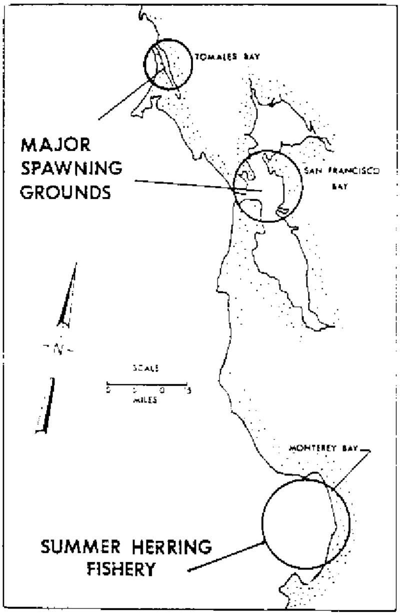

Figure 1. Herring fishery off central California.

Most fish examined in the 1980-81 survey contained both larval nematodes, <u>Contracaecum</u> sp. and <u>Hysterothylacium</u> sp. Since it is relatively time consuming to distinguish between the two genera for each specimen, and most fish contained both, these genera were combined into <u>Contracaecum</u> sp./<u>Hysterothylacium</u> sp. category.

Differences in prevalence were compared by doubling the standard deviation to account for approximately 90% of the variation. The differences in intensity was compared using a Mann-Whitney U test.

RESULTS

The results of the 1980-81 parasite survey of herring from Monterey, San Francisco and Tomales Bays are given in Table 1. From this survey and the average dominances (Table 2), four candidates were selected to be monitor for nine years. They were <u>Lacistorhynchus</u> <u>dollfusi</u> (Cestoda), <u>Anisakis</u> <u>simplex</u> and <u>Contracaecum</u> sp./<u>Hysterothylacium</u> sp. (Nematoda) and <u>Parahemiurus</u> <u>merus</u> (Digenea).

Parasites and Infection Loci	Tomales Bay N=28♂, 72♀	San Francisco Bay N=50♂, 72♀	Monterey Bay N=17♂, 7♀
Acanthocephala			
Rhadinorhynchidae			
Rhadinorhynchus trachuri Harada, 1935 intestine, stomach, caeca	0	p=1.0 I=1.0	0
Cestoda			
Lacistorhynchidae			
Lacistorhynchus dollfusi Beveridge and Sakanari, 1987 muscle	P=62 I=1.97(1.4)	P=96.0 I=9.9(6.0)	P=70.8 I=3.6(9.1)
Copepoda			
Bomolochidae			
Bomolochus cuneatus Fraser, 1920 gills, opercular cavity	P=8.0 I=1.2(.5)	P=16.0 I=1.1(.35)	P=50.0 I=1.6(.63)
Caligidae			
Caligus clemensi Parker and Margolis, 1964 gills, opercular cavity	0	P=5.0 I=1,2(.58)	0
Digenea			
Hemiuridae			
Parahemiurus merus (Linton, 1910) Woolcock, 1935 intestine, stomach, caeca	P=4.0 I=1.0	P=1.0 I=10.0(6.3)	P=95.8 I=7.0(6.3)
Bucephalidae (metacercaria) fins, nose, head	*P=♂ 97.1 ♀ 81.1 I=5.0(4.9)	*P=♂ 76.0 ♀ 46.0 I=2.5(1.5)	P=50.0 I=2.6(2.3)
Nematoda			
Anisakidae			
Anisakis simplex (larva), (Rudolphi, 1802) muscle, mesentery	P=93.0 I=8.8(7.5)	P=61.0 I=4.1(3.0)	P=16.7 I=1.7(1.5)
Contracaecum sp./ *Hysterothylacium* sp. (larva) caecae, mesentery	P=99.0 I=6.9)4.3)	P=96.0 I=10.6(6.9)	P=100 I=10.7(8.9)
Protozoa			
Myxospora			
Ceratomyxa auerbachi Kabata, 1962 gall bladder	P=44.0	P=52.0	P=33,3
Coccidia			
Eimeria nishin Fujita, 1934 testes	P=21.0	P=36.0	P=16.6
Goussia clupeaum (Thelohan, 1894) liver	P=44.0	P=55.0	P=70.0

Table 1. Preliminary Parasite Survey 1980-1981. (N=number hosts; P=prevalence; Intensity (standard deviation); *=significant differences between sexes, Mann-Whitney U P<.05).

	Anisakis simplex	Contracaecum/ Hysterothylacium	Lacistorhynchus dollfusi	Parahemiurus merus
Tomales Bay	35.26%	33.20%	7.45%	0.28%
San Francisco Bay	10.05%	38.31%	37.21%	0.44%
Monterey Bay	1.22%	43.04%	6.82%	31.42%

Table 2. Average dominances of select parasites.

Lacistorhynchus dollfusi

The prevalence of infection (number infected/number examined) was similar between San Francisco and Monterey Bays and both were two standard deviations greater than Tomales Bay throughout the study (Figure 2). The prevalence increases with age of the host. There is a significant increase between the two and the three and four-year-old from Monterey Bay fish (Figure 3). There was no significant difference in the intensity of infection (number parasites/ infected fish) among the three bays (Figure 4).

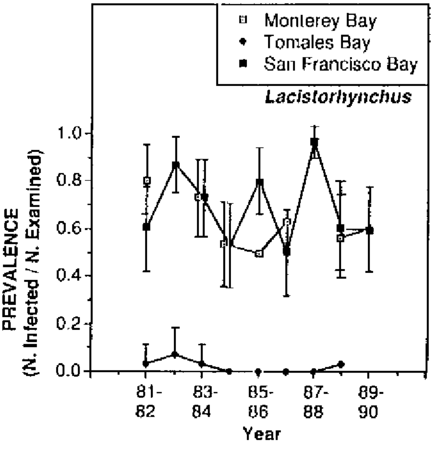

Figure 2. Prevalence of infection of L. dollfusi (error bar = 2 SD)

Anisakis simplex

The prevalence of infection was similar between Monterey and San Francisco Bays and both were consistently two standard deviations lower than Tomales Bay (Figure 5). The prevalence, increases with host age (Figure 6). Similar to the prevalence, the intensity of infection is significantly greater in Tomales Bay fish than San Francisco and Monterey Bays (Figure 7). The intensity of infection in Monterey Bay significantly increased with age (R^2=.541).

Contracaecum sp./Hysterothylacium sp.

There was no significant difference in prevalence among the bays (Figure 8). The prevalence of infection in Monterey Bay was 100% among two to four-year-olds. The intensity was similar between San Francisco and Monterey Bays and significantly different between Tomales and San Francisco Bays (Figure 9). The intensity increased in Monterey Bay fish with age (r^2=.39).

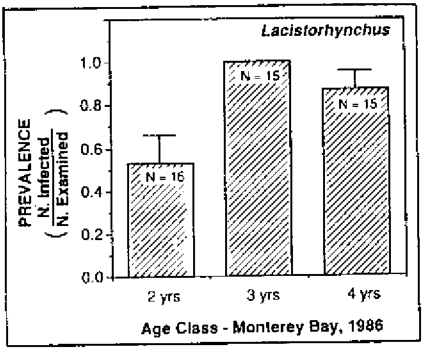

Figure 3. Prevalence of *L. dollfusi* by age class (error bars = SD)

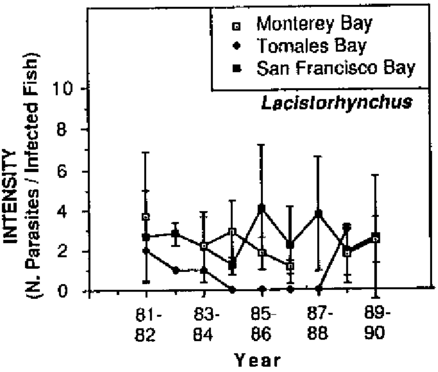

Figure 4. Intensity of infection *L. dollfusi* (error bars = SD)

Parahemiurus merus

The prevalence of infection between Monterey and San Francisco Bays were similar and generally two standard deviations greater than Tomales Bay (Figure 10). The prevalence decreases with age in Monterey Bay between two and four year olds (Figure 11). There was no significant difference in intensity among the three bays (Figure 12).

Effects of "El Niño" on Parasitism

The prevalence and intensity of *Anisakis simplex* (Figures 5 and 7 respectively) and the intensity of *Contracaecum* sp./*Hysterothylacium* sp. infections (Figure 9) increased in 1984-85 collections.

DISCUSSION

Spratt (1981), using a growth curve, showed that Tomales Bay fish are larger than those from San Francisco Bay, hence might separate stocks. Graham Worthy (Long Marine Lab., University of California, Santa Cruz, in preparation) compared the total caloric content of the Tomales and San Francisco Bay herring collected from 1981-82 to 1989-90 during this present study. Worthy showed that the caloric content of these two stocks were different throughout the nine seasons. Dougald Scott (Cabrillo College, Aptos, CA) examined herring collected from the 1980-81 survey for genetic differences between San Francisco and Tomales Bays using gel electrophoresis. Six loci were examined from muscle tissue: PGI, PGM, ADA; PEP-2, LDH-1 and LDH-2. Scott found no significant difference in the genotypes and frequencies of alleles between these two bays. In fact, neither differed significantly from samples reported from Seattle, Washington (personal communication).

MacKenzie summarized the use of parasites as biological tags in fish populations (1983) and herring in particular (1987). MacKenzie (1987) list twelve studies in which parasites had been successfully used in herring population studies.

The consistent difference in the prevalence of *L. dollfusi* infections between San Francisco and Tomales Bays suggest that these stocks are separate and repeatedly return to spawn in the same bay. As mentioned, adult herring do not feed on the spawning grounds. Therefore, fish become infected either during their first summer on the nursery grounds or while at sea. If fish become infected only as juveniles on the nursery grounds, the prevalence of infection would not increase with age. The prevalence, however, increased with age. This suggests that they are becoming or continuing to be infected while at sea. The life cycle of L. dollfusi includes the adult in sharks, the procercoid larva in microcrustaceans and the plerocercoid larva in fish (Sakanari and Moser 1989). The increased prevalence of these larva with age, and the fact that adult herring do not feed on the spawning grounds, suggests that Tomales Bay and San Francisco Bay stocks do not mix while at sea.

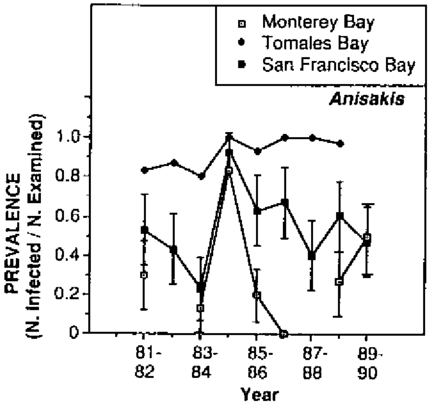

Figure 5. Prevalence of infection of A. simplex (error bars = 2 SD)

The similarity in the prevalence of infection between San Francisco and Monterey Bays suggest that the fish which are caught in the summer in Monterey Bay are part of San Francisco Bay spawning stock. This possibility needs further investigation because the size of the San Francisco Bay stock is an order of magnitude greater than Tomales Bay. If both Tomales and San Francisco Bay stocks were found in the summer in Monterey Bay, the disproportionate number of San Francisco Bay fish present would bias the samples. Future collections in Monterey Bay will be increased by a factor of ten to control for this difference in stock sizes.

Adult A. simplex are found in cetaceans. The eggs pass into the sea water and hatch. They are eaten by microcrustaceans, which are in turn consumed by fish or macroinvertebrates such as squid. If a fish eats an infected squid or fish, the larval nematodes will reinfect the new host. Serial infections result in rapid increases in the prevalence and intensity of infections.

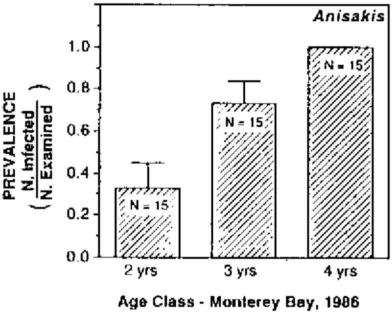

Figure 6. Prevalence of A. simplex by age class (error bars = SD)

The prevalence and intensity of A. simplex in Tomales Bay herring are greater than those from San Francisco and Monterey Bays. The rationale for these differences are the same as L. dollfusi. Consistent differences in prevalence and intensity suggest that Tomales and San Francisco Bays are separate spawning stocks and repeatedly spawn in the same bay. The lack of feeding by adults on the spawning grounds and increased infections with age suggests that these stocks do not mix while at sea. The similarity between San Francisco and Monterey Bay infections may indicate that they are the same stock. However, as with *L. dollfusi*, larger future collections in Monterey Bay are needed to confirm this possibility.

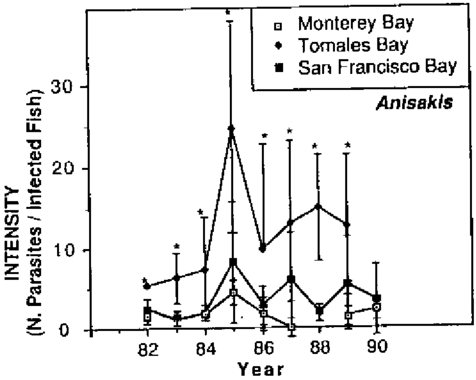

Figure 7. Intensity of infection of *A. simplex* (error bars = SD; * = Mann-Whitney U test, $p < 0.05$)

Adult *Contracaecum* are found in pinnipeds and marine birds and adult *Hysterothylacium* in marine fish. In other aspects, the life cycles are similar to that of *Anisakis*. The variety of definitive hosts for *Contracaecum* sp./*Hysterothylacium* sp. may be the reason most fish were infected with these parasites. The high prevalence of infection in the two to four-year-olds indicates that the larva are long lived and/or the fish continue to become infected after they leave the nursery grounds. The difference in the intensity of infections between Tomales and San Francisco Bays may indicate the adults are feeding in different areas.

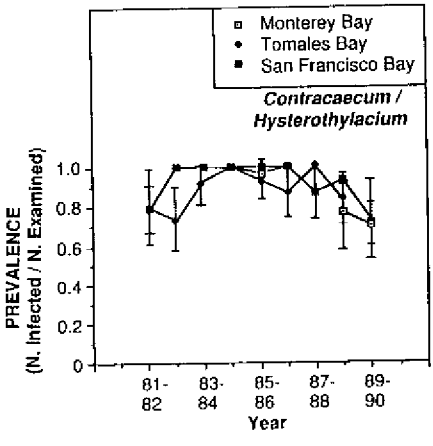

Figure 8. Prefalance of infection of *Contracaecum* sp./*Hysterothylacium* sp. (error bars = 2 SD)

The differences in infections of *L. dollfusi*, *Contracaecum* sp./*Hysterothylacium* sp. and *A. simplex* between Tomales and San Francisco Bays have suggested that these two stocks are separate herring, repeatedly spawn in the same bay and remain separate while at sea. The latter suggestion is supported by the distribution of the definitive hosts. Off central California, cetaceans (definitive hosts for *A. simplex*) are more offshore than pinnipeds and marine birds (definitive hosts *Contracaecum* sp.) and elasmobranchs (*L. dollfusi*). Onshore and offshore fish (definitive hosts for *Hysterothylacium* sp.) abundance is more difficult to estimate. Given the geographic distribution of the various definitive hosts, it might be suggested that Tomales Bay fish become infected offshore with *A. simplex* and San Francisco Bay fish are infected with *L. dollfusi* and *Contracaecum* sp. onshore. These correlations depend on discrete onshore and offshore population of infected intermediate hosts. These populations could maintain by the north-south currents found off central California. Interestingly, Cannon (1977a, b) describe a similar

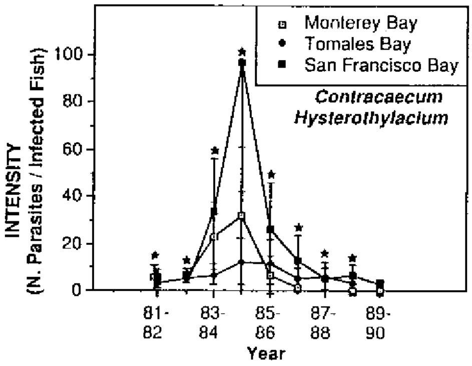

Figure 9. Intensity of infection of Contracaecum sp./Hysterothylacium sp. (error bars = SD; * = Mann-Whitney U test, p < 0.05)

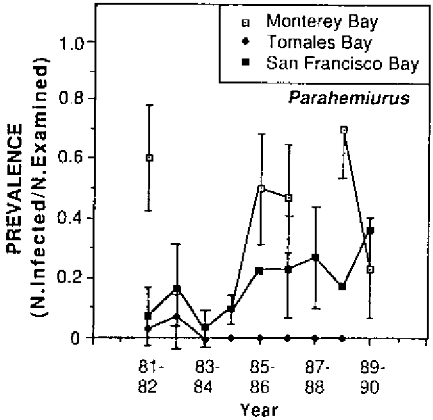

Figure 10. Prevalence of infection of P. merus (error bars = 2 SD)

correlation in inshore and offshore fish off Queensland, Australia. Anisakis was found in open water fish, Contracaecum in inshore shallow water fish and Hysterothylacium (=Thynnascaris) had an intermediate distribution.

The life span of the adult Parahemiurus merus most probably is less than one year. The decrease in prevalence with age may reflect a change in the diet of the herring as they get older. Similar to the above parasites, the difference between the prevalence of Parahemiurus merus infection in Tomales and San Francisco Bay fish suggest they are separate spawning stocks and remain separate while at sea. The similarity between San Francisco and Monterey Bay infections suggest they are the same stock but, as mentioned, needs farther sampling. However, the higher prevalence of infection in Monterey than San Francisco Bay may strengthen the latter suggestion. If fish are infected with this seasonal parasite relatively soon after spawning, more parasites will be present in the fish in the summer in Monterey Bay than in the winter in San Francisco Bay. By Winter, most of the parasites have died. Miller and Schmidtke (1956) noted that the summer Monterey fishery is predominantly the younger age classes and suggested they move into San Francisco Bay to spawn as they mature.

In 1983-84 central California experienced "El Niño" currents from South America. The average water temperature rose to above 16°C from an average of approximately 14°C. The herring fishery significantly decreased, as did the herrings' body condition factor, mean length and weight (Spratt 1987). Fish collected during 1984-85 season had spent much of their life in the warm El Niño" currents. The increase in prevalence and intensity of A. simplex and the intensity of Contracaecum sp./Hysterothylacium sp. infections in 1984-85 may be related to the effects of these currents. During this "event", there was a significant increase in the influx from southern California of California sea lions on the Farallon Islands (David G. Ainley, Pt. Reyes Bird Observatory, personal communication). The sea lions had moved north to escape

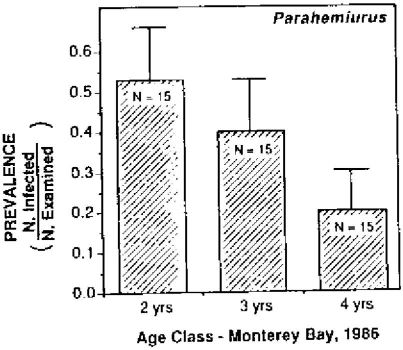

Figure 11. Prevalence of P. merus by age class (error bars = SD)

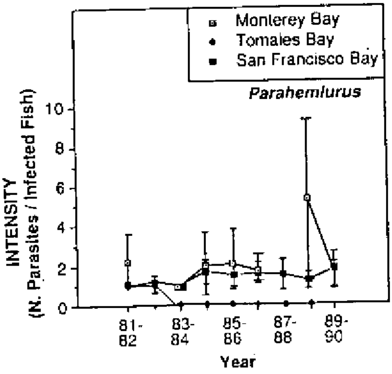

Figure 12. Intensity of infection of P. merus (error bars = SD)

unusually warm southern California temperatures. The Monterey Bay recorded new northern range extensions for several cetaceans and large numbers of bottlenose dolphins. These animals had followed the warm currents from south of the Mexican border. The rise in A. simplex infections may be due to increased numbers of cetaceans during this period. The increase in Contracaecum sp. may have been the result of the influx of large numbers of sea lions.

The possible relationship between "El Niño" and fish parasitism has also been suggested for rockfish off British Columbia (John Holmes, University of Alberta, personal communication). There was a marked increase in intestinal digenetic trematodes at this time. Holmes suggest that the warmer water may have increased the metabolism of the fish, hence they consumed more food and more infected intermediate hosts.

In summary, select parasites appear to be useful in separating the San Francisco and Tomales Bay spawning stocks and suggest that these stocks repeatedly spawn in the same bay and remain separate while at sea. Further collections are needed to determine if San Francisco and Monterey Bay fish represent a single stock. There is some evidence that "El Niño" may have affected fish parasitism off central California.

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ACKNOWLEDGMENTS

I thank the California Department of Fish and Game and Monterey Fish Co. for providing specimens; Janet Hsieh, Moss Landing Marine Lab, CA for assistance in the initial survey; Dougald Scott, Cabrillo College, CA for the gel electrophoresis; David Ainley, Pt. Bird Observatory, for the information on California sea lions; Graham Worthy, UC Santa Cruz for the total caloric content analysis; Ken MacKenzie and Alistar McVicar, Aberdeen Lab for suggestions; the staff and Beth Mathews at Long Marine Lab for preparation of the manuscript and; California Sea Grant for travel funds to attend the International Herring Symposium, Anchorage, Alaska.

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Stock Identification of Pacific Herring in the Eastern Bering Sea Trawl Bycatch and in the Dutch Harbor Directed Food and Bait Fishery

K.A. Rowell, H.J. Geiger, and B.G. Bue
Alaska Department of Fish and Game
Juneau, Alaska

ABSTRACT

Scale pattern analysis was used to examine stock definition of Pacific herring (*Clupea harengus pallasi*) spawning populations in the eastern Bering Sea. This was done to determine contribution of these populations to fisheries occurring in their post spawning migration routes. Cluster analysis was used to define three stock groupings of populations, or clusters, for age-6 and two for age-11 herring. Surrogate stocks were selected from each stock group. These surrogates were used to develop discriminant functions. Unknown fishery mixtures were classified with the discriminant models, and the proportional contribution of each cluster was estimated using the correction of Cook and Lord. Monte Carlo, or simulation, distributions of the estimated proportions were generated to test the hypothesis of random mixing of stocks in the mixed-stock fishery samples.

Classification of two of three mixtures from the Port Moller Pacific cod fishery fell within the acceptance region of the simulation distributions. This result led to no conclusion as the power of this test is likely to be low. Classification results of the third sample were outside the acceptance region of the simulation distribution, indicating disproportionate stock mixing. Analysis of samples from the two Dutch Harbor food and bait fishing periods were again uninformative as the estimated properties fell within the acceptance region of the simulation distribution. A single herring school sampled independently of these fishery mixtures in the Dutch Harbor food and bait fishery and samples from a single herring school caught in the Unimak pollock trawl fishery showed estimated mixing rates inconsistent with random mixing of spawning populations.

Contribution PP-033 of the Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau.

INTRODUCTION

Pacific herring (*Clupea harengus pallasi*) in the eastern Bering Sea migrate to coastal waters from offshore areas to spawn in the spring (Shaboneev 1965). Herring in spawning condition have been documented along the eastern Bering Sea coast off western Alaska from Kotzebue Sound south to Unalaska Island (Figure 1). Annual spawning population assessment to facilitate subsequent commercial harvesting of herring sac roe has occurred since 1976. Fisheries for herring sac roe have been managed in the Port Clarence, Norton Sound, Cape Romanzof, Nelson Island, Nunivak Island, Cape Avinof, Security Cove, and Port Moller, and Togiak Districts (Figure 1).

The largest spawning biomass and commercial sac roe fishery has historically occurred in the Togiak District of Bristol Bay where the 1989 harvest was approximately 12,000 tons of herring (Table 1). The Norton Sound spawning biomass has been second in abundance; it supported a 1989 sac roe harvest of 4,000 tons herring. The remaining documented coastal populations sustained commercial harvests ranging in size from 129 to 474 tons (Funk and Savikko 1990). Exploitation of these smaller populations for subsistence use has an important socio-cultural history in western Alaskan villages.

After spawning, eastern Bering Sea herring migrate offshore to feeding areas. The migratory path of herring spawning in waters north of Bristol Bay has yet to be confirmed. In May herring that have spawned in the Togiak District and to the south along the Alaska Peninsula migrate out along the Alaska Peninsula and arrive at feeding grounds near Unalaska Island in July and August. In August and September these fish begin to move offshore to the Pribilof Island area to overwinter (Shaboneev 1965; Rumyantsev and Darda 1970; Wespestad and Barton 1981; Funk 1990).

Herring from these eastern Bering Sea spawning populations have been captured incidentally to groundfish targeted by domestic and joint venture trawl fisheries in recent years. A directed food-and-bait fishery for herring in nonspawning condition has also been prosecuted by the state of Alaska on the feeding grounds. These interceptions have been located in the offshore herring migratory routes. Western Alaskan fishermen have been maintained that the interception of herring in these fisheries reduces the spawning populations that support the commercial and subsistence sac roe fisheries. The reduction could be exacerbated should herring maintain stock-discrete schools as they migrate from the spawning grounds.

In response to those concerns, the Alaska Department of Fish and Game (ADF&G) received funding in 1989 to (1) determine stock composition of herring caught in the domestic trawl fisheries for groundfish in the Port Moller and Unimak areas, (2) estimate stock composition of herring caught in the Dutch Harbor food-bait-fishery, and (3) examine stock homogeneity of single herring schools in nonspawning condition.

METHODS

Scale growth characteristics of fish from a known area (reference standards) have been used to develop stock-discriminant models by which members of a mixed stock fishery may be classified. Because of interannual variation in growth, the models must be age specific. In past studies, at least 200 samples from each age class and spawning location have been required to develop the classification model.

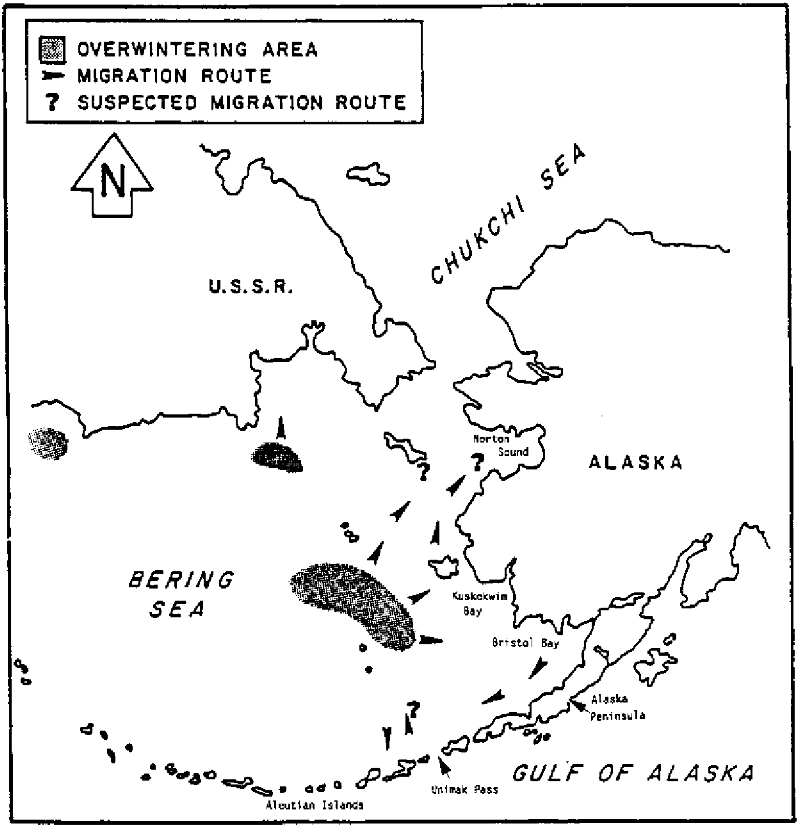

Figure 1. Herring migration routes and overwintering areas in the eastern Berring Sea (after Wespestad and Barton 1981).

Table 1. Estimated biomass and harvest in tons of nine herring spawning population in the eastern Bering Sea, 1989.

Spawning Location	Biomass (tons)	Harvest (tons)
Norton Sound	25,980	4,741
C.Romanzof	4,400	926
Nunivak Island	620	116
Nelson Island	3,320	220
C.Avinof	2,780	129
Goodnews Bay	4,040	616
Security Cove	2,830	554
Togiak	98,965	12,258
Port Moller	1-2,000	745
Total	144,435	20,305
Estimated Bycatch		4,980-8,900

Nine reference standards from the coastal spawning areas were selected for this study and were based upon documented growth and migratory timing differences by Barton (1978) and Wespestad and Barton (1981) and upon results of past stock identification studies (Walker and Schnepf 1982, Rogers et al. 1983, 1984; Schnepf 1984; Rogers and Schnepf 1985; Rowell 1980, 1986). These standards represented the primary herring fishing districts and included Norton Sound, Cape Romanzof, Nelson Island, Nunivak Island, Cape Avinof, Goodnews Bay, Security Cove, Togiak District, and Port Moller (Figure 2).

Herring from these spawning populations were collected by purse seine, beach seine, or variable-mesh gill net in 1989. Collected samples were processed for standard length in millimeters, sex, and gonad maturity, and a scale was selected from the preferred area of the fish (approximately 0.75 inches behind the opercle and just below the lateral line) when possible. Sample sizes of 2,000 herring were desired to assure adequate representation of major age classes from each spawning location (Table 2). Sampling occurred during the spring months from May through mid-June. Sample collection corresponded with peak abundance on the spawning grounds for all populations, with the exception of Port Moller. In the Port Moller District samples were collected only during open commercial fishing periods between the end of May through mid-June. Samples were not collected from the early spawning run of herring in Port Moller, which occurred in mid-May, from any other spawning population along the Alaska Peninsula or Aleutian Islands, nor from the small population of herring that spawn in Margaret's Bay on Unalaska Island.

Data were collected from three fishery mixtures of unknown origin: (1) Port Moller Pacific trawl fishery for cod, (2) Unimak trawl fishery for pollock, and (3) the Dutch Harbor food-and-bait fishery. ADF&G also coordinated with the National Marine Fisheries Service (NMFS) observer program for collection of herring sex, length and scale data from the groundfish fisheries. Samples were collected from the Port Moller trawl fishery for Pacific cod from 13 June through 7 July 1989. The fishery occurred over the length of the Alaska Peninsula. Most samples from this fishery were collected from herring bycatch in the vicinity of Port Moller and north of Unimak Island.

Sample dates for the Unimak pollock trawl fishery ranged from 27 July through 2 August. This fishery covered an area extending from the coast of Unalaska Island to the Pribilof Islands. During July and early August, much of the fishing effort has been concentrated at the 100-fathom line north of Unimak Pass, called the "Horseshoe". Most samples from this fishery were collected from herring bycatch within the Horseshoe fishing area (Figure 3).

Herring were collected in the Dutch Harbor food-and-bait fishery from 15 July through 4 August of 1989. This is an inshore purse seine fishery occurring on the northwest side of Unalaska Island (Figure 3). To obtain a representative sample of the overall harvest, about 30-65 fish were collected from each boat as the catch was delivered. These samples were not weighted by the proportion each delivery or vessel contributed to the total harvest. Approximately 12% of the catch during the first period of the fishery was taken by 5 vessels we sampled. During the second period, samples were collected from vessels that collectively harvested approximately 38% of the catch.

Samples from two discrete herring schools were also processed. Samples from a single herring school, about 200 tons in size, were collected on 4 August from a purse seine

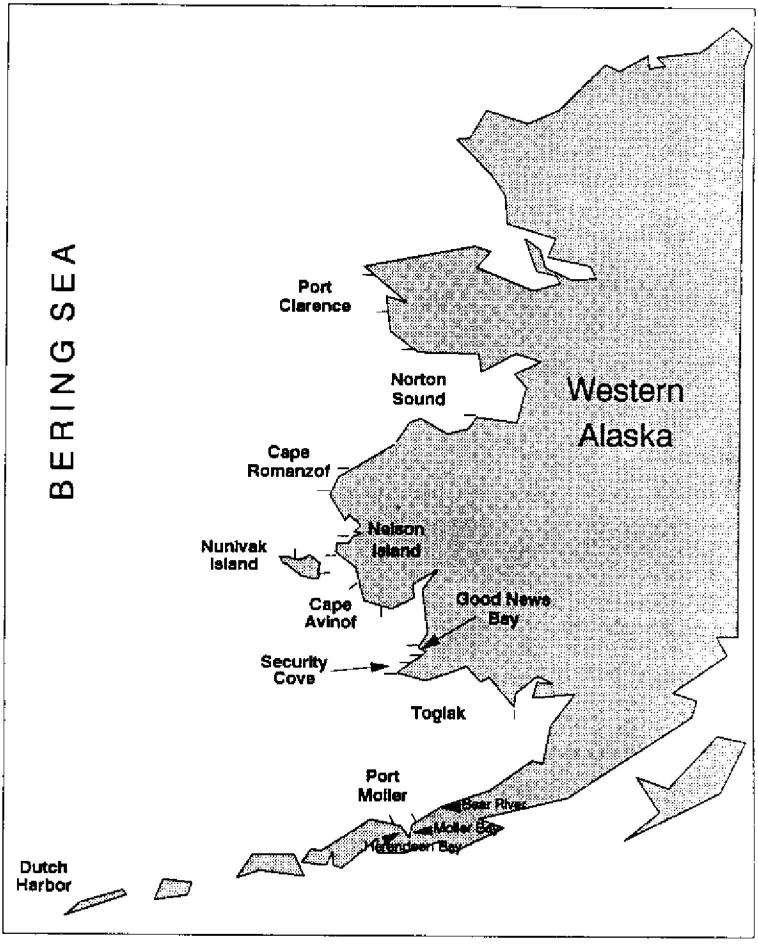

Figure 2. Eastern Bering Sea fishing districts for the sac roe harvest of Pacific Herring.

Table 2. Sample sizes of herring collected from spawning populations and offshore fisheries, 1989.

SAMPLING LOCATION	GEAR	SAMPLE
SPAWNING POPULATIONS		
Norton Sound	Variable-mesh Gill Net & Beach Seine	2,884
Cape Romanzof	Variable-mesh Gill Net	2,003
Nelson Island	Variable-mesh Gill Net	2,140
Nunivak Island	Variable-mesh Gill Net	1,320
Cape Avinof	Variable-mesh Gill Net	2,100
Goodnews Bay	Variable-mesh Gill Net	2,190
Security Cove	Variable-mesh Gill Net	1,670
Togiak	Variable-mesh Gill Net & Purse Seine	7,800
Port Moller Area		
Bear River[a]	Purse Seine	662
Port Moller (Outer)	Purse Seine	1,253
Port Moller (Inner)	Purse Seine	297
Subtotal		24,319
OFFSHORE FISHERY MIXTURES		
Dutch Harbor		
Herring Food & Bait	Purse Seine	1,100
Single School	Purse Seine	539
Unimak Trawl		
Pollock	Trawl	473[b]
Single School	Trawl	1,115
Port Moller		
Pacific Cod	Trawl	2,478
Subtotal		5,705
Total All Samples		30,024

[a] Samples collected from non-spawning, but sexually mature biomass.

[b] Samples of poor quality, used only for age composition.

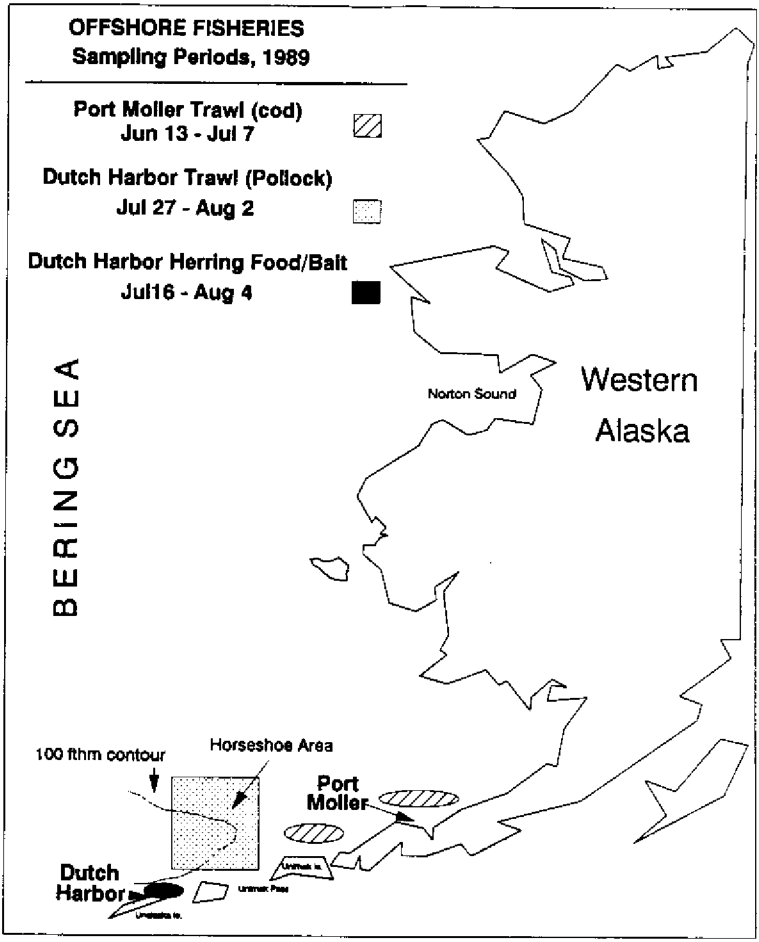

Figure 3. Timing and location of Pacific herring samples collected from the Dutch Harbor food and bait fishery and the groundfish trawl fisheries.

vessel participating in the Dutch Harbor food-and-bait fishery. These fish were collected independently from data used to determine overall stock composition of the Dutch Harbor food-and-bait fishery, but samples from the same set were included in the larger-scale fishery data set. The second sample from a single herring school was collected on 2 August from a trawl vessel participating in the Unimak pollock trawl fishery. It had intercepted a single school of herring approximately 10-20 tons in size.

Age composition of the spawning biomass and fishery samples of unknown origin were determined from scale interpretation. Scales were projected at a magnification of 64 X on a Calcomp digitizing tablet. The equipment was similar to that described by Ryan and Christie (1976). Measurements from the focus of the scale to each annulus were digitized along an axis 40° from the center of the scale (Schnepf 1984). Symmetrical scales were selected for digitizing.

Two age classes were selected for analysis based on their dominance in the fishery mixtures: age 11, or the 1978 year class, and age 6, or the 1983 year class.

Plus-growth was present on scales collected from the offshore fisheries occurring late in the season, indicating a probable increase in fish length over the duration of the fishing season. To accommodate for this change, length was backcalculated to the last annulus for samples from the fishery mixtures to estimate the variable length at annulus formation comparable to length at capture for the spawning populations

$$L_n = \frac{C_n L_o}{C_0}$$

where L_n is the estimated standard fish length when annulus n was formed, C_n is the distance from the focus of the scale to the annulus n, L_o is the length of fish at time of capture, and C_o is the total scale size.

Stock-specific means were calculated for each scale measurement or length at spawning. These stock means were transformed so that (1) the overall mean of stock means was zero, and (2) the among-stock mean standard deviation equalled the *F*-statistic (from the univariate analysis of variance; SAS 1987) used to test for no stock differences in that particular scale measurement or estimated length at spawning.

These *F*-statistic scaled means were then used in a single-linkage cluster analysis (SAS 1987). The weighting by the *F*-statistic was to allow for greater variation among stock means which contain large stock differences.

Sets of similar stocks were pooled into stock groups or stock clusters, based on the results of the cluster analysis. A surrogate stock was selected from each cluster for discriminant function analysis to represent all of the stocks in the cluster. A surrogate stock was selected from each cluster based on the successful classification of all of the stocks in the cluster. A discriminant function model (Johnson and Wichern 1988) was developed from these surrogate stocks. The unknown mixtures were then classified using this linear discriminant model with a Cook and Lord (1978) adjustment. Because the Cook and Lord procedure can result in classification proportions less than zero or greater than one, we rounded estimates outside these boundaries to zero or one, except in Figures 10 and 12.

Classification simulations with 1000 Monte Carlo replications each using Cook and Lord's (1978) correction were then developed to test the null hypothesis that all spawning populations were randomly mixed in proportion to biomass in the fishery mixtures. Test sets of 100 scales were randomly selected from the scale collection for each spawning population. The number of random selections from each population was, on average, proportional to the age-specific biomass contribution to the total observed eastern Bering Sea biomass for that age. The acceptance region for the hypothesis test consisted of the inner 90% of the Monte Carlo distribution of estimated proportion, that classified to the largest non-Togiak Cluster in the simulated distribution.

RESULTS

Timing

In 1989 the first recorded observation of spawning biomass among coastal fishing districts of the eastern Bering Sea was in the Togiak District during the first week in May. Spawning occurred later for the more northerly locations. Herring arrived in Security Cove and Goodnews Bay about the second week of May; the remaining stocks further north arrived in the third week of May. Port Moller herring were the latest, spawning from the end of May through mid-June. With the exception of Togiak and Security Cove, spawning was concurrent with the prosecution of the Port Moller trawl fishery for cod. Herring had disappeared from all the spawning grounds by the time the Dutch Harbor food-and-bait and the Unimak trawl fishery were prosecuted.

Age Composition

Ages ranged from 2-16 years for the 30,000 samples processed. Reference standards for Norton Sound, Cape Avinof, and Goodnews Bay were primarily comprised of younger fish, ages 5, 7, and 8 (Figure 5). Three sets of samples were collected to represent the Port Moller reference standard. Samples were collected at Bear River, located north of Port Moller, and at the entrance of Port Moller (outer Port Moller) during the last week of May. The third set of samples were collected from Moller and Herendeen Bays within Port Moller (inner Port Moller) in mid-June (Figure 6). As with Cape Romanzof, Norton Sound, and Cape Avinof, young herring comprised a greater portion of the biomass of the inner and outer Port Moller samples. Herring sampled from the entrance of Port Moller and those collected within Port Moller were primarily 5- and 6-year-old herring. The age distribution for samples collected at Bear River, though similar to the early Port Moller herring, showed greater proportions of 6-, 8-, and 11-year-old herring. The fish sampled from the Bear River area, although sexually mature, were the only reference standard collected from nonspawning herring.

Herring age 8 and older dominated samples from the Port Moller trawl fishery, the Unimak trawl fishery, the Dutch Harbor food-and-bait fishery, and the single-school sample from the Dutch Harbor food-and-bait fishery (Figure 7). The single-school sample caught in the Unimak trawl fishery, unlike the other fishery mixtures, was primarily age-5 and -6 herring.

Age composition of the Port Moller trawl bycatch changed in age structure over time. From 13 June through 19 June, herring age 10 and older dominated the samples, but herring age 8 and younger increased gradually from 22 June through 3 July. Age-5 and age-6 herring dominated the samples collected on 5 and 7 July.

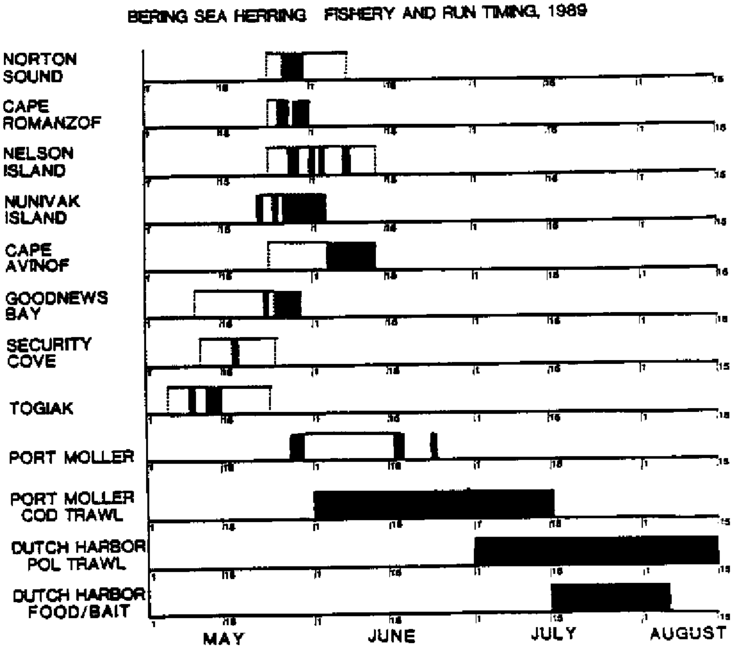

Figure 4. Run timing of Pacific herring to spawning locations and fisheries in the eastern Bering Sea, depicted by the range of dates of aerial survey observations (----) or dates of fishing periods (■) in the eastern Bering Sea.

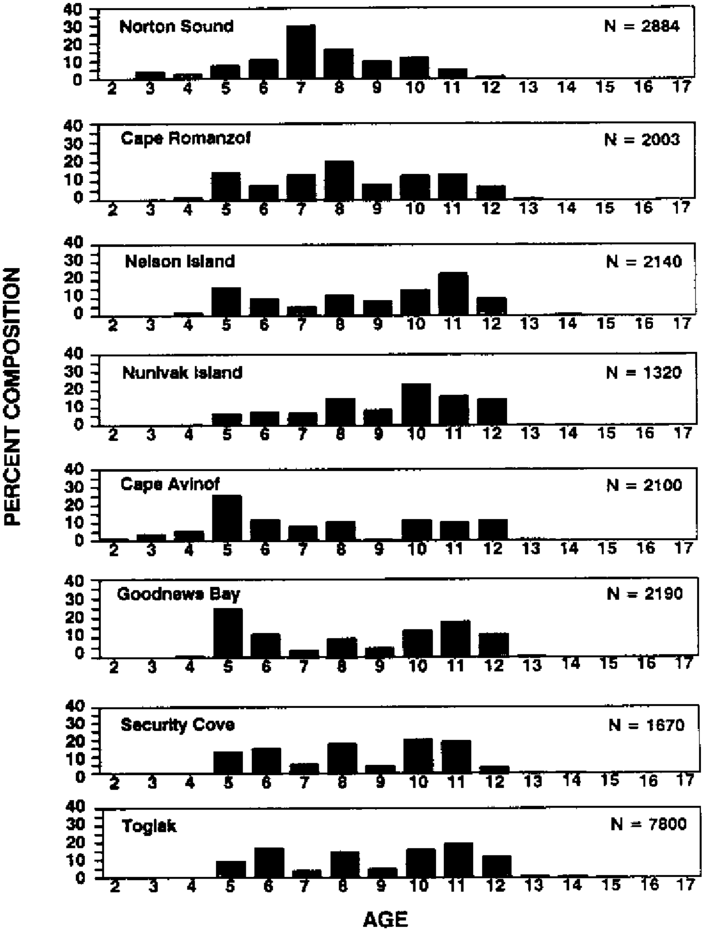

Figure 5. Age composition of Pacific herring spawning populations in the eastern Bering Sea from Norton Sound south to Togiak, 1989.

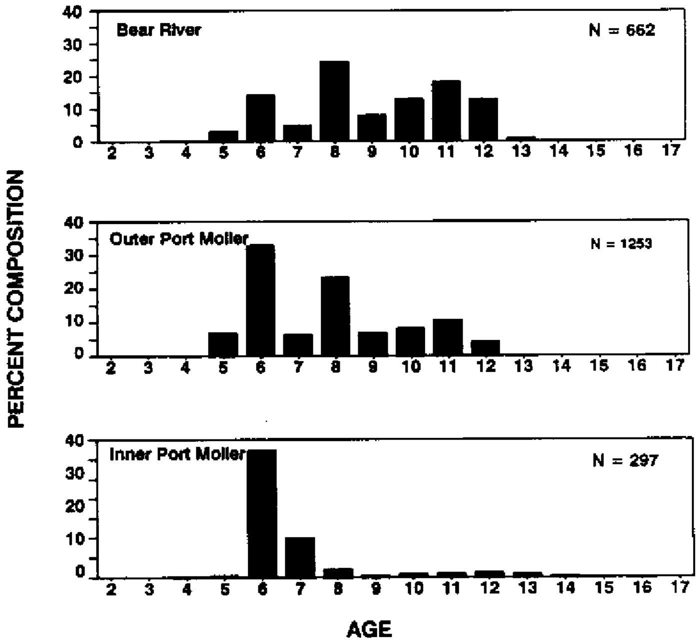

Figure 6. Age composition of Pacific herring spawning populations in the eastern Bering Sea from the Alaska Peninsula, 1989.

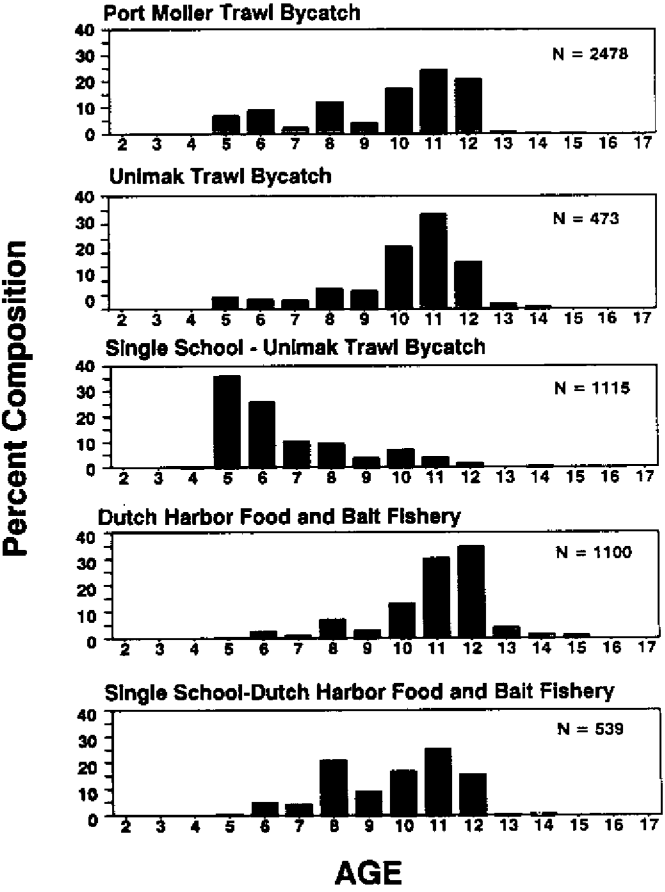

Figure 7. Age composition of Pacific herring samples collected from the Dutch Harbor food and bait, and the domestic groundfish trawl fisheries, 1989.

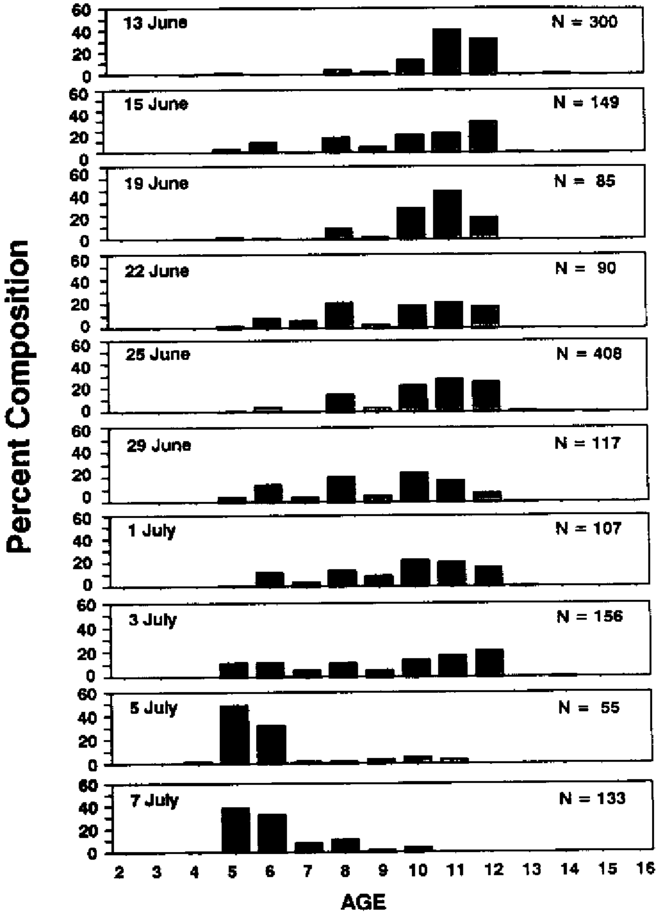

Figure 8. Age composition of samples collected from the herring bycatch in the Port Moller trawl fishery for Pacific cod, 1989.

Age-6 Analysis

Cluster analysis of the age-6 herring resulted in three groups (Figure 9): (1) Cluster A, or the non-Togiak Cluster, consisted of the more northerly stocks of Norton Sound, Cape Romanzof, Cape Avinof, Nunivak Island, Nelson Island and Goodnews Bay; (2) Cluster B, or the Togiak Cluster, consisted of Security Cove, Bear River, Togiak, and outer Port Moller; (3) Cluster C, or the Inner Port Moller Cluster, was very distinct and was represented by the inner Port Moller samples collected in mid-June. These clusters were robust in respect to variable scaling and clustering algorithms. Stocks in each cluster which best represented the others when classified in a linear discriminant model were Cape Avinof for Cluster A, Togiak for Cluster B, and inner Port Moller for Cluster C. Overall classification accuracy for the three surrogate stocks in the final linear discriminant model was 81.3% (Table 3).

Two fishery mixtures contained adequate numbers of age-6 samples to classify with this model. The first fishery mixture consisted of 78 samples from the Port Moller trawl fishery and classified 15% to Cluster A, 86% to Cluster B, and 0% to Cluster C.

The inner 90% of the simulation distribution of proportions classifying to clusters other than Clusters B or C, was used as the acceptance region (Figure 10). Adjusted classification results of the Port Moller trawl sample fell within the acceptance region of this distribution. The actual classification of samples to Cluster A (non-Togiak) was similar to the expected classification. We therefore failed to reject the null hypotheses that all representative stocks were present in proportion to relative abundance of the spawning stocks, although our test may not have been powerful enough to detect the relative absence of some stocks.

The second unknown mixture, 74 samples collected from a single herring school caught as bycatch in the Unimak trawl fishery, classified 100% to Cluster A (non-Togiak). This classification fell well outside of the acceptance region (Figure 9). These data provide strong evidence that stocks were not present in the sample in proportion to relative abundance of the biomass for this age class and the proportion of samples classifying to Cluster A was actually much greater than expected.

Age-11 Analysis

Cluster analysis defined two groups for age-11 herring (Figure 11). The first, Cluster D or the non-Togiak Cluster, consisted of spawning populations extending from Norton Sound south to Goodnews Bay and also included Bear River. The second, Cluster E, or the Togiak Cluster, consisted of the Security Cove, outer Port Moller, and Togiak spawning populations. The surrogate stocks selected for this analysis were Nelson Island from Cluster D and Togiak from Cluster E. Classification accuracy with the surrogate stocks for this two-way model was 70%. Fish collected within Herendeen and Moller Bays during June were smaller at-age than herring from the other spawning populations and were the same as the Inner Port Moller Cluster described above in the age-6 analysis. This third cluster was represented by only four digitized scales, and because the sample size was so small, it was eliminated from the model.

Five fishery mixtures were examined for age-11 herring. These were the Port Moller Pacific trawl fishery for cod divided into two periods, the Dutch Harbor purse seine

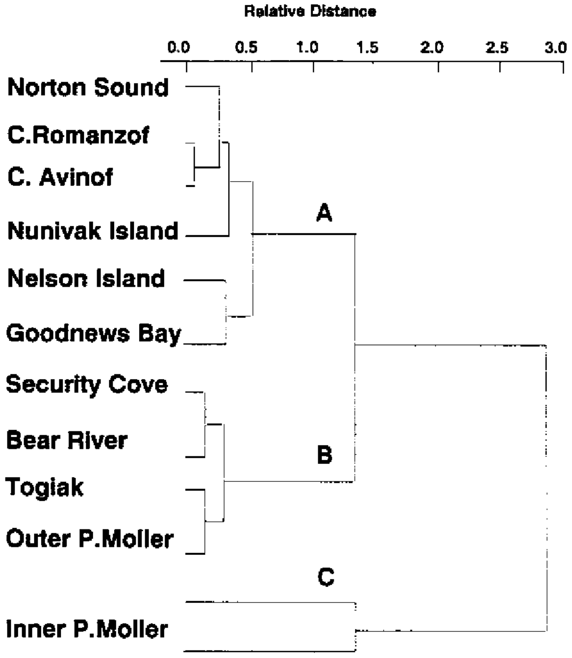

Figure 9. Results of average-linkage cluster analysis of age 6 herring from each of the sampled spawning populations.

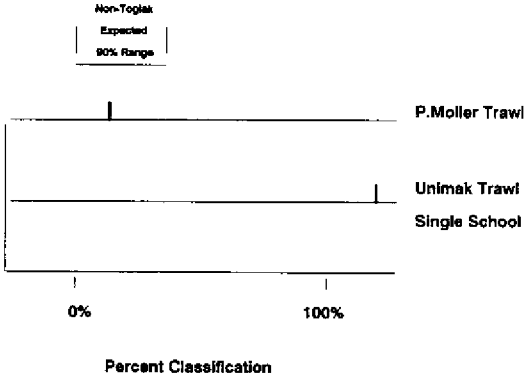

Figure 10. Classification of fishery mixtures using linear discriminant function analysis compared to the distribution of classification results from the Monte Carlo simulation for age 6 herring testing presence of herring in proportion to biomass.

Table 3. Classification matrix from linear discriminant analysis with sample size, classification to actual stock cluster and classification of the unknown fishery mixtures for age-6 herring, eastern Bering Sea 1989.

CLASSIFICATION MATRIX

Stock Cluster	Sample Size	Classification (%) Cluster A	Cluster B	Cluster C	Total
Cluster A	70	71.4			100.0
Cluster B	200		72.5		100.0
Cluster C	16			100.0	100.0
FISHERY MIXTURE CLASSIFICATION (Adjusted Cook and Lord, 1978)					
Port Moller Trawl (6/13-7/07)	78	14.6	86.2	0.0	100.0
Unimak Trawl Single School (8/02)	74	100.0	0.0	0.0	100.0

Table 4. Classification matrix from linear discriminant analysis with sample size, classification to actual stock cluster and classification of the unknown fishery mixtures, for age 11 herring, eastern Bering Sea, 1989.

CLASSIFICATION MATRIX

Stock Cluster	Sample Size	Classification (%) Cluster D	Cluster E	Total
Cluster D	148	68.2		100.0
Cluster E	200		71.5	100.0
FISHERY MIXTURE CLASSIFICATION (Adjusted Cook and Lord, 1978)				
Port Moller Trawl Period 1 (6/13-6/15)	50	0.0	100.0	100.0
Port Moller Trawl Period 2 (6/19-7/07)	75	82.6	17.4	100.0
Dutch Harbor Period 1 (7/15-7/27)	103	25.9	74.1	100.0
Period 2 (7/28-8/04)	106	20.9	79.1	100.0
Dutch Harbor Single School (8/04)	38	80.6	19.4	100.0

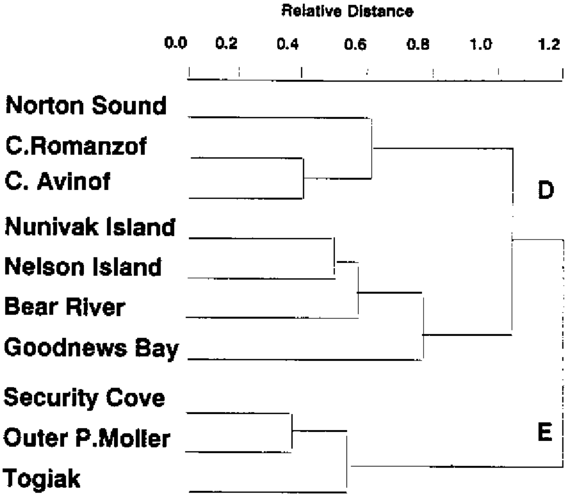

Figure 11. Results of average linkage cluster analysis for age 11 herring from each of the sampled spawining populations.

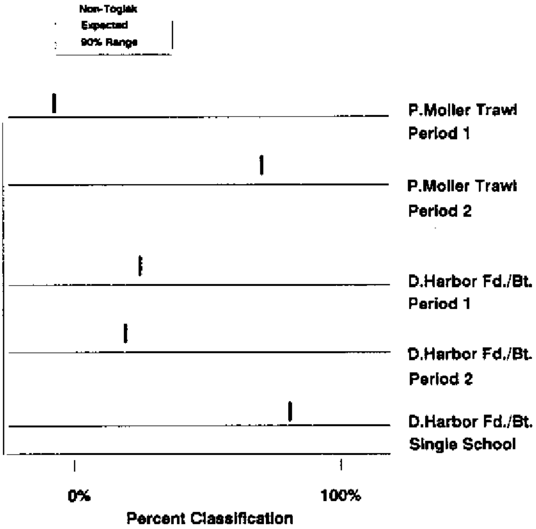

Figure 12. Classification of fishery mixtures using linear discriminant function analysis compared to the distribution of classification results from the Monte Carlo simulation for age 11 herring testing presence of herring in proportion to biomass.

fishery for food-and-bait divided into two periods, and samples collected from a single herring school in the Unimak pollock trawl fishery. With exception of samples collected from the single school-sample, the quality of scale samples from the Unimak Trawl fishery was very poor, could not be digitized, and therefore were eliminated from any overall stock composition analysis.

Samples for the Port Moller trawl fishery were divided into two periods. The first period extended from 13-15 June; the second period extended from 25 June through 3 July. The classification of the first period samples were 100% to Cluster D (non-Togiak; Table 4). This classification was within the left extreme of the acceptance region of the simulation distribution (Figure 12). We concluded that these data offer no evidence that the spawning stocks were not present in proportion to abundance of this age class in these samples, although again, our test may not have been powerful enough to detect the absence of some stocks.

In contrast, the second period samples from the Port Moller trawl fishery classified 17% to Cluster E (Togiak) and 83% to Cluster D (non-Togiak). Classification of herring to Cluster D for these samples was greater than the expected range of the simulated distribution, indicating a greater than expected presence of herring classifying to the non-Togiak Cluster in these samples. These data present strong evidence that spawning stocks were not present in this fishery in proportion to abundance for this age class.

Samples from the 1989 Dutch Harbor food-and-bait fishery were divided into two periods commensurate with open commercial fishing periods. The first period extended from 15-27 July. Classification of these samples to Cluster E (Togiak) was 74%. The second fishing period extended from 28 July through 4 August. Similar to the first period, the majority (79%) of the samples classified to the Togiak Cluster (Table 4). Classification results of both these samples fell within the acceptance region range of the simulation distribution.

The samples from the single herring school collected from the second Dutch Harbor food-and-bait fishing period classified only 19% to Cluster E (Togiak). Classification to Cluster D (non-Togiak) was 81% (Table 4). This classification to non-Togiak stocks fell well outside the acceptance region of the simulation distribution. These data provide evidence that herring in this single school sample were not mixed in proportion to abundance of the spawning biomass (Figure 12).

DISCUSSION

Observed differences in growth rates, spawning behavior, age composition (suggesting differences in survival rates), and spawning timing of herring returning to different eastern Bering Sea spawning locations indicate these fish home to a generalized spawning area each spring (Wespestad and Barton 1981; Barton 1978). Differences in growth between some spawning populations has also been documented (Walker and Schnepf 1982; Rogers et al. 1983, 1984; Schnepf 1984; Rogers and Schnepf 1985; Rowell 1980, 1986). Fried and Wespestad (1985) used analysis of growth curves to categorize herring spawning populations between Togiak and Norton Sound into two groups. Faster growing fish from more southerly stocks of Togiak, Security Cove, and Goodnews Bay represented one group. The second group was comprised of Nelson Island, Cape Romanzof, and Norton Sound herring and exhibited slower growth rates.

This 1989 study was the first to include data representing all known major spawning populations along the eastern Bering Sea coast. Cluster analysis defined three groups of herring from nine spawning populations by which fishery mixtures of unknown origin were classified. Differences in annual growth rates were apparent between some spawning populations. In most instances, differences in growth rates were very gradual and confused the delineation of each spawning population. It is possible that herring from spawning populations not represented in this study, particularly along the Alaska Peninsula, exhibit growth patterns similar to the three stock clusters we defined. The actual stock definition as a genetically discrete reproductive unit for herring in the eastern Bering Sea may span several fishing districts or may be even more discrete than definition by fishing districts assumed in this study. Genetic or biochemical differences between populations may be present and should be the focus of future studies.

Two herring types were present in the Port Moller District. In 1989 samples collected within Moller and Herendeen Bays (inner Port Moller) in June were smaller at-age than those collected within the entrance of Port Moller (outer Port Moller) at the end of May. The inner Port Moller samples were distinctly different from those of the other spawning populations, and the outer Port Moller samples were similar to samples from the Togiak District. These differences in size-at-age for Port Moller herring were also described by Schnepf (1984) in the early Bering Sea herring stock identification studies and may imply presence of two discrete herring spawning stocks in the Port Moller Bay complex.

Togiak herring represent the largest herring sampled on the eastern Bering Sea coast (Walker and Schnepf 1982; Rogers et al. 1983, 1984; Schnepf 1984; Rogers and Schnepf 1985; Wespestad and Barton 1981; Fried and Wespestad 1985). The Togiak Cluster defined in this study represented spawning populations with faster growth rates. Growth of Bear River fish was similar to other stocks in the Togiak Cluster for the age-6 analysis but for the age-11 samples was similar to the non-Togiak Cluster (northern stocks). The sampled biomass at Bear River was sexually mature; however, spawning was not observed in the Bear River area, and herring may have been migrating to Port Moller or another Alaska Peninsula location.

Results of our age-11 analysis supported past studies. The Dutch Harbor food-and-bait fishery was dominated by herring representing the Togiak Cluster. Classification rates of 74% and 79% to the Togiak stock for herring from this fishery were similar to the range of 70% to 100% of past studies (Walker and Schnepf 1982; Rogers et al. 1983, 1984; Schnepf 1984; Rogers and Schnepf 1985). Herring representing stocks other than Togiak were also present in the Dutch Harbor food-and-bait fishery. Samples from the Port Moller trawl fishery classified to the Togiak Cluster during the first period. The presence of herring from the non-Togiak Cluster in the migratory corridor was emphasized by domination of this cluster in the second period of the Port Moller trawl fishery, the single-school sample in the Unimak trawl fishery, and the single school from the Dutch Harbor food-and-bait fishery.

None of the fishery mixtures classified large numbers of fish to the Inner Port Moller Cluster. This cluster may represent either a residential population within the Port Moller complex or are a stock whose timing of migration does not coincide with the timing of the fisheries we analyzed.

Any spawning population present in the mixed fishery samples and not represented in this analysis, such as the spawning populations at Unalaska Island or the early run at

Port Moller, would classify to a stock cluster included in our model. The consistent trend of a decrease in growth rates or size of herring from spawning locations progressively north from Togiak has been documented (Fried and Wespestad 1985; Wespestad and Barton 1981; Walker and Schnepf 1982; Rogers et al. 1983, 1984; Schnepf 1984; Rogers and Schnepf 1985; Rowell 1980, 1986). We speculate that a similar decreasing trend in size from the Togiak District progressing south exists for herring spawning along the Alaska Peninsula and within the Aleutian Islands. Herring from these southern spawning populations such as Margaret's Bay or the inner Port Moller complex were are smaller at-size than Togiak herring (Walker and Schnepf 1982; Rogers et al. 1983, 1984; Schnepf 1984; Rogers and Schnepf 1985). Herring from spawning populations with slower growth rates, such as those from the Alaska Peninsula area, could be present in fishery mixtures we examined. These fish would be most similar to the more northern stocks and could classify to either the non-Togiak or inner Port Moller Clusters.

Segregation of herring by size and age in the eastern Bering Sea was observed on the overwintering grounds during the years of Soviet exploitation (Rumyantsev and Darda 1970). Some degree of segregation has been observed during the spring spawning migration where the proportion of younger herring moving into the spawning grounds increases as the season progresses. This change in age composition suggests segregation by size and age in the analysis of samples from the Port Moller trawl fishery. Herring age 10 and older dominated the samples at the beginning of the fishery and shifted to predominantly age 6 and younger towards the end of the fishery. In the Unimak trawl fishery, age composition of a single herring school was predominantly young fish, whereas the age composition of samples collected from the several vessels in the fishery were comprised of older-age herring. Size segregation of schooling fish species has been attributed to the relationship of swimming speed to body length (Breder 1976; Radakov 1973). Larger fish are able to swim faster and would therefore precede younger herring in the migratory corridor and on the spawning grounds. It is conceivable that herring from spawning populations that are smaller at-age than other populations could arrive in migratory corridors later than other stocks.

Apparently herring stocks may not only be segregated by size but could also be disproportionately mixed in the migratory corridors relative to their spawning biomass. The size of the Togiak spawning population and spawning biomass has historically been the largest in the eastern Bering Sea. The Togiak and non-Togiak Clusters were not mixed in proportion to the biomass of their respective spawning populations. The stock composition of the age-11 herring in the Port Moller trawl fishery changed from primarily herring of the Togiak Cluster during the first period to non-Togiak herring during the second period. Stock composition of the Dutch Harbor food-and-bait fishery indicated that herring from the Togiak Cluster dominated the harvest for both fishing periods, but samples collected from a single herring school during the second fishing period were primarily non-Togiak herring. The single school sampled in the Unimak pollock fishery was primarily younger-aged herring. The age-6 sample from this school classified to the non-Togiak Cluster. The overall stock composition of the Unimak trawl fishery was unknown, but it is expected that herring of the Togiak Cluster when present, may also dominate this fishery.

A sample size of two herring schools provides minimal experience on which to base conclusions but does provide evidence that herring schools from different spawning populations may remain segregated in the migratory corridors. Coastal spawning locations are geographically separated, and differences in the timing of spawning activity have historically been consistent for each location. Because of the distance separating the spawning locations, if all or some of these stocks move to the Unimak area to feed, they could remain temporally and spatially separated from other populations migrating from the spawning grounds. Other than the classification rates observed in this study, the degree of stock mixing or segregation in the migratory corridor was not determined. Segregation of these spawning populations could continue to some degree as they recombine with other spawning populations throughout their migration.

CONCLUSIONS

1. Three scale types based on growth were identified for herring from nine spawning populations in the eastern Bering Sea.
2. Similar to results of past studies, the Togiak Cluster dominated the samples collected in the Dutch Harbor food-and-bait fishery and comprised an estimated 74-79% of the commercial catch sampled.
3. Stock mixing rates within a single school may differ from those of the overall fishery. This indicates herring stocks are not evenly mixed in proportion to their biomass as they reintegrate into mixed stock areas from temporally and spatially separated spawning areas.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Comparison of Meristic and Morphometric Characters Among Spawning Aggregations of Northwest Atlantic Herring, *Clupea harengus* L.

R.L. Stephenson and D.J. Gordon
Department of Fisheries and Oceans
St. Andrews, New Brunswick, Canada

ABSTRACT

This stock identification project grew out of a need to partition juvenile herring from mixed aggregations to stock units for assessment. First, however, it was necessary to test for the ability to discriminate the stocks of origin. The study involves univariate and multivariate analyses performed on seven meristic traits, a shape (truss) analysis based on 15 anatomical landmark points, otolith shape analysis and a study of the presence of eight parasite types. It differs from most previous studies in that it includes only documented spawners ("ripe and running fish") and is therefore free from potential bias of prespawning fish which may have belonged to other spawning groups. Approximately 2900 fish were collected from 13 discrete spawning locations, 9 of which were sampled in 2 consecutive years. These spawning collections were mostly from within the Bay of Fundy and Gulf of Maine, but some were from as far away as Newfoundland and Cape Cod. Preliminary analysis has shown that within-group variance in meristic traits is stable over the 2-year period examined. Several meristic characters were uniform but some differentiation is possible based upon pectoral, raker and caeca counts, parasite loads and combinations of characters.

INTRODUCTION

Atlantic herring spawn at discrete locations over a wide geographical, physical and temporal range (Blaxter, 1985). At specific sites, however, spawning is predictable in timing and location. The attributes of the recurring spawning group are such that the species is commonly believed to return to sites of previous spawning - and likely to home (a summary of evidence for and against this view presented by Stephenson 1990, this volume). As such, spawning groups of herring are considered to be discrete populations, and although the scale and degree of discreteness can be debated, it is this model which forms the basis for stock assessment and management (Stephenson, 1990).

Stock assessment/management units are (or are assumed to be) individual populations or aggregations of populations. But Atlantic herring migrate extensively and spawning groups commonly mix outside of the spawning season. This complicates assessment and management of almost all fisheries except those on the spawning grounds.

In the Gulf of Maine/Bay of Fundy area, for example, herring from three assessment/management units (each with several spawning locations) are thought to mix extensively as juveniles (ages 1-3) and to some extent as adults in overwintering and summer feeding aggregations - causing a problem of apportioning catch among assessment units (e.g. Stephenson et al., 1990; Stephenson and Power, 1990; Fogarty et al., 1990). As a case study, this situation is made more interesting by the presence of the international (Canada/USA) boundary which has resulted in greater differences in fisheries and management regimes for adjacent populations than might otherwise have been the case.

It is as a result of these questions, particularly in the hope of being able to resolve the question of the affinity of juveniles which mix in coastal fisheries, that we initiated a study of stock identification. In this paper we summarize herring stock structure in the Bay of Fundy and Gulf of Maine and provide an overview of the stock identification study including its approach, methods and some initial results.

HERRING STOCK STRUCTURE IN THE GULF OF MAINE

The Bay of Fundy/Gulf of Maine area contains several major herring spawning sites (Fig. 1), plus a number of smaller coastal sites. These spawning groups exhibit a range in timing (May-November), size (including the largest in the northwest Atlantic) and physical conditions (depth, substrate, etc.) typical of Atlantic herring.

For assessment and management, herring spawning groups have been aggregated into three units (Fig. 1). These recognize as far as it is practical the assumption of biological discreteness (particularly for major spawning groups) - but also reflect political boundaries and historical precedent.

Figures from ICNAF assessment documents in the 1970s (Fig. 2) show development of these units. The current situation is not unlike the view presented by the ICNAF 1976 map (Fig. 2). A 4WX stock is dominated by fish which spawn off southwest Nova Scotia (late summer and autumn spawners) and are believed (from tagging results) to overwinter off eastern Nova Scotia (Cape Breton). This assessment area also includes a number of smaller spawning areas including upper Bay of Fundy spring and summer spawners (Fig. 1). A coastal US stock (5Y) is dominated by Jeffries Ledge spawners which overwinter off Cape Cod, but also includes a number of spawning locations along the coast of Maine. The Georges Bank unit (5Z) was

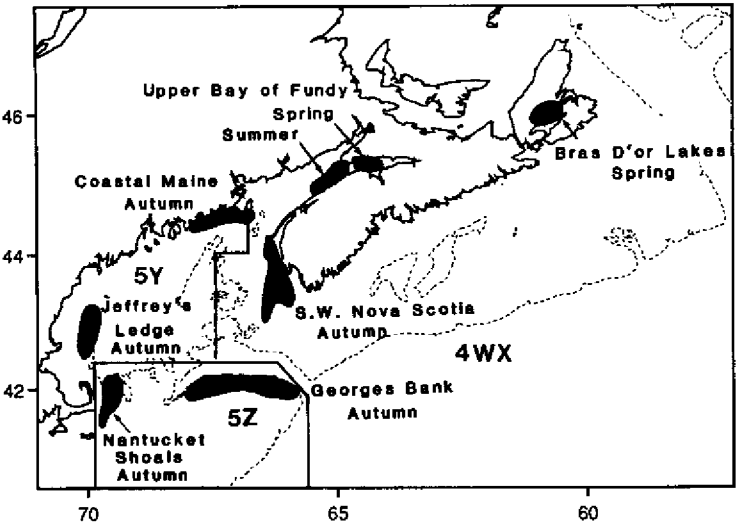

Fig. 1. Management units of the Bay of Fundy and Gulf of Maine showing location of major spawning areas.

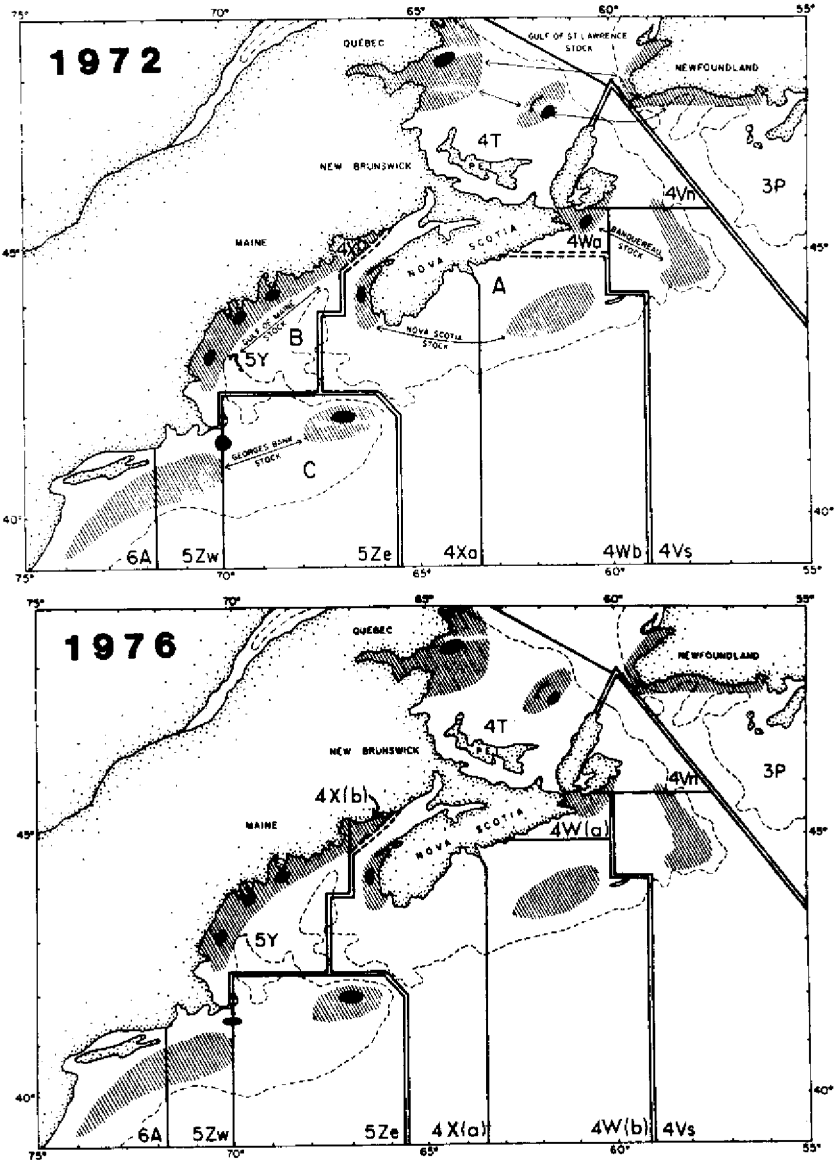

Fig. 2. Historical view of herring stock structure of the Gulf of Maine and Scotian Shelf as perceived by ICNAF in 1972 and 1976 (from ICNAF Redbooks 1972, 1976).

traditionally assumed to be dominated by fish that spawned along the northern edge of the bank (straddling what is now the Canada/USA border) and overwintered south of Cape Cod.

The fisheries of the management units of the Gulf of Maine/Bay of Fundy region have had different histories (Fig. 3), including the dramatic "boom and bust" pattern exhibited by the Georges Bank fishery.

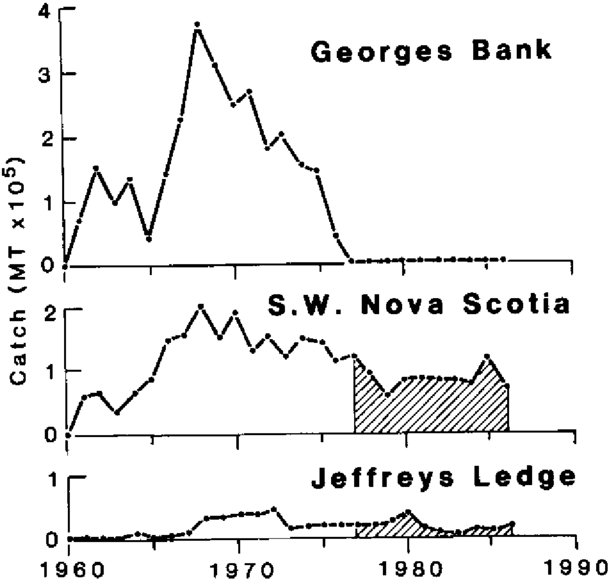

Fig. 3. Historical performance (landings) by the three herring stocks of the Gulf of Maine, 1960-86. Shaded area highlights the situation after the collapse of the Georges Bank stock.

Although there has been agreement on the overall stock structure, several questions led to the stock identification study described here. Paramount among these was the question of the origin of juvenile herring (ages 1-3) that aggregate along the shore of western New Brunswick and eastern Maine. Here, for well over a century, a coastal weir fishery has trapped juvenile herring which still form the basis for the Canadian and American canned sardine industry. It has long been recognized that these fish are not only from local populations and it is assumed that they have a strong 5Y and possibly an historical 5Z link. Tag returns from herring marked in weirs (restricted to larger juveniles) (Fig. 4) show mixing with adjacent fisheries, but do not resolve the question of spawning group affinity and do not provide any information on Georges Bank affinity.

The situation is conceptualized in Fig. 5. Three assessment units are based upon major spawning populations, but also subsume smaller spawning units.

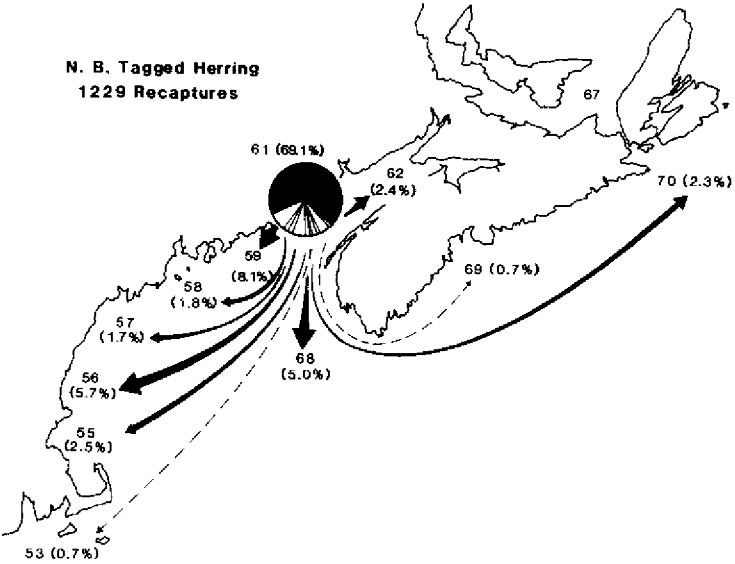

Fig. 4. Tag returns (number and %) from herring tagged in area of juvenile aggregation along the coast of New Brunswick.

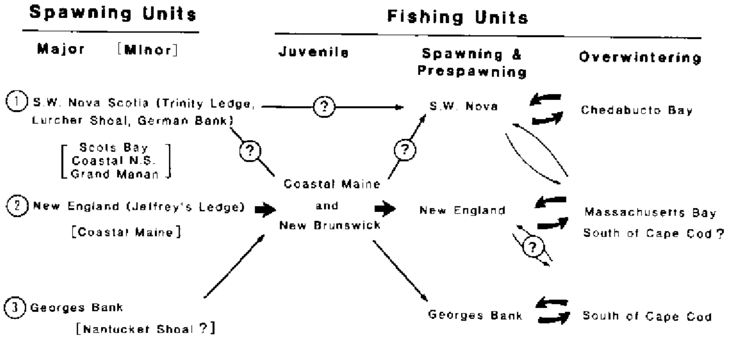

Fig. 5. Conceptual view of stock mixing in the Bay of Fundy and Gulf of Maine herring.

While these groups have been tracked (from fishery and tagging information) to summer feeding and overwintering areas, there is a major question concerning the affinity of juveniles of coastal Maine and New Brunswick.

Another major question concerns the affinity of Georges Bank herring which have recently reappeared - almost a decade after collapse of the commercial fishery (Stephenson and Kornfield, 1990). Related to the Georges Bank reappearance, there is an unresolved question concerning the affinity of spawning herring in the Nantucket Shoals area ... are they part of a Georges Bank (5Z) or coastal Gulf of Maine (5Y) complex?

STOCK IDENTIFICATION STUDY

Our approach to determine how to partition juvenile herring from mixed aggregations into stock units was to first test for the ability to discriminate the stocks of origin. This involved ensuring that samples of adults were ripe and running (discrete populations) and collected from (traditional) spawning sites (i.e., same time, same place each year for a particular stock). This approach differs from many previous studies of herring stock identification in that it restricted collection of samples solely to ripe and running herring, as opposed to collection from a potentially mixed aggregation (Jean, 1967; Boyer and Perkins, 1971; Parsons and Hodder, 1971; Parsons, 1972, 1975; Scott, 1975; McGladdery and Burt, 1985; Chenoweth et al. 1986).

It was felt that a multi-attribute study in conjunction with a multivariate analysis would be the best way to determine stock differentiation. Comparisons are based on meristic traits, fish shape (truss), parasite loads, otolith morphology and genetics (Table 1). This is in contrast to many studies which are restricted to a single attribute or, at best, a few attributes (Parsons and Hodder, 1971; Arthur and Arai, 1980; Coté et al., 1980; McGladdery and Burt, 1985; Roby et al., 1985; Chenoweth et al., 1986; and others).

MATERIALS AND METHODS

Sampling

To avoid sampling from a mixed-stock situation, we collected ripe and running Atlantic herring, *Clupea harengus* at well documented spawning sites in the Gulf of St. Lawrence, Bay of Fundy, Gulf of Maine, southwest Nova Scotia, Bras d'Or Lakes and Georges Bank (Fig. 6). These are assumed to be discrete populations.

A total of 24 samples (2921 specimens) was collected, of which nine populations were sampled during the spawning season on two consecutive years (eight in the years 1985 and 1986 and one in the 1986 and 1987 years) (Table 2). Four other populations were chosen to increase the area of coverage (Bonavista Bay, Nfld., Western Bank, Nauset Harbour and Jeffries Ledge). In 1986, Trinity Ledge spawners were sampled in September in addition to the usual sample taken in August. These samples (Table 2), each consisting of about 100 fish per area, per year, were obtained from commercial fishing vessels (purse seiners and gillnetters), Department of Fisheries and Oceans research vessels J.L. HART and the LADY HAMMOND, and from fixed gear fishermen (weirs and gillnets) during the period May 1985-November 1987. An additional sample of Georges Bank fish was collected by the U.S. National

Table 1. Summary of attributes compared in a northwest Atlantic herring stock identification project.

Category	Attribute
Morphology	Fish shape analysis based on 15 truss point locations.
Meristics	Vertebral count, fin ray counts - pectoral, pelvic, dorsal, anal; gill raker count; pyloric caecae count.
Parasites	Nematodes - *Anisakis simplex* and *Hysterothylacium aduncum*; Digenea - *Derogenes varicus, Brachyphallus crenatus, Lecithaster* spp.; Acanthocephala - *Echinorhynchus gadi*; Cestoda - *Scolex pleuronectis.*
Otolith morphology	Fourier shape analysis - based on nucleus as origin and 72 points around the shape periphery (every 5 degrees). Truss analysis based on 22 point locations.
Genetics	Mitochordrial DNA and electrophoresis (PGI-2, LDH-2, PGM-2) on a limited subsample.

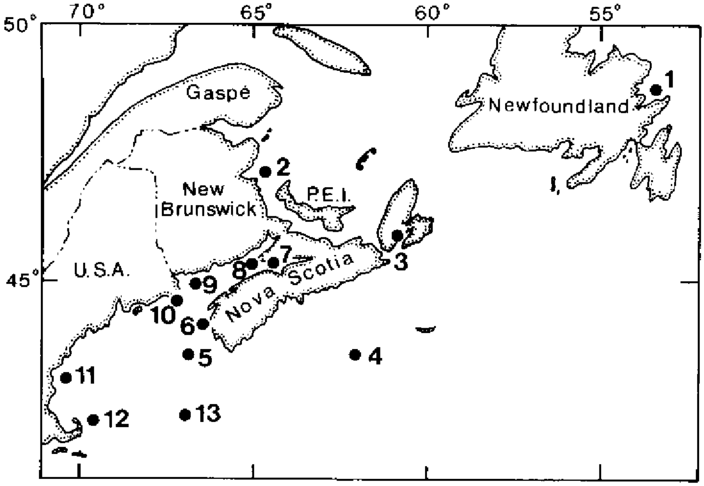

Fig. 6. Locations of collection of spawning herring used in stock identification project: 1 - Bonavista Bay, 2 - Escuminac, 3 - Bras d'Or Lake, 4 - Western Bank, 5 - German Bank, 6 - Trinity Ledge, 7 - Parrsboro, 8 - Ile Haute, 9 - Grand Manan, 10 - Cutler, 11 - Jeffreys Ledge, 12 - Nauset Harbor, 13 - Georges Bank.

Table 2. Details of samples compared in a northwest Atlantic herring stock identification project, 1985-87.

			1985			1986			1987		
Assmt. unit	Spawning group	Month collected	Male	Female	Total	Male	Female	Total	Male	Female	Total
3L	Bonavista Bay	May				1	44	45			
4T	Escuminac	May	47	56	103	53	45	98			
4V	Bras d'Or Lake	May	47	54	101	55	28	83			
4W	Western Bank	Oct.				57	54	111			
4X	German Bank	Sept.	47	51	98	50	50	100			
	Trinity Ledge	Aug.	50	51	101	50	61	111			
		Sept.				2	99	101			
	Parrsboro	May	76	59	135	53	52	105			
	Ile Haute	July	41	59	100	51	56	107			
	Grand Manan	Sept.	49	61	110	50	59	109			
5Y	Cutler	Aug./Sept	50	54	104	111	78	189			
	Jeffreys Ledge	Oct.							119	131	250
	Nauset Harbour	Nov.							64	58	122
5Z	Georges Bank	Oct.				20	13	33			
		Nov.				53	56	109	232	164	396
Total numbers of fish			407	445	852	606	695	1301	415	353	768

Marine Fisheries Service (R.V. ALBATROSS). Herring were measured, individually wrapped in plastic bags, placed flat in fish boxes and frozen as soon after collection as possible (within 1 hour).

Fish shape

Frozen herring were thawed in groups of 15 or 20 and numbered (each fish received a unique numbered tag placed under the gill flap). Total length was measured to the nearest millimeter and weight taken to the nearest 0.1 g. Body thickness was measured just anterior to the insertion of the dorsal fin and at the neurocranial crease using vernier calipers (nearest 0.1 mm).

Landmarks chosen for the truss system (Strauss and Bookstein, 1982) were obtained from whole body radiographs of the left lateral view of each fish. The truss we used contains six cells (31 measurements; Fig. 7). The landmarks, easily seen when the radiograph was placed on a light table, were highlighted using white ink and subsequently digitized for calculation of the interlandmark distances (Winans, 1984).

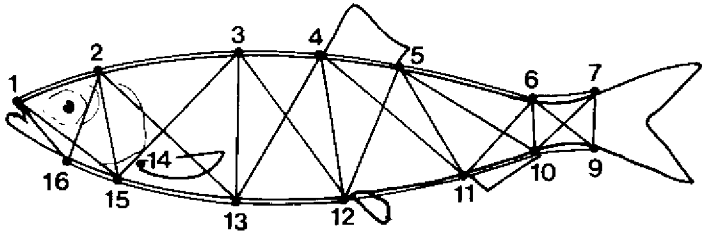

Fig. 7. Truss points used for analysis of herring morphology.

Meristics

For meristic analysis, the dorsal, anal, left pelvic and left pectoral fins were removed, placed flat on a tray, labelled and x-rayed. In general, fin ray counts followed those of Hubbs and Lagler (1958). The dorsal and anal fin rays were counted from radiographs of whole fish. All 'rudimentary' rays preceding the first well developed ones were included in these counts but the last two bases were counted as one ray. All rays of the pectoral and pelvic fins were counted from radiographs using a stereomicroscope. These counts included the smallest ray at the lower or inner end of the fin base and the small ray preceding the first well developed ray. The vertebral counts were done from radiographs of whole fish and included all the vertebrae between the skull and the terminal urostylar segment. The left first gill arch of each fish was removed and counts were taken, on the lower limb only, using a binocular microscope. This count included the bifurcated gill raker straddling the angle of the arch, as well as the smallest protuberances identifiable as rakers. Bifurcated rakers having a common base were counted as a single raker. Pyloric caecae counts were done using a binocular microscope to count the base of each diverticulum. Bifurcated caecae were counted as a single caecum.

Gill rakers, caecae and fins of each fish were preserved in alcohol in a labelled vial for future reference.

Otolith shape

Both otoliths (sagittae) were removed, cleaned and placed in black otolith trays to which they were permanently bound using a clear resin (Hunt, 1987). They were mounted with their concave (distal) surface upwards, ready for ageing and shape analysis. The right otolith was used for shape analysis. Otoliths were drawn, using a camera lucida attachment on a binocular microscope, with the outer edge being drawn first, followed by the first annulus and nucleus. The otolith shape was based on measurements from 1) 26 truss points (Fig. 8), 2) 72 polar coordinates for Fourier shape analysis (Ehrlich and Weinberg, 1970; Ehrlich and Full, 1983), 3) area, and 4) perimeter.

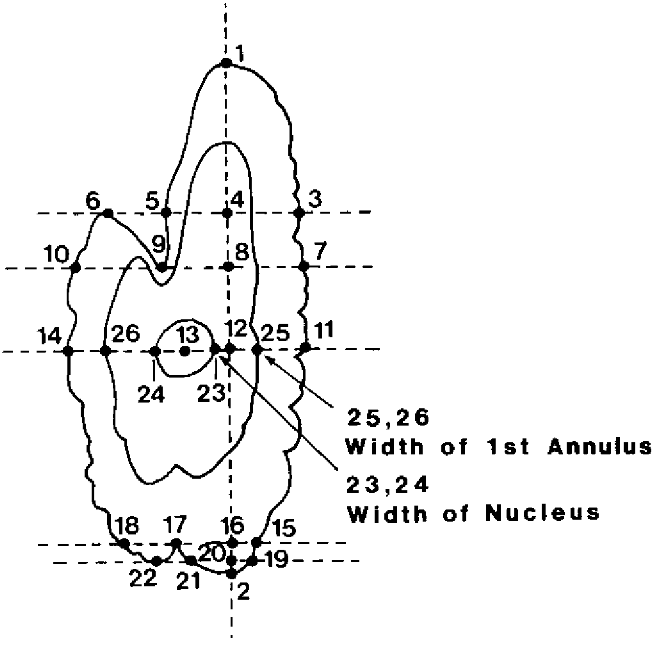

Fig. 8. Points used for herring otolith shape analysis.

Parasites

Fish were examined thoroughly for eight parasite types including: *Anisakis simplex* located in the body cavity, mesentaries and musculature; *Hysterothylacium aduncum* located in the pyloric mesentaries; *Echinorynchus gadi* from the intestine; *Brachyphallus crenatus* and *Derogenes varicus* from the stomach; *Lecithaster* spp. from the intestine; *Scolex pleuronectis*, a cestode tetraphyllidean from the intestine and stomach; and the myxosporidian *Kudoa clupeidae* beneath the skin.

As a preliminary look at the parasite data, comparisons from several stocks have been done with little regard for standardization for host age/length. We are presently attempting to describe types of parasite frequency distributions as a function of host age/length. It is hoped that by modelling changes in the abundance and dispersion patterns of parasites within different stocks we will be able to determine if a common model exists for all stocks. A common model allows a comparison of all data from several populations using a regression approach (Myers and Brattey, 1990), instead of the usual comparisons to a single host age/length group for stock comparisons as is generally done (Bichop and Margolis, 1955; Davey, 1972).

RESULTS AND DISCUSSION

This study is still in progress. Laboratory analysis has been completed and results are being compiled for separate papers dealing with morphometric/meristics, parasites and otolith shape. Here we summarize preliminary results of meristic and parasite analyses.

Meristic data analysis

The samples shown in Table 2 are arranged, in general, in order of decreasing latitude and each sample is further subdivided by sex. An evaluation of within-sample variability indicated that no significant differences occurred between each attribute in regards to sex or age so that data from each category could be pooled to increase sample size.

A one-way analysis of variance (meristics vs populations) resulted in statistical differences occurring between populations for all meristic traits in both 1985 and 1986. A multiple range test (Student-Newman-Keuls) shows that the pectoral, gillraker and caecae counts have been the most useful attributes in separating populations on a univariate analysis basis. Pectoral counts separate Escuminac and Bonavista Bay from all other populations but not from each other (Fig. 9). Bras d'Or Lake is different from Bay of Fundy, Georges Bank and Western Bank populations. Parrsboro is different from remaining Bay of Fundy populations, Georges Bank and Western Bank (Fig. 9). A similar pattern exists for gillraker counts and caecae counts (Fig. 10 and 11, respectively).

Parasite prevalences

Seven parasite species were identified from the herring examined (Table 1). *Scolex pleuronectis* was rarely observed but, when it occurred, it was generally restricted to fish from Georges Bank. Also, *Echinorhynchus gadi* was rare and of little use as a biological indicator for different stocks. *Anisakis simplex*, however, was sufficiently common to show potential as a biological indicator for herring in the study area.

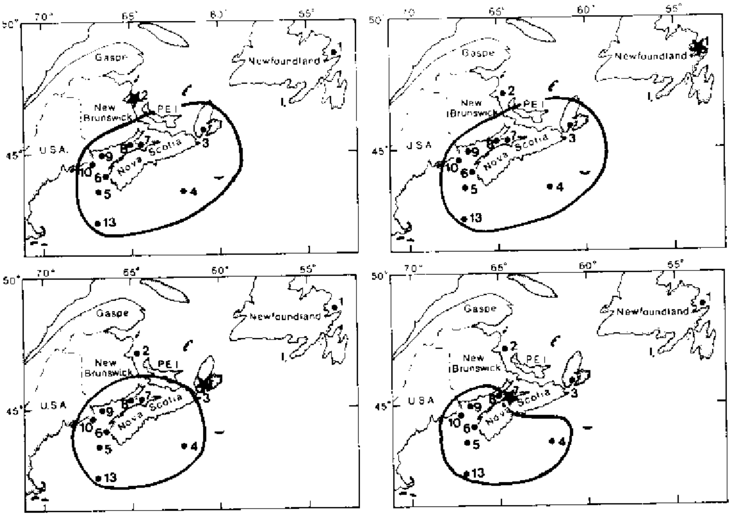

Fig. 9. Discrimination of spawning groups of herring of the Bay of Fundy and Gulf of Maine on the basis of pectoral fin ray counts in 1986.

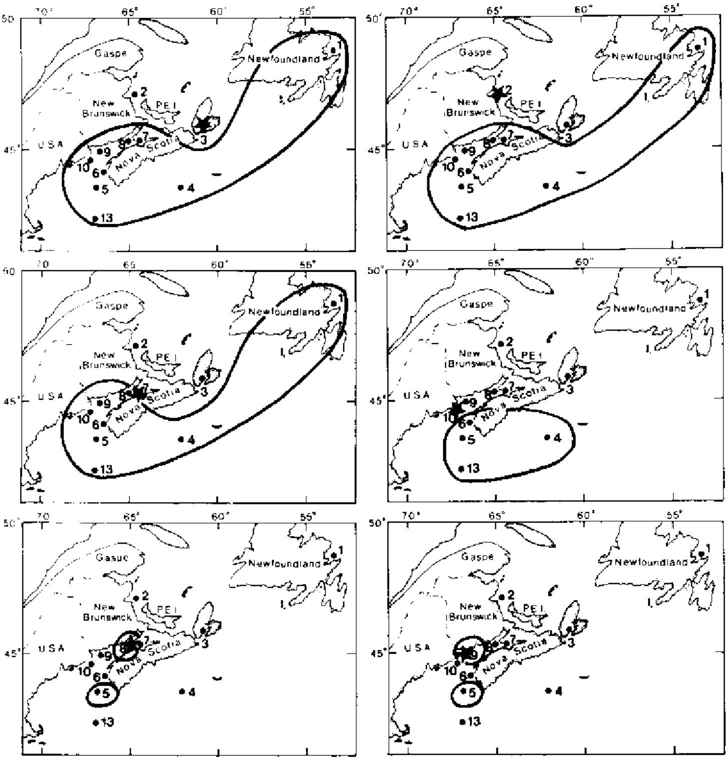

Fig. 10. Discrimination of spawning groups of herring of the Bay of Fundy and Gulf of Maine on the basis of gill raker counts (1986).

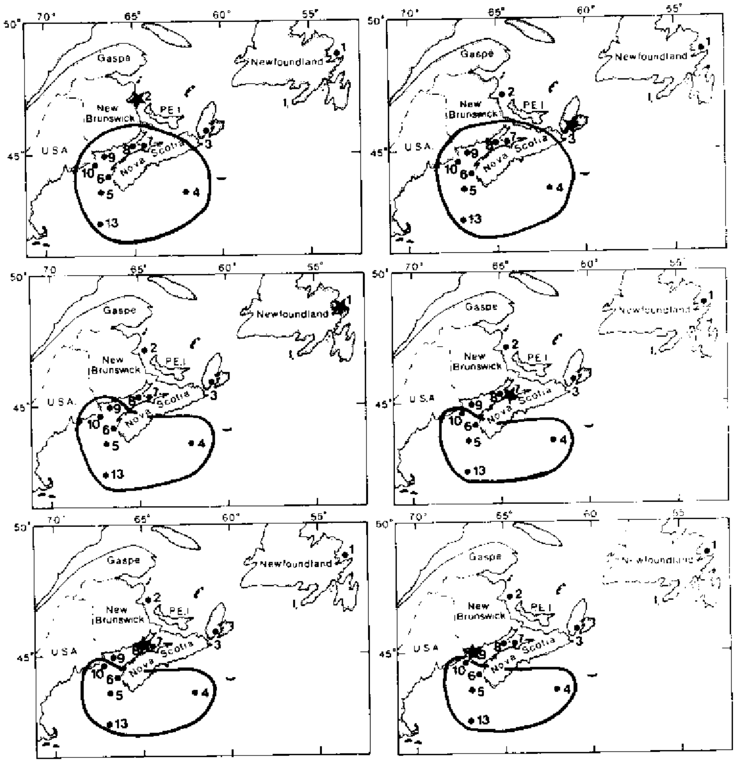

Fig. 11. Discrimination of spawning groups of herring of the Bay of Fundy and Gulf of Maine on the basis of pyloric caecae counts (1986).

Prevalence (percent infected; Margolis et al., 1982) of *Anisakis simplex* increased with herring age/length and showed fairly consistent variation in geographic distribution. Herring collected from Grand Manan and off Cutler Harbor in 1986 and 1987 consistently showed the lowest prevalence of all fish examined, except for Jeffreys Ledge in 1987 (6.8%). The highest prevalence occurred in fish collected from Ile Haute in 1985 (67%) and Parrsboro in 1986 (70%). Thus, there appear to be stock differences which we hope to demonstrate by using a regression approach for interpopulation comparisons.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Estimation of Spawning Biomass for Pacific Herring of Port Moller, Alaska: Comparison of Larval Surveys with Aerial Surveys

M.D. McGurk
Triton Environmental Consultants Limited
Richmond, British Columbia, Canada

It is difficult to estimate the spawning biomass of Pacific herring, *Clupea harengus pallasi*, in the Bering Sea because its coastal waters are often too turbid to permit aerial surveys of spawning adults. Stock assessments based on densities of newly-hatched herring larvae may be more reliable.

In May-June, 1989, a fortuitous coincidence of excellent 'seeing'conditions for aerial surveys and a study of the population dynamics of herring larvae in Port Moller on the northern shore of the Alaska Peninsula (Fig. 1) provided a unique opportunity to compare spawning biomasses estimated from aerial surveys and from larval surveys.

On May 28, 1989, aerial surveyors spotted a substantial biomass of herring travelling southwest along the coast of the Alaska Peninsula between Port Heiden and Port Moller. The next day, approximately 1,182 t of herring was observed by pilots of the Alaska Department of Fish and Game (ADF&G) near Bear River northeast of Port Moller. On May 30, peak biomasses of 1,016 and 748 t were observed in Herendeen and Moller Bays, respectively, for a total spawning escapement of 1,764 t. These fish must have spawned quickly and then left because only 7 t were observed on May 31 and June 1.

Samples of plankton were taken in Port Moller with a 60 cm diameter bongo net (333 μm mesh) between June 11 and 14 by Triton Environmental Consultants Ltd. By multiplying the density of herring larvae at each of 15 plankton stations by the volume of water around each station, I calculated that the May 30 spawners produced one cohort of 7.0641×10^9 larvae with an average age of 5 d (Figs. 2-4). The cohort had a mortality rate (Z) of 0.53 d^{-1} over the 2-8 d age range and a Fickian diffusion rate (K) of 1.361×10^7 $m^2 \cdot d^{-1}$ (Fig. 5), which was equivalent to an average velocity of dispersion (v) of 5.4 $km \cdot d^{-1}$, assuming that $v = \pm 2(KZ)^{1/2}$ (Okubo, 1980). Since no larvae were found outside the estuary, I concluded that the larvae either did not have sufficient time to disperse out of the estuary, or that dispersion rapidly decreased with ages greater than 5 d.

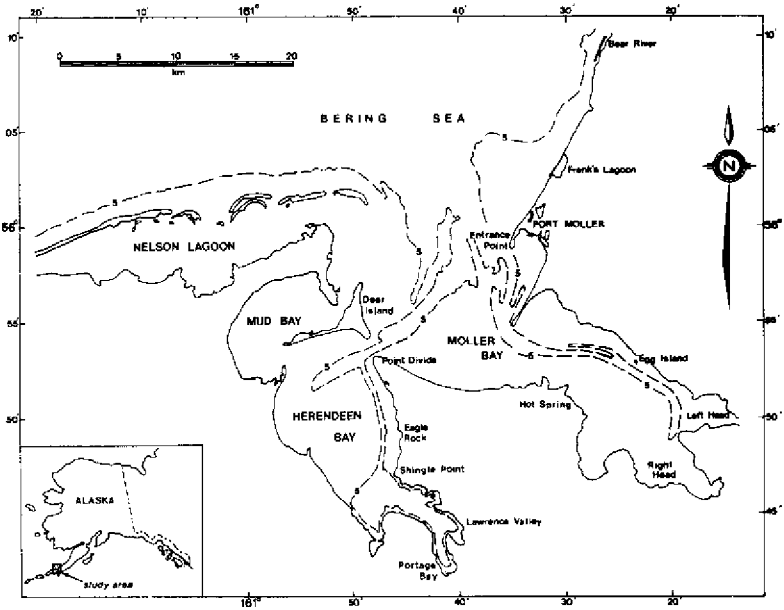

Fig. 1. Map of Port Moller, Alaska, showing the 5 fathom line. In early June, 1989, Pacific herring spawned on beds of eelgrass at the heads of both Moller and Herendeen Bays. The spawning events were not seen because of turbid water.

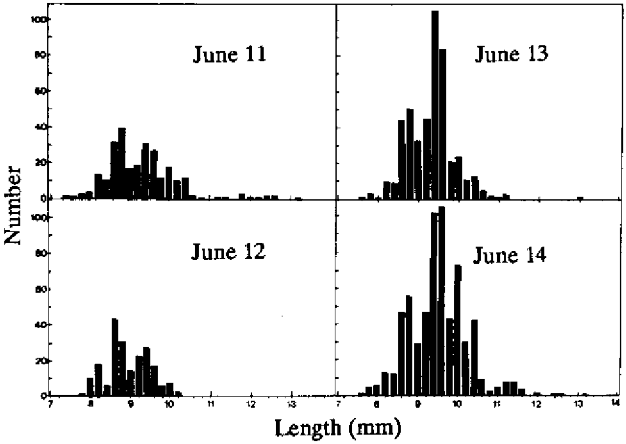

Fig. 2. Length frequencies of herring larvae taken in Port Moller in June 1989 show two cohorts: cohort 1 in the the length range 11-14 mm and cohort 2 in the length range 7-11 mm. There were too few cohort 1 larvae to allow any population analysis. Most of the cohort 2 fish still carried a yolk sac. From their average length and an estimated growth rate of 0.25 $mm \cdot d^{-1}$, cohort 2 larvae were calculated to have hatched on June 10-11 from eggs laid two weeks earlier. They are the subject of this report.

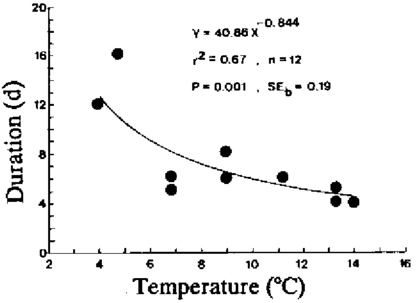

Fig. 3. Duration of the yolk sac stage of herring larvae decreases with increasing water temperature. Data from Alderdice and Velsen (1971). This relationship was used to assign an average age to samples of cohort 2 herring larvae.

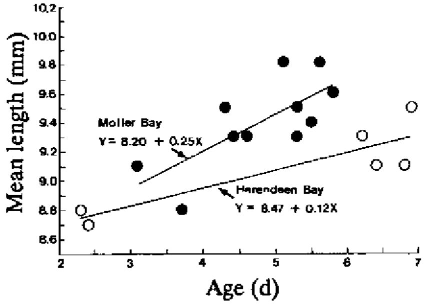

Fig. 4. Growth rate (but not length at age 0 d) of cohort 2 herring larvae was significantly (P=0.001) higher in Moller Bay than in Herendeen Bay because average water temperatures were 2-5°C higher in the head of Moller Bay due to its shallower water.

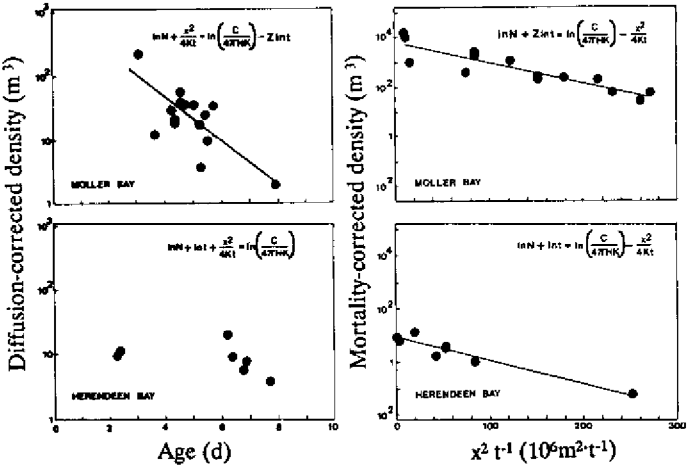

Fig. 5. Diffusion- and mortality-corrected densities of cohort 2 herring larvae show the fit of the population model N = (C/4πHKt)exp[-(x^2/4Kt)-Zt], where N = density (m^{-3}) of herring larvae, C = the number of newly-hatched herring larvae, H = the mean depth of larval distribution (m), K = the coefficient of Fickian diffusion ($m^2 \cdot d^{-1}$), x = distance (m) from a plankton station to the origin of the x-coordinate system laid over the estuary, and Z = coefficient of mortality (d^{-1}). A constant mortality fit the data from Moller Bay, but no mortality function fit the data from Herendeen Bay. The assumption of Fickian diffusion was well supported by the data from both bays.

A spawning biomass ranging from 1,788 to 2,241 t was back-calculated from larval abundance by assuming a sex ratio of 1:1, an average fecundity of 200 eggs·g^{-1} of wet female body weight, an egg incubation time of 14.2 d, 79 to 99% egg survival during incubation, 71% hatching success, and 83% viability of the larvae. These values were obtained from a review of the scientific literature (Table 1). Egg incubation time was based on average water temperature at the head of Moller Bay. The latter three percentages are appropriate for light intensity spawning on eelgrass beds, which was the most probable spawning intensity and substrate for Port Moller herring. Back-calculated spawning biomass was most sensitive to perturbations in larval age and mortality and least sensitive to perturbations in egg incubation time and egg mortality (Table 2).

Table 1. Parameters used to backcalculate the biomass of spawners that produced cohort 2. The equation was $B = (2N_t/10^6 s_2 s_3 F_r)\exp(Z_e t_e + Zt)$ where B = spawning biomass (t), F_r = fecundity (eggs·g^{-1}), Z_e = mortality (d^{-1}) of eggs during incubation, t_e = duration (d) of incubation, s_2 = fraction of larvae that survive hatching, and s_3 = fraction of larvae that are sufficiently viable to enter the plankton, Z = mortality (d^{-1}) of larvae, t = age of larvae and N_t = total number of herring larvae at age t. Biomass was doubled under the assumption of a 1:1 sex ratio.

Parameter	Value	Source
F_r	200	Hay (1985), K. Rowell (pers. comm., ADF&G, Anchorage, Alaska)
Z_e	0.0008-0.0166	Tibbo et al. (1963), Caddy and Iles (1973), Dragesund and Nakken 1973), Johannessen (1986)
t_e	14.2	This report, Alderdice and Velsen (1971)
s_2	0.71	Hourston et al. (1984), Johannessen (1986)
s_3	0.83	Hourston et al. (1984)
Z	0.53	This report
t	2-8	This report
N_t	1.361×10^7	This report

Table 2. Response of the equation shown in Table 1 to perturbation of its parameters.

		Perturbation			
Parameter	Value	-25%	-5%	+5%	+25%
N_t	1.361×10^7	-25.0	-5.0	5.0	25.0
Z	0.53	-49.0	-12.6	14.3	96.0
t	5.0	-49.0	-12.6	14.3	96.0
Z_e	0.0008	-0.2	0.0	0.2	0.4
t_e	14.2	-0.2	0.0	0.2	0.4
s_2	0.71	33.3	5.3	-4.8	-20.0
s_3	0.83	33.3	5.3	-4.8	-20.0
F_r	200	33.3	5.3	-4.8	-20.0

This comparison shows that larval surveys may be used to estimate herring spawning biomass if reliable estimates of larval age and larval mortality can be calculated directly from the surveys. More comparisons of larval surveys with aerial surveys are needed to determine if larval surveys are truly reliable and cost-effective. Comparisons with SCUBA surveys of egg density or sonar surveys of adult spawning biomass should also be attempted. It is possible that larval surveys may be more cost-effective than these latter two techniques because larvae are more easily located than eggs in turbid waters, and because larvae are more easily captured than sonar images of adult spawners, especially in Port Moller where spawners rarely spend more than two tidal cycles near the spawning grounds.

ACKNOWLEDGEMENTS

This study was wholly funded by the Minerals Management Service of the U.S. Department of the Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program (OCSEAP).

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Population Biology

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Changes in Larval Survival and Subsequent Recruitment to the North Sea Herring Stock, Year-Classes 1980–1989

P. Munk
Danish Institute for Fisheries and Marine Research
Charlottenlund, Denmark

ABSTRACT

After a period of low recruitment to the North Sea herring stock, the magnitude of recruitment steadily increased from year-classes 1980 to 1986. However, from year-class 1987 onwards, a new decline in recruitment is observed.

Two survey programs measuring larval abundance in the North Sea supply information about larval survival in the period. Until 1986, there was a good correlation between abundance of newly hatched larvae, 6-month-old larvae, and 18-month-old recruits. The subsequent increase in stock size resulted in increasing production of early larvae; however, from year-class 1987, the abundance of 6-month-old larvae (as well as recruitment) was no longer correlated to amount of early larvae produced. Surveys of larval abundance in November 1986 and 1987 indicated that survival already was different between years in the October–November period. Thus, the latest changes in recruitment to the North Sea herring stock can be interpreted from larval data, and observations suggest that events in the autumn period of larval life determine recruitment level.

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Feeding Behavior and Prey Size Spectra of Larval Herring (*Clupea harengus* L.)

P. Munk
Danish Institute for Fisheries and Marine Research
Charlottenlund, Denmark

ABSTRACT

The traditional interpretation of an increasing niche width with fish size has lately been questioned. Renewed analysis of stomach content data (Pearre 1986) suggest that the ratio-based niche width remains constant when fish grow.

In the present study, the development in prey size spectra of larval herring has been investigated in detail. An experimental series was set up for comparing feeding behavior by a range of larval sized against a range of prey sizes (copepods).

Levels of activity, attack rates, and feeding success showed relation to prey size. The calculated effective search rate increased with prey size until a given size, whereafter the rate declined. The width of the ratio-based prey size spectra was approximately the same irrespective of larval size.

Experimental findings are related to observations on field collected larvae, and prey availability during the autumn-winter growth period of North Sea herring larvae is evaluated.

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Egg Loss in Herring Spawns in Georgia Strait, British Columbia

C.W. Haegele and J.F. Schweigert
Department of Fisheries and Oceans
Nanaimo, British Columbia, Canada

Abstract-We sampled herring spawn for egg loss in Lambert Channel. Eight transects with 10-25 stations per transect were examined on alternate days from day 4-14 of the incubation period. We developed a statistical model to explain the observed variation in egg density. Results indicated that egg density declined at different rates on different vegetation types. In addition, the rate of egg loss was related to transect location. Consequently, no general model of egg loss could be formulated without accounting for this location effect in some way. Egg loss was greater in shallow water and at sites where diving ducks congregated. Egg loss for all samples was 58%. It was highest on *Fucus* sp. in shallow water (92%) and lowest on red algae in deep water (46%). Reduced egg density on vegetation occurred with small decreases in egg layers and percent cover of the vegetation, but no observed change in plant height. Egg density on bottom substrate decreased dramatically in the intertidal zone, where *Fucus* sp. was the dominant vegetation, but showed no significant trend with time elsewhere. There were up to 50,400 birds in the study area. Most fed on spawn. Gulls, diving ducks, geese, and crows consumed an estimated 198 t of spawn. Epibenthic invertebrates (mostly crabs, snails, and starfish) consumed about 264 t of spawn. About 7.1% of the eggs were lost to predation. The other egg loss, i.e. from physical removal and translocation, could not be directly estimated.

INTRODUCTION

Herring egg loss from spawning grounds in British Columbia is of concern primarily because stock assessments use spawn survey data to estimate spawner biomass. Spawning ground surveys, especially those conducted by SCUBA divers, collect data on vegetation type, density, and height and on the number of egg layers on vegetation and bottom substrate. Egg density is then calculated from these observations and used with information on spawning bed size and patchiness of egg deposition to estimate egg numbers and ultimately spawner biomass (Schweigert and Fournier 1982; Schweigert et al. 1985, 1990). If egg loss before spawn surveys is sufficient to alter visual observations, then this would result in underestimates of spawner biomass. In addition, egg loss causing egg death reduces the number of larvae produced, which may affect recruitment and hence, ultimately, stock size.

Several studies examined egg loss from Pacific herring spawns but there is no consensus on its magnitude. The two major causes of egg loss are predation and physical translocation through wave action. Munro and Clemens (1931) observed, inventoried, and sampled birds on herring spawning grounds over several years. They concluded that, near Nanaimo on the east coast of Vancouver Island, 12,000 ducks consumed the spawn from 36 t of herring and that 40,000 gulls ate an undetermined number of eggs. Outram (1958) found that 56-99% of eggs on intertidal eelgrass (*Zostera* sp.) in Barkley Sound, on the west coast of Vancouver Island, were lost during incubation. Egg loss from bird predation amounted to 30-55%, with the remainder due to wave action. Vermeer (1981) estimated that 75,000 surf scoters (*Melanitta perspicillata*) occurred along the west and east coasts of Vancouver Island during two weeks in March, 1978. They consumed the eggs from 1030 t of herring. The herring spawning stock biomass for the west and east coasts of Vancouver Island in 1978 was estimated at 75,000 t (Haist et al. 1987); consequently surf scoters would have removed about 1.4% of the eggs. About 22,000 birds (chiefly gulls and diving ducks), 26 million invertebrates (starfish and snails), and 8 gray whales consumed the eggs from an estimated 271, 1021, and 235 t of herring, respectively, during the 1988 spawning season in Barkley Sound (Haegele and Schweigert 1989). This accounted for about 20% of the eggs deposited in the study area. Palsson (1984) reported egg losses of 95-99% from very light density spawns in Puget Sound. Bird predation was the major cause of loss, followed by snail and gammarid predation. Two studies on the east coast of Vancouver Island examined egg loss from wave action. Hart and Tester (1934) estimated that 40% of eggs in one spawn was washed ashore and that 70% of these eggs died. Hay and Miller (1982) found that 26% of eggs in a spawn was cast ashore in windrows. Both studies noted that adjacent spawns did not appear to experience this magnitude of egg loss.

Egg loss may be estimated in two ways. Spawn can be sampled throughout the incubation period to quantify any decrease in egg density. Alternately, sources of egg loss can be identified and estimated. In this study, both approaches were used. Spawn was sampled by making standard visual observations of the type used to estimate egg density from SCUBA surveys of herring spawn (Schweigert and Fournier 1982) and spawn samples were harvested for egg density estimates. Predators were identified and enumerated. No attempt was made to determine rations for avian predators. Results from laboratory experiments were used to estimate rations for epibenthic predators. Egg loss from wave action was not estimated because no substantial windrows of eggs were encountered.

METHODS

Herring spawn sampling

Herring spawn was sampled on Denman and Hornby islands in Georgia Strait (Fig.1), from March 10-19, on transects marked with gillnet leadline, laid perpendicular to shore. At least 10 samples were collected on each transect and the maximum distance between sampling stations was 20 m. Hence, spacing between sampling stations and the number of stations per transect depended on spawn width; minimum distances between stations were 5 m and maximum number of stations was 25. Sample plots were 0.5 m^2 quadrats, a square with 0.7 m sides. We attempted to make quadrat placement non-selective by laying one side of the quadrat along the transect line and flipping the quadrat once to the left.

Transects were sampled on alternating days, beginning on incubation day 6 for earlier spawn and incubation day 4 for later spawn. It was not possible for SCUBA divers to sample spawn safely earlier in the incubation period because of gillnet fishing. Visual observations of (1) % cover of vegetation (the proportion of the quadrat covered by vegetation), (2) vegetation type (*Fucus* sp., *Sargassum muticum*, *Zostera* sp., and red algae, (3) plant height, (4) egg layers on vegetation and on bottom substrate, and (5) depth were made at each station. Vegetation rooted within the quadrat and attached eggs were removed for further analysis. Observed depth was corrected to chart datum.

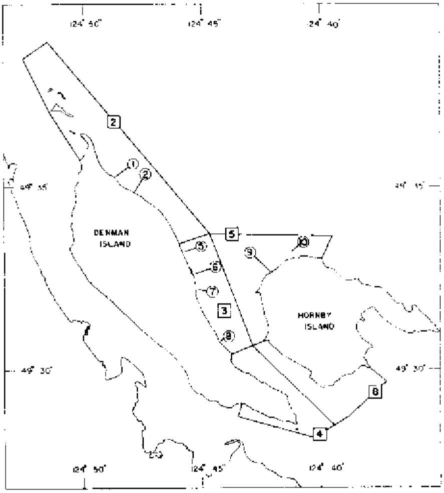

Fig. 1-Lambert Channel study area in Georgia Strait, British Columbia. Outlined areas are bird count sectors and lines are transects used in bottom sampling.

Harvested vegetation and eggs were separated by vegetation type into fractions, which were weighed, and weighed subsamples preserved in Gilson's fluid. These were immersed in alcoholic (25% by volume) 1N KOH at 40° C for approximately 30 minutes to liberate the eggs. (This solution dissolves the glue by which herring eggs are attached.) Eggs were then stored in 10% formalin for at least 1 week to harden. The preservative was vacuum extracted, the eggs weighed, and two aliquots of approximately 200 to 400 eggs removed. Eggs were weighed and counted. The number of eggs on each vegetation type was then calculated and eggs•m^{-2} was twice the sum of these estimates. Each sample was assigned to a dominant vegetation type based on which type had the most eggs attached. Eggs on the bottom were estimated from egg layer observations [1 layer = 340,000 eggs•m^{-2} (Haegele et al. 1979)].

Predator censusing

Invertebrates that were observed or suspected of eating herring eggs were enumerated once at each site by counts in quadrats (small organisms) and by counts within 1 m of the transect leadline (larger organisms). Birds were surveyed from a boat, travelling near and parallel to the beach at low speed, by two observers using binoculars. Counts were made in each of 5 sectors (Fig. 1) on alternate days, from March 3-19, and on March 22 and April 4, 1989. Birds were identified to species, where possible, and grouped into abundance and behaviour categories (gulls, scoters, other diving ducks, other diving birds, and non-diving birds).

When required, egg weights were converted to egg numbers using an individual egg weight of 2.38•10^{-3} g (Hay and Miller 1982). Egg numbers were converted to spawners using a relative fecundity of 1.0•10^{8} eggs•t^{-1} (Hay 1985).

RESULTS

Herring spawned in the study area March 2-16, 1989. Spawning activity was periodic and increased near high tides. In each location, spawning activity averaged 4 days. On Denman I. spawning began in sector 3, and progressed NW to sector 2 and SE to sector 4 (Fig. 1). On Hornby I. spawning began in sector 5 and progressed SE into sector 8, as well as along the NE shore, which was outside of the study area. Thus, for an average 14 day incubation period, spawn was available to highly mobile predators (birds and fish) for 28 days, March 2-29, and to sessile and less mobile predators (bottom invertebrates) for 18 days.

Herring Spawn Samples

We tried to develop a model to describe variation in egg density over the incubation period in the most parsimonious fashion possible. Several models were evaluated. These included some or all of the following factors: depth, dominant vegetation type, transect, incubation day, as well as various interactions among these factors. The model which best described variation in egg density was:

$$\ln \left(Eggs_{ij} \right) = Day + Veg_i + \left(Veg_i \cdot Trans_j \right) \qquad (1)$$

where

$Eggs_{ij}$ = number of eggs in thousands in each sampling quadrat on each transect for each incubation day,

Day = incubation day

Veg$_i$ = predominant vegetation, 1 of 6 potential classes: *Fucus* sp, *Sargassum muticum*, *Zostera* sp., red algae (stringy or leafy), and kelp.

Trans$_j$ = 1 of the 8 sampling transects

This model accounted for 49 percent of the total variation in egg density. It is based on 592 observations from which 36 parameters were estimated. All models investigated explained a similar proportion of the total variation in these data. However, those models which did not include a logarithmic transformation for egg numbers accounted for about 10 percent less of total variation. Equation 1 indicates that there were significant differences in the rate of egg loss over the course of the incubation period depending on the vegetation substrate and that this rate of egg loss differed between transects for a given vegetation type. The latter effect could be a reflection of differences in depth or degree of exposure of the eggs to wind and wave action. Due to the complexity of this model it is not possible to determine an average rate of egg loss over the incubation period.

Furthermore, the data are difficult to examine visually since there are several samples

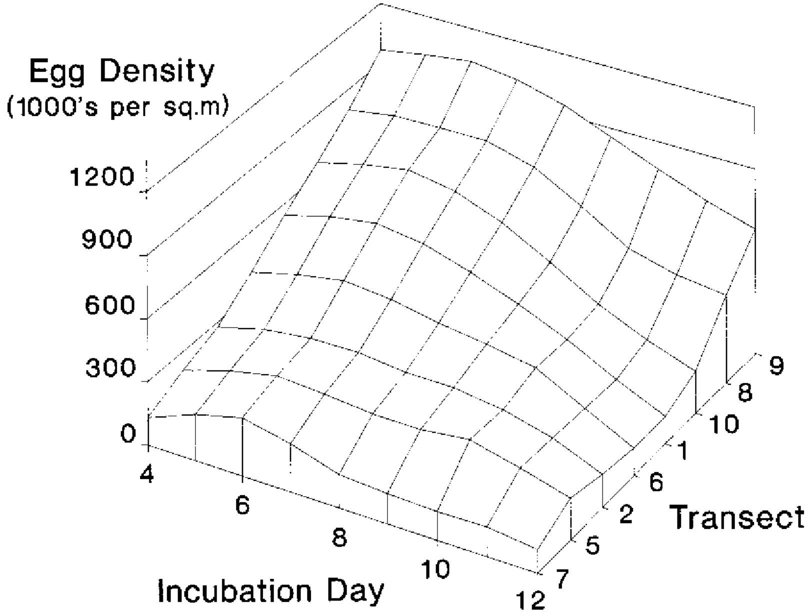

Fig. 2-Smoothed surface, using PROC G3GRID in the Statistical Analysis System (SAS, 1985), fitted to the mean egg density for each day for each transect.

for each transect on each sampling day making it impossible to discern trends in egg numbers over time due to. the sampling variability. To clarify the relationship between egg loss and incubation day, the average egg density for each transect on each day was determined and PROC G3GRID in the Statistical Analysis System (SAS, 1985) was used to fit a smoothed surface to these data which are plotted in Fig. 2. Egg density differed substantially between transects but the rate of egg loss over time was similar for all transects. This suggests that a similar proportion of the total egg numbers was lost independent of the absolute egg numbers. Some of the initial increase in egg numbers on some transects is probably due to sampling variation associated with redeploying the transect line on each sampling day.

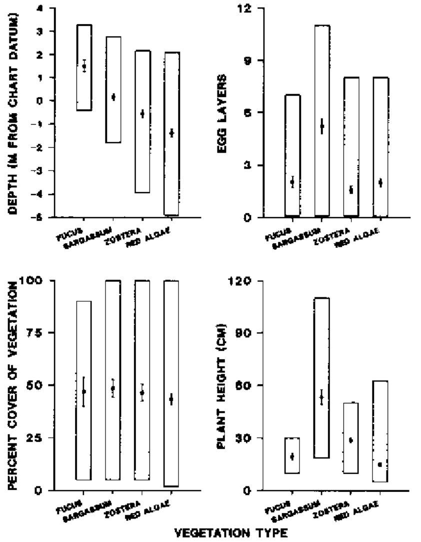

Fig. 3-Range (box), mean (circle), and 95% confidence interval (bars) for observations, by vegetation type of sample.

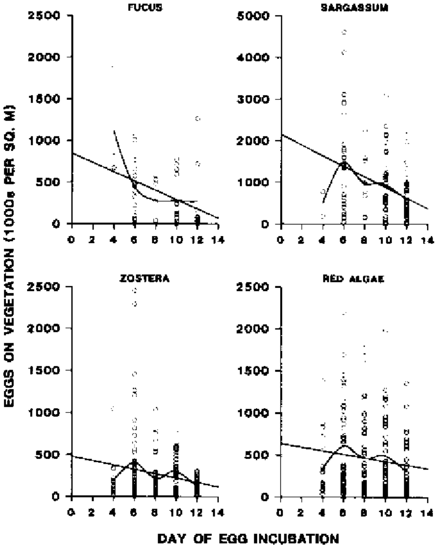

Fig. 4-Plot of egg density on vegetation by incubation day. Distance weighted least squares and linear regression lines were fitted.

Spawn was deposited between 3.2 m above to 4.9 m below Chart Datum. Mean depth of spawn was shallowest on *Fucus* sp., intermediate on *Sargassum muticum* and *Zostera* sp. samples, and deepest on red algae samples (Fig. 3). Egg layers were thicker and plant height greater on *Sargassum muticum* than on the other vegetation types (Fig. 3). Percent cover was similar for all vegetation types (Fig. 3). The data were extremely variable and linear regressions of measurements and observations with incubation day at best explained 17% of the variation. Plots of egg density with incubation day showed a decline for all vegetation types (Fig.4). For all samples, mean egg density declined from 607,966 eggs•m^{-2} on the first sampling day (incubation day 4 or 6) to 303,786 eggs•m^{-2} on incubation day 1 2. A loss of 58% of the eggs over the 14 day incubation period is

Table 1. Observed means of measurements and observations for first sampling period (day 4 and 6) and last sampling period (day 12) and predicted values from linear regressions (y = a + bx) of observations or measurements (y) for first and last incubation day (x).

Veg.	Measurement or	Observed mean		Predicted value	
type	observation[a]	day 4 & 6	day 12	day 0	day 14
All	Egg_v	608.0	303.8	732.0	301.0
	Egg_b	73.7	53.2	224.1	137.3
	Lay_{ev}	2.5	2.5	2.1	2.8
	PC	51.6	38.9	57.3	39.8
	Ht	26.4	31.9	18.9	34.3
Fucus	Egg_v	534.2	267.8	846.4	65.2
	Egg_b	202.1	33.1	515.6	2.3
	Lay_{ev}	2.5	1.5	2.5	1.7
	PC	54.7	50.6	57.2	41.2
	Ht	15.6	25.0	13.2	23.4
Sargassum	Egg_v	1443.9	575.2	2147.7	368.6
	Egg_b	77.2	45.0	180.6	119.1
	Lay_{ev}	5.8	5.0	6.9	4.7
	PC	59.3	39.7	70.1	40.9
	Ht	47.1	64.0	37.8	58.8
Zostera	Egg_v	357.9	115.5	480.3	118.1
	Lay_{ev}	1.7	1.3	1.3	1.8
	PC	50.2	34.6	59.8	39.2
	Ht	31.2	27.4	32.2	27.2
Red algae	Egg_v	526.3	295.3	634.5	338.8
	Egg_b	111.6	113.8	170.6	179.1
	Lay_{ev}	2.0	1.9	2.3	1.8
	PC	49.8	40.2	53.3	36.5
	Ht	14.3	16.2	13.0	16.5

[a]-Egg_v = eggs on vegetation in $1000\text{s}\bullet\text{m}^{-2}$
-Egg_b = eggs on bottom substrate in $1000\text{s}\bullet\text{m}^{-2}$ (samples with no observed eggs on bottom were omitted)
-Lay_{ev} = egg layers on vegetation
-PC = percent cover of vegetation
-Ht = height of plants in cm

indicated by the regression (Table 1). Egg loss varied with the vegetation type on which the eggs were deposited (Fig. 4). On *Fucus* sp., which occurred mostly intertidally, 92% of the eggs, from an initial density of 846,420 $\text{eggs}\bullet\text{m}^{-2}$, were estimated to have been lost. Initial egg density was estimated at 2,147,740 $\text{eggs}\bullet\text{m}^{-2}$ for spawn on *Sargassum muticum* and 83% of the eggs were estimated to have been lost. On *Zostera* sp., the initial egg density was estimated at 480,260 $\text{eggs}\bullet\text{m}^{-2}$ and egg loss to hatching at 75%. Egg loss was least on the red algae, which occurred in deeper water, with an estimated egg loss of 46% from 634,449 $\text{eggs}\bullet\text{m}^{-2}$ over the 14 day incubation period.

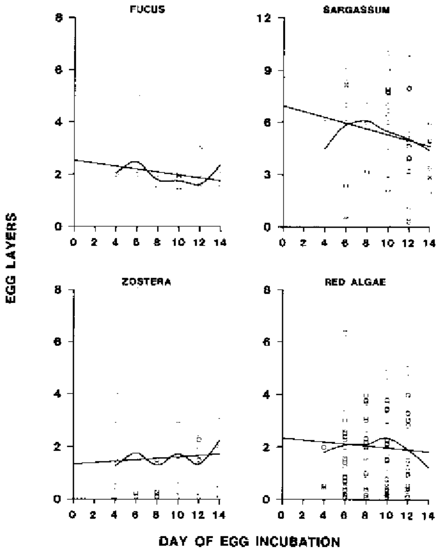

Fig. 5-Plot of egg layers on vegetation, fitted with distance weighted least squares and linear regression lines.

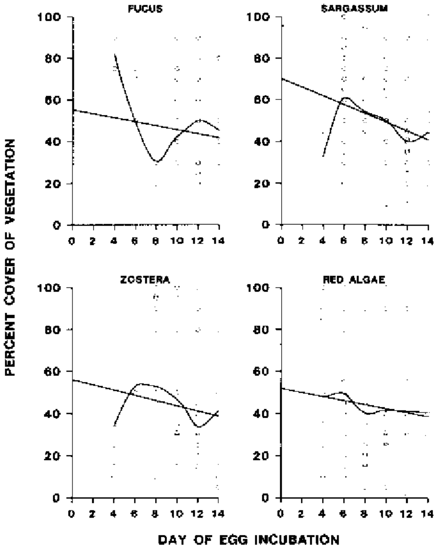

Fig. 6-Plot of vegetation percent cover, fitted with distance weighted least squares and linear regression lines.

Egg layers showed no clear trend with time. On the first sampling day mean egg layers for all samples was 2.50 and on incubation day 12 the mean was 2.48 egg layers (Table 1). Plots of egg layers with incubation time, for the four vegetation types, indicate a slight downward trend (Fig. 5). Mean egg layers on *Sargassum muticum* were significantly higher with a mean of 5.76 (SE = 0.44) egg layers in the first sampling period. Initial sampling period mean egg layers for the other vegetation types was 2.45 (SE = 0.27) for *Fucus* sp, 1.65 (SE = 0.21) for *Zostera* sp., and 2.00 (SE = 0.19) for red algae.

Percent cover of vegetation appeared to be randomly distributed over the available range and there seemed to be a slight decrease with time (Fig. 6).

Plant height, for all samples, showed an increase over the incubation period, but this observation was not made for 115 of the 645 samples. Tall, over 80 cm high, *Sargassum muticum* plants were prevalent in the latter but not the first half of the sampling period, which was probably due to sampling variation and not an increase in plant height. Otherwise, plants appeared to be uniformly distributed over the range in height, which was 10-30 cm for *Fucus* sp., 19-110 cm for *Sargassum muticum*, 10-50 cm for *Zostera* sp., and 5-62 cm for red algae (Fig. 7).

There were eggs on bottom substrate in 44% of the quadrats. *Fucus* sp. samples had eggs on bottom in 33 of the 48 quadrats, *Sargassum muticum* samples in 62 of 108 quadrats, *Zostera* sp. samples in 1 of 196 quadrats, and red algae samples in 159 of 210 quadrats. Eggs on bottom appeared to decline over the incubation period for *Fucus* sp. samples, but not for the others (Fig. 8).

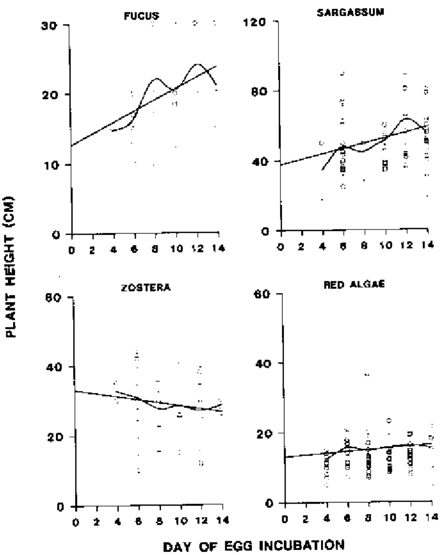

Fig. 7-Plot of plant height, fitted with distance weighted least squares and linear regression lines.

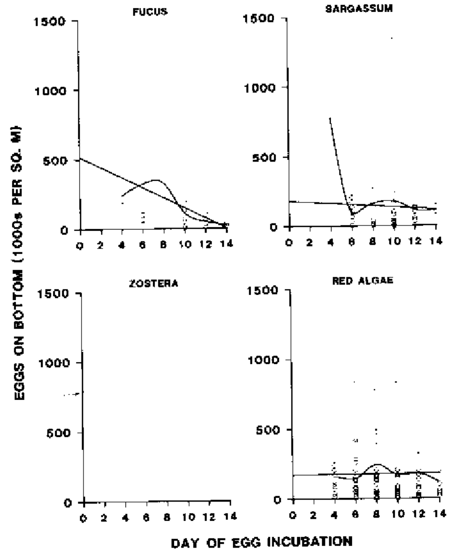

Fig. 8-Plot of eggs on bottom, fitted with distance weighted least squares and linear regression lines.

Birds

Birds increased from 23,188 on March 3 to 50,407 on March 17. On April 4, about 1 week after hatching was completed, there were 8213 birds (Fig. 9). Gulls (*Larus* sp.) were present in large numbers (20,632) at the beginning of the survey, when they were seen feeding on herring. A peak of 41,182 gulls were counted on March 13, after which they declined to a low of 606 on April 4. Gulls occurred in substantial numbers in all sectors and were more likely than other birds to move to sectors where there was active spawning. Gulls were observed feeding on spawn, when it was exposed in the intertidal zone. Scoters (*Melanitta* sp.) occurred almost exclusively in sectors 3 and 5. Scoters increased from 522 on March 3 to 13,500 on March 15. A relatively large number of scoters (2058) were still in the area by April 4. Scoters were never observed feeding on spawn, occurring mostly some distance offshore, but, on the evidence of scoters collected in previous studies (Haegele and Schweigert 1989, Vermeer 1981), they were assumed to be eating herring spawn. The other diving ducks (eg. *Bucephala* sp.) showed a similar pattern to scoters, increasing from 1563 on March 3 to 8214 on March 19, with 4512 remaining on April 4. They also frequented sectors 3 and 5 and were observed feeding on spawn in shallow water. The other diving birds (eg. *Phalacrocorax* sp.) were most abundant when there was active spawning, but they never exceeded 1290 birds and were not observed eating spawn. Numbers of non-diving birds, other than gulls, were relatively stable over the survey period and there were never more than 498 of these birds. Early in the survey, bald eagles (*Haliaeetus leucocephalus*) were the most common non-diving bird, while later in the survey crows (*Corvus* sp.), Canada geese and brant (*Branta* sp.) were commonly observed. Crows and the geese were observed eating spawn when it was exposed in the intertidal zone. Eagles were occasionally seen in the intertidal zone but were not observed eating spawn.

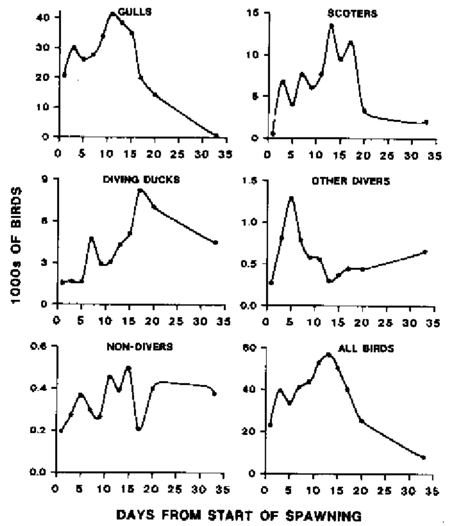

Fig. 9-Abundance of birds on or near herring spawning grounds in Lambert Channel in 1989.

To estimate the amount of spawn consumed by birds, daily rations were calculated from the body weights of birds collected in 1988 in Barkley Sound (Haegele and Schweigert 1989) and the regression from Nilsson and Nilsson (1976):

$$F = 0.51 \cdot W^{0.85} \qquad (2)$$

where

F = daily food consumption,

W = bird weight.

Abundances of gulls, scoters, and diving ducks for days with no bird count were interpolated from the census data. Since crows and geese were not always seen, it was assumed that the maximum number observed, 247 and 165, respectively, were present throughout the incubation period.

Gulls consumed 139.1 t, scoters 33.2 t, diving ducks 21.8 t, and crows and geese 4.2 t of eggs. Total egg consumption by birds was estimated at 198.2 t, equivalent to the eggs from 833 t of herring.

Invertebrates

Total abundance of bottom feeding organisms was estimated by applying length (35.96 km) and area (738.9 ha) of spawn in the study area, as determined from fishery officer diving surveys (Haist and Schweigert 1990), to the invertebrate density estimates. Abundance estimates from quadrats and area were used for the smaller organisms (small crabs, snails, most sea anemones, amphipods, and shrimp) and abundance estimates from transect counts and spawn length were used for larger organisms (large crabs, starfish, sea cucumbers, sea urchins, and fish) and infrequently occurring small organisms (some sea anemones, tubeworms, chitons, limpets, and nudibranchs) for calculations of spawn consumption by bottom feeders. Daily rations were the mean of experimental results (unpublished data) for those species tested and rations of similar species or speculative rations for species not tested. In the laboratory, the kelp crab (*Pugettia producta*) was observed to be an especially voracious feeder, initiating feeding on herring eggs immediately upon prey introduction. Kelp crabs consumed an average of 218 eggs per day, which was equivalent to 5.6% of their average body weight. Starfish, by contrast, were slow to react to prey introduction and, although leather stars (*Dermasterias imbricata*) ate up to 744 eggs per day, the average daily consumption by starfish was only 0.5% of body weight. The snails, which averaged from 0.03 g (*Margarites* sp.) to 0.11 g (*Bittium eschrichtii*) in weight, consumed an average of 0.21 (*Margarites* sp.) to 0.77 (*Mitrella* sp.) eggs per day, which was an average daily consumption of 2.7% of body weight. Speculative rations were based on body size, in relation to those animals used in feeding experiments, and feeding behaviour as observed by divers.

In total, bottom feeders were estimated to have eaten 263.9 t of spawn, which is equivalent to the eggs from 1109 t of herring. Crabs, especially the hermit crab, *Pagarus* sp., were the major predator, consuming an estimated 201.7 t of spawn. Snails, although they ate less than 1 egg per day, were estimated to have consumed 13.5 t of spawn because they occurred frequently and at high densities. Starfish, which occurred infrequently and at relatively low densities, were estimated to have consumed only 4.2 t of spawn. The other predators, for which speculative rations were used, were estimated to have eaten 44.5 t of spawn.

DISCUSSION

An estimated 27,385 t of herring spawned in the study area, 13,537 t on Hornby Island and 13,828 t on Denman Island (Haist and Schweigert 1990). Birds and invertebrates were estimated to have consumed the eggs from 833 and 1109 t of herring, respectively. Hence, egg loss to predation was about 7.1% in Lambert Channel. Predation by birds was 3.0% of eggs, which is nearly identical to the 3.5% estimate made for Barkley Sound in 1988 (Haegele and Schweigert 1989). If the bird population is relatively constant, then lower herring stock levels would experience higher rates of predation. For the above two stocks, which are at relatively high levels, the bird to herring ratio, using maximum estimates for gulls and ducks, was 2.79 and 2.30 birds•t^{-1} for Barkley Sound and Lambert Channel, respectively. Predation by invertebrates was not well determined in this or the Barkley Sound study. An increase in surveying is required to better estimate invertebrate densities.

If predation were uniform throughout the spawning bed and were the only source of egg loss, it would not be possible to detect this small loss by spawn sampling. However, predation by birds appears to be both stratified and localized. Gulls were observed to feed only on exposed spawn and they were distributed throughout the study area. Scoters and the other diving ducks, however, frequented mostly sector 3 and 5. It appears that where these birds are concentrated, egg loss can be detected with sampling of spawn. For example, on *Sargassum muticum*, which occurred mostly in sectors 3 and 5, the decrease in egg density was substantial.

The main difficulty in determining egg loss by sampling spawn was that egg density varied considerably with location and vegetation type. Only with extensive sampling can time trends be separated from this variability. Unfortunately, we were unable to sample early in the incubation period because of hazards to SCUBA divers from gillnet fishing for herring in the study area.

Sources of egg loss other than predation were not estimated. Much of the spawn in the study area was relatively shallow and hence susceptible to physical removal and translocation by waves and current. However, there were no major storms in the study period and no accumulations of eggs on the foreshore were observed. This was also the stratum where gulls were feeding and they probably consumed any eggs washed ashore. Loose eggs were observed in the water, mainly near the bottom in shallow water. We had no technique to quantitatively sample these loose eggs for abundance estimates, but they appeared to increase with time. It is expected that these eggs would survive to hatching.

Egg loss was as high as 92% on *Fucus* sp. in shallow water but only about 45% on red algae in deep water. Thus, while egg loss on some transects and vegetation types was substantial, overall egg loss did not approach the extreme estimates of 99% loss made by Palsson (1984) and Outram (1958). Rather, it would appear that egg loss in southern British Columbia from predation by birds and invertebrates is 4% and 4-13%, respectively (Haegele and Schweigert 1989 and this study). Egg loss from physical translocation may be an additional 26-40% (Hay and Miller 1982, Hart and Tester 1934), but only in portions of the range where the spawn is exposed to wave action generated by storms.

Apart from trying to understand the effects of various factors on egg loss during the incubation period, it is important to adjust any stock biomass estimates for declines in egg number in relation to when in the incubation period a survey of the spawning beds is made. For a statistical model to be useful for adjusting for egg loss prior to the completion of a spawn survey for stock assessment requires that the variables to be measured be easy to observe and quantify. In this respect Equation 1 described earlier may be appropriate. Although there were significant differences in the rate of egg loss associated with the type of vegetation substrate, this variable is readily measured. Unfortunately, there was also a significant interaction effect between the transect and the vegetation type indicating that the rate of egg loss for any particular vegetation substrate differed significantly between transects as a result of some unknown factors, perhaps exposure and bird abundance. Development of a comprehensive model of egg loss is thus complicated by this effect and unless transect location could somehow be related to some readily measured quantity it would be very difficult if not impossible to develop a general model to quantify egg loss from herring spawns during incubation.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

The Reproductive Biology of Herring in the Western Bering Sea with Reference to Spawning Stock Numbers

N.I. Naumenko
Kamchatka Department of the Pacific Fisheries and Oceanography Research Institute
Petropavlovsk-Kamchatsky, USSR

Korfo-Karaginsk stock of Pacific herring (Clupea harengus pallasi) inhabits the shelf of western Bering Sea. The great exploitation of this stock by USSR was begun in 1939. The catch of herring increased progressively from 4890 mt in 1939 to 21540 mt in 1953. Korfo-Karaginsk herring was an important object of fishery in the northwest of the Pacific between 1955 and 1968. Average annual catch in this period was about 100 thousand mt. In 1961, Japan initiated herring gillnet fishery, and total catch (USSR and Japan) rapidly reached its peak - 268 thousand mt. Since then herring stock progressively decreased. In 1970 interdiction of fishery Korfo-Karaginsk herring implemented in force, but in 1986 it was abrogated. Thus for the space of 16 years maintain only notgreat fishery for monitoring of structure and spawning stock size. However, even this drastic measure hadn't allowed to restore optimum numbers of adult fish in the population. In recent years, the catch of herring in the Olyutorskiy and Karaginskiy Bays fluctuated from 15 to 30 thousand mt.

Materials and Methods

During more than 50 years, Kamchatka Department of TINRO exercises monitoring for the western Bering Sea herring. The regular observations have taken place in the last 30 years. The standardised pattern of investigations developed includes:
- spring (May) estimating of the spawning stock,
- summer (June) observations of larval herring including their food supply,
- fall (September-October) collection of fishery and biostatistical information,
- fall-winter (November-December) trawl survey that makes it possible to assess herring group-0

Numbers of annually collecting materials as followed: 40-60 samples of substratum with the herring eggs; 500-1000 adult fish for full biological information (length,weight, sex, maturity, age,etc.); 2000-5000 fish for length frequency and 50-100 gonads for estimating of fecundity in spring; 25-45 samples of ichthyoplancton for estimating larval abundance and 10-15 samples of zooplancton for studing their food supply in each herring reproduction area; about 500 fish for full biological information, 5000 fish for length frequency and 500 fish of definite special length (22-30cm) for revealing their maturity in the period of fishery; 65-100 bottom trawl haul for estimating herring group-0 abundance.

Results and Discussion

The spawning stock of Korfo-Karaginsk herring is subjected to the great year-to-year variations. For 50 years of observations, it fluctuated from 20 to 3400 mln fish and total fecundity of all females varied from $0{,}5 \cdot 10^{12}$ to $63{,}3 \cdot 10^{12}$ eggs.

Spawning of the Korfo-Karaginsk herring takes place in shallow lagoons and bays of Northern Karaginskiy Bay. Natural relationship is observed between the number of spawning regions and spawners abundance. In the 1940s-1950s, when herring resources were average or above the average, the fish laid their eggs near the Karaginskiy Island, Shilka Island, Ilpinskiy Cape, Ilpyur Cape, False News Bay, Ossora Bay, Tyumlat Bay, Uala Bay, Anapka Bay, Geck Bay, Skryutaya Harbour, Siberia Harbour, Skobelev Harbour. Total number of spawning regions in this period were maximum - from 6 to 14. In the late 1960s - early 1970s, when spawning potential was near its minimum, the reproductive area was often limited only by one Siberia Harbour. In the 1980s the most common herring reproduction areas were found to be the Uala Bay, Anapka Bay, Korf Bay.

The pattern of herring distribution in the spawning period and total number of spawning regions releated to parental abundance are approximated as followes:

$$\Delta\,\text{Siberia Harbour} = 46.15\,N_0^{-0.8893} \qquad \eta = 0.648 \quad n = 31 \qquad (1)$$

$$\Delta\,\text{Skobelev Harbour} = 9.76\,N_0^{-0.3779} \qquad \eta = 0.384 \quad n = 31 \qquad (2)$$

$$\Delta\,\text{Korf Bay} = 103.809\,N_0^{-0.526} \qquad \eta = 0.453 \quad n = 31 \qquad (3)$$

$$\Delta\,\text{Geck Bay} = \Delta\,\text{Korf Bay} - \Delta\,\text{Siberia Bay} - \Delta\,\text{Skobelev Bay} \qquad (4)$$

$$\Delta\,\text{Uala Bay} = 1.0036\,N_0 - 3.3032 \qquad r = 0.769 \quad n = 31 \qquad (5)$$

$$\Delta\,\text{Another} = 0.2778\,N_0 - 2.1453 \qquad r = 0.911 \quad n = 31 \qquad (6)$$

$$\Delta\,\text{Anapka Bay} = 100 - \Delta\,\text{Korf Bay} - \Delta\,\text{Uala Bay} - \Delta\,\text{Another} \qquad (7)$$

$$n_s = 0.196\,N_0 + 2.1864 \qquad r = 0.897 \quad n = 31 \qquad (8)$$

where Δ = part of parents, reproducting in this region(%), N_0 = total fecundity of all females (10^{12}), n_s = numbers of spawning region.

The entire herring spawning area in Karaginskiy Bay is about 60 km^2. Only part of it in annually used for herring reproduction. The increase in the abundance of spawners results in the widening of the reproduction area in the southernly and westernly directions - from 2 to 40 km^2. The correlation is found to be close:

$$S = 3.1324\, N_0^{0.6068} \qquad \eta = 0.867 \qquad n = 31 \qquad (9),$$

where S = reproduction area, km^2. The density of eggs spawned on the substrate varies among years from 0,22 to 1,72 mln eggs per m^2. It is smaller than other populations of Pacific herring. The relation between eggs density and spawning stock is weaker:

$$P = 0.3142\, N_0^{0.3978} \qquad \eta = 0.830 \qquad n = 31 \qquad (10),$$

where P = density of eggs spawned on the substrate, mln eggs per m^2.

The success of herring reproduction in the period of the increase of the spawning stock has been enhanced as a result of occupation of the new spawning grounds rather than more intensive using of the previous ones.

Korfo-Karaginsk herring appertain to spring spawning fishes. The time of the begining of their spawning has been caused rather, by the paternal numbers and age of females than by hydrometeorological conditions. With the increase of the number of spawning, spawning begins earlier(1-29 May) and ends later (20 May-6 June). In years, when the number of parents was similar, spawning began early if old-aged fish prevailed in the population:

$$T_{b.s.} = 220.174\, N_0^{-0.3392} \cdot (\bar{t})^{-1.08} \qquad R = 0.745 \qquad n = 41 \qquad (11),$$

where $T_{b.s.}$ = time of the begining of spawning, from 1 May, $\bar{t}$ = average age of females. The prediction based on the above relationship was satisfactory in 78% of cases, while 22% the difference between empirical and estimated dates accounted for 5 days.

Duration of spawning period depends on parental stock as followed:

$$D_{s.} = 4.5534\, N_0^{0.4484} \qquad \eta = 0.853 \qquad n = 41 \qquad (12),$$

where D_s = duration of spawning period, in days. Time of the end of spawning is estimated as:

$$T_{e.s.} = T_{b.s.} + D_s \qquad (13),$$

where $T_{e.s.}$ - time of the end of spawning, from 1 May.

Duration of incubation of the Korfo-Karaginsk herring was subjected to the great year-to-year variations - from 11 to 30 days. Close relationship between duration of incubation and temperature of water on the spawning grounds was found:

$$D_i = 69.3974\, (\bar{t}_{s.g})^{-0.8334} \qquad \eta = 0.819 \qquad n = 8 \qquad (14),$$

where D_i = duration of incubation, $\bar{t}_{s.g}$ = average temperature of water on one spawning ground in the period of incubation(C°). Inverse proportion represents summer of degreeday, which is necessary for embriogenesis:

$$\Sigma t^{\circ} = 69.3974 \left(t_{s.g}\right)^{0.1664} \qquad (15),$$

where Σt° = summer of degreeday, which is necessary for embriogenesis.

In the years, when parental stock was average or above average (1948-1964), eggs laying in first day of spawning, developed during 19-30 days (in average 23 days). Duration of incubation eggs, which was laid in the last day of spawning, considerably smaller - 13-18 days (in average 15 days). Total duration of incubation (from the first day of spawning to last day of hatching larval) changed from 27 to 38 days (in average 35 days). In some years of this period spawning continued already after beginning of larval hatching. In the years with minimum parental stock (1968-1975) spawning was transient, late, when temperature of water was high. Therefore duration of spawning decreased to 11-17 days and total duration of incubation of - to 20 days. Relationship between total duration of incubation and reproductive potential of Korfo-Karaginsk herring as followed:

$$\mathcal{D}_{t.i.} = 17.7792\, N_{o}^{0.187} \qquad \eta = 0.875 \qquad n = 41 \qquad (16),$$

where $\mathcal{D}_{t.i.}$ = total duration of incubation.

Time of beginning larval hatching depend on temperature of water on spawning grounds, time of spawning beginning, numbers of spawners:

$$T_{b.h.} = 1.0694\, T_{b.s.} + 0.0141\, N_{o} - 2.9572 \left(\bar{t}_{i}\right) + 28.1 \qquad R = 0.809 \quad n = 41 \quad (17).$$

where $T_{b.h.}$ = time of beginning larval hatching, from 1 May. Time of larval hatching end and duration of hatching period estimate by relationship:

$$T_{e.h.} = T_{b.s.} + \mathcal{D}_{t.i.} \qquad (18)$$

$$\mathcal{D}_{h.} = T_{e.h.} - T_{b.h.} \qquad (19).$$

where $T_{e.h.}$ = time of larval hatching end, from 1 May, $\mathcal{D}_{h.}$ = duration of hatching period.

The duration of migration period and summer feeding area of herring is attributed, to a great extent, to the status of the stocks. In years with average and high abundance of adult fish, they reach eastern slopes of Navarinsk valley (178°E), and when the parental stock is less than 100 mln fish they leave Oluytorskiy Bay.

The time of wintering migration of Korfo-Karaginsk herring is consistent, as least, with 3 factors: temperature regime on the two wintering grounds (Oluytorskiy Bay with depths 50-100 m and 100-200 m), the number of the principal food competitor of herring - Alaska pollock:

$$T_{w.m.} = 19.3 + 5.7816 \left(\bar{t}_{1}\right) + 5.0 \left(\bar{t}_{2}\right) - 0.0033\, N_{p} \qquad R = 0.743 \quad n = 20 \quad (20),$$

where $T_{w.m.}$ = time of beginning wintering migration, from 31 August, $\bar{t}_{1}$ = average temperature near bottom in November in the Oluytorskiy Bay with depths 50-100 m, $\bar{t}_{2}$ = average temperature near bottom in November in the Oluytorskiy Bay with depths 100-200 m, N_{p} = stock of Alaska pollock in Western Bering Sea, mln fish. The first factor is of the greatest importance. The migration begins earlier (I-II decades of September) in years with large herring spawning stock. In the periods of its decrease, herring continues their feeding till I-II decades of November.

The duration of wintering migration is entirely related to the number of migrants. The relationship is:

$$\mathfrak{D}_{w.m.} = \left(0.02815 + \frac{0.4784}{N_0}\right)^{-1} \qquad \eta = 0.792 \quad n = 34 \quad (21),$$

where $\mathfrak{D}_{w.m.}$= duration of wintering migration.

The natural mortality of adult fish variable owing to the effect of different causes, including the abundance of herring. In the 1950s, when herring resources were maximum, the natural mortality amounted to 38% adult fish. In 1980s, with low herring stock, it was only 23% (Table).

Table

Natural mortality of Korfo-Karaginsk herring,%

Years	Age											
	4	5	6	7	8	9	10	11	12	13	14	15
1950s	20	26	33	42	52	64	77	91	1			
1960s	26	23	23	26	31	40	51	66	83	1		
1970s	25	23	23	26	31	39	49	62	77	94	1	
1980s	22	19	17	18	20	25	32	41	52	65	81	98

ABSTRACT

Review influence of spawning stock numbers of Korfo-Karaginsk herring on some elements of reproductive cycle: distribution of the parents in spawning period, spawning area and density of eggs, time of the begining of spawning and its duration, duration of incubation and time of larval hatching, duration of migrations.

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Spawning Stock Structure and Population Fecundity of the Atlanto-Scandian Herring

E.I. Seliverstova
Polar Research Institute of Marine Fisheries and Oceanography
Murmansk, USSR

ABSTRACT

A great variety of herring habitat from south-west coast of Norway to Novaya Zemlya results in appearance of groupings which can be distinguished in a yearclass by scale structure and growth rate. These groupings occurring in coastal waters of South-West Norway form a southern stock component, in coastal waters of Central and North Norway - a northern stock component, in the Barents Sea - a Barents Sea stock component.

Weak yearclasses consist mainly of herring of southern and northern components (herring with a high growth rate and early maturation). Specimens of northern component predominate in average yearclasses. The Barents Sea component peculiar to a rich yearclass and having a low individual absolute fecundity as compared with southern and northern components decreases the population fecundity when recruiting the spawning stock. The lower number of eggs spawned in the 1960s was one of the factors which caused a sharp decrease of herring stocks.

The level of critical population fecundity of spawning stock consisting of southern component is equal to no less than $40x10^{12}$ eggs, that of northern component-$71x10^{12}$ eggs and that of the Barents Sea component-$152x10^{12}$ eggs which corresponds to biomasses of 0.3, 0.6 and 1.3 mill.t. These data agree with the fact that in 1983 spawning stock consisted merely of specimens of southern and northern components of poor 1969-1980-yearclasses and its biomass reached 0.6 mill.t. Favourable conditions for egg and larval development gave rise to appearance of the rich yearclass in 1983. To restore herring range of the 1950-

1960s the spawning stock biomass should make up 6.9-7.5 mill.t which complies with a minimum tolerance level of population fecundity of 850-906x10^{12} eggs maintaining its natural yearclass strength variations.

INTRODUCTION

With a sharp decrease in spawning stock abundance the Atlanto-Scandian herring ceased to perform migrations of a "large" circle (Marti, 1956; Marti and Wilson, 1960; Yudanov, 1960; Devold, 1963). Their whole life cycle passes in Norwegian territorial waters (Anon., 1970) where they perform migrations of a "small" circle not leaving for open Norwegian Sea. The Atlanto-Scandian herring stock is observed to recover in recent years. With rich 1983-yearclass recruiting, the spawning stock increased in 1988 to 1.35 mill.t (Table 1) and migration cycle of the 1950-1960s was partially renewed. Feeding postspawning herring were found in July-August 1987-1990 by Soviet research vessels in open Norwegian Sea from 64 to 72°N between 5°W and 5°E.

An adverse impact of immature herring fishery on adult fish abundance and catch has been already investigated by Soviet and Norwegian scientists (Marti, 1956; Marti and Yudanov, 1962; Benko and Seliverstov, 1969, 1973; Dragesund and Ulltang, 1975). They showed that the intensive fishery for young and adult herring changed age composition and numbers of spawning stock, and they suggested that due to this its reproductive capacity decreased. Fecundity of Atlanto-Scandian herring was exhaustively covered by Lyamin (1966). He revealed the dependence of individual absolute fecundity on the fish length, age and weight as well as on the yearclass strength, and he studied it on the spawning population as a whole. However, the investigations (Seliverstova, 1969, 1973, 1978; Telkova, 1962, 1969; Shutova-Korzh, 1960; Lea, 1929; Ottestad, 1934; Runström, 1936) showed that spawning stock consisted of groupings with different growth and maturation rates singled out by scale structure. Groupings form three stock components (southern, northern and Barents Sea). The yearclass structure is heterogeneous and depends on the yearclass strength. Weak yearclasses consist mainly of herring of southern component. Specimens of northern component prevail in average yearclasses. Herring of the Barents Sea component dominate in abundant yearclasses (Seliverstova, 1978, 1990).

The analysis of individual absolute fecundity (IAF) showed that herring of southern groupings in all age classes had the higher IAF than specimens of northern and Barents Sea groupings. In view of this the IAF of herring of poor yearclasses was considerably higher than that of average and rich ones. The IAF of abundant yearclasses was determined by IAF of groupings forming northern and especially Barents Sea components (Seliverstova, 1990).

Table 1. Spawning stock and yield of Atlanto-Scandian herring in the Norwegian Sea in 1950-1989

Year	Spawning stock		Yield, thou.t		
	thou.t	spec.x10^9	Adult and maturing	Small and fat	Total
1950	9400	36.9	826.1	106.9	933.0
1951	9100	30.3	994.2	284.2	1278.4
1952	8800	28.8	919.2	335.6	1254.8
1953	7100	23.5	849.9	240.7	1090.6
1954	7600	27.0	1306.4	338.1	1644.5
1955	8800	34.1	1217.5	142.3	1359.8
1956	8900	32.3	1460.6	198.8	1659.4
1957	10000	35.8	1148.3	171.2	1319.5
1958	8500	28.7	784.0	201.6	985.6
1959	7500	23.3	883.1	228.0	1111.1
1960	5600	17.3	821.1	280.7	1101.8
1961	4200	13.1	497.9	332.2	830.1
1962	3300	9.9	551.2	297.4	848.6
1963	1600	7.5	670.8	313.7	984.5
1964	3700	13.6	1117.9	163.9	1281.8
1965	4500	17.8	1325.8	221.9	1547.7
1966	2700	11.2	1723.5	231.5	1955.0
1967	1300	4.8	1131.5	545.7	1677.2
1968	240	1.0	273.1	439.1	712.2
1969	80	0.29	24.1	43.7	67.8
1970	60	0.17	20.9	41.4	62.3
1971	30	0.09	6.9	14.2	21.1
1972	-	-	-	13.2	13.2
1973	99	0.38	0.1	6.9	7.0
1974	119	0.37	0.9	6.7	7.6
1975	118	0.39	0.1	3.6	13.7+
1976	180	0.74	-	0.4	10.4
1977	331	1.28	0.4	12.3	22.7
1978	426	1.26	0.5	9.3	19.8
1979	454	1.20	0.7	2.2	12.9
1980	518	1.35	0.9	7.7	18.6
1981	530	1.49	0.8	7.9	13.7
1982	532	1.51	1.0	10.7	16.7
1983	592	1.60	3.9	14.2	23.1
1984	621	1.74	18.7	29.8	53.5
1985	552	1.55	29.4	41.7	169.9
1986	491	1.99	71.1	55.7	225.3
1987	513	3.02	62.9	49.8	127.5
1988	1353	6.63	73.4	66.7	164.5
1989	1514	5.99	53.4	-	53.4

Note: Spawning stock and yield in 1950-1971 (Dragesund and Ulltang, 1975); in 1972-1989 (Anon., 1990); in 1989 - preliminary data; + - unreported 5-10 thou.t are included in total yield since 1975.

The application of the method of definition of different reproductive levels for commercial fish populations under various ecological conditions of yearclass survival in early ontogeny (Serebryakov, 1988) allowed to analyse the dynamics of population fecundity of the Atlanto-Scandian herring depending on spawning stock numbers and its structure, and to recognize one more reason that provoked deterioration of stock reproduction conditions and decrease of stock numbers.

MATERIAL AND METHODS

PINRO materials on age composition of spawning stock for 1950-75, data on its biomass and abundance used from the ICES Working Group Documents and a paper of Dragesund and Ulltang (1975) are presented. Samples on herring fecundity were collected in wintering and spawning grounds. Ovaries at maturity stages III-IV, IV, V, V-VI were fixed in 4% formalin. Eggs were counted in a one-gramme weight and recalculated thereupon to total gonads weight. In all 4325 samples of herring females aged 3-20 were analysed for fecundity in the period from 1954 to 1975.

SPAWNING STOCK STRUCTURE AND POPULATION FECUNDITY

Analysis of spawning stock population fecundity in 1951-1975 showed that it decreased with the stock numbers reduction (Tables 1 and 2). But more detailed study indicated that the relation between female numbers and population fecundity value was not always direct. Investigations included years when female abundance was the same in the spawning stock and the number of eggs spawned in compared years was different. Five pairs of years having nearly similar female abundance were taken (Table 3). In the 1950s there was, in general, a direct relation between female numbers and population fecundity value. The equal number of females spawned the equal amount of eggs and with the decrease or increase of female number the population fecundity decreased or increased respectively. The relation changed in the 1960s. With the increase of female number the amount of eggs spawned decreased (Table 3).

In the 1950s specimens of northern and southern components prevailed in spawning stock, in the 1960s - those of the Barents Sea component. The Barents Sea specimens had much lower IAF as compared with herring of southern and northern components (Seliverstova, 1990). In the 1950s the lower absolute fecundity of the Barents Sea herring did not affect adversely since the many-aged structure of spawning stock (16-18 age classes), large per cent of older age groups in all stock components having the highest fecundity, delayed recruitment of spawning stock with rich 1950-yearclass reduced the influence of the Barents Sea specimens on the amount of eggs laid in that period. In the 1960s when there were only 8-10 age groups in the the spawning stock the older specimens constituted no more

Table 2. Population fecundity, yearclass strength (numbers of 3-year-olds) and survival rate of Atlanto-Scandian herring in early ontogeny in 1951-1975

Year	Population fecundity, eggs x 10^{12}	Numbers of 3-year-olds; spec.x10^6	Yearclass strength	Survival rate to age of 3 full years, %
1951	1200.3	7380	Above average	0.000615
1952	1046.3	3448	Average	0.000330
1953	931.1	3220	Average	0.000346
1954	1007.3	600	Poor	0.000060
1955	1421.6	494	Poor	0.000035
1956	995.1	169	Poor	0.000017
1957	1292.3	252	Poor	0.000019
1958	1141.2	241	Poor	0.000021
1959	946.6	21175	Very rich	0.002237
1960	718.4	7337	Above average	0.001021
1961	578.6	2175	Average	0.000376
1962	437.3	203	Poor	0.000046
1963	202.5	8281	Above average	0.004089
1964	347.5	3832	Above average	0.001102
1965	471.3	107	Poor	0.000023
1966	334.6	230	Poor	0.000069
1967	179.7	21	Poor	0.000012
1968	36.4	10	Poor	0.000027
1969	10.2	513	Poor	0.000029
1970	7.0	7	Poor	0.000104
1971	4.0	1	Poor	0.000025
1973	10.1	886	Poor	0.008772
1974	9.0	575	Poor	0.006389
1975	11.1	127	Poor	0.001144

Note: Numbers of 3-year-olds of the 1951-1968-yearclasses (Dragesund and Ulltang, 1975)., that of 1969-1975-yearclasses (Anon., 1987).

Table 3. Abundance and population fecundity of spawning stock and separate components of Atlanto-Scandian herring in some years

Characteristic	Year	Abundance, spec.x10^9	Population fecundity, eggs x 10^{12}
Spawning stock	1952	14.4	1046.3
	1958	14.4	1141.2
	1953	11.8	931.1
	1959	11.6	946.6
	1960	8.6	718.4
	1965	8.9	471.3
	1961	6.5	578.6
	1964	6.8	347.5
	1962	5.0	437.3
	1966	5.6	334.6
Northern component	1952	7.2	514.4
	1958	7.9	668.3
	1953	5.7	467.2
	1959	6.5	554.7
	1960	4.6	408.1
	1965	2.4	156.5
	1961	3.3	303.6
	1964	2.8	157.2
	1962	2.5	226.4
	1966	1.4	96.3
Barents Sea component	1952	4.1	295.7
	1958	4.9	346.5
	1953	4.8	350.1
	1959	4.1	312.3
	1960	3.4	258.9
	1965	5.4	249.6
	1961	2.3	199.6
	1964	3.0	133.1
	1962	1.6	143.2
	1966	3.7	206.3

than 2-4% and herring of abundant 1959-yearclass - about 70%, the Barents Sea component prevailing in the yearclass and, consequently, in the spawning stock (Table 4), the importance of the Barents Sea specimens turned to be decisive in these years (Table 3). Combined with adverse abiotic conditions pronounced in the 1960s the decrease in the number of eggs laid together with simultaneous increase of immature and adult herring catches (Table 1) was one of the factors which entailed a sharp reduction of fish stocks.

The numerical strength of herring yearclasses fluctuated very much. The highest survival rate was observed in rich 1959-yearclass. Yearclasses of above average numbers appeared as well in years with favourable conditions for juvenile survival. The survival rate of poor 1969-, 1973-, 1974-yearclasses was high. However, favourable conditions for juvenile survival and growth did not lead in these years to appearance of rich yearclasses since the spawning stock numbers and, accordingly, population fecundity were low. Survival rates of poor yearclasses varied in ten-year periods by an order (Table 5).

Habitat of different herring stock components is diverse. In the years with a considerable heat content increase in the Norwegian Current waters the conditions are favourable for rich and above average yearclasses of northern and Barents Sea components. In hydrologically cold years conditions are favourable for southern component (Table 6).

Knowing survival rates for a yearclass, on the whole, and for its components, in particular, we can estimate different levels of population fecundity and spawning stock biomass. There are following levels of population fecundity (Serebryakov, 1988): guaranteed population fecundity (GPF) when a rich yearclass can appear under average conditions - the ratio of numbers of 3-year-olds of the rich yearclass (in this paper yearclasses of above average numbers due to their higher frequency of occurrence) to survival rate corresponding to average conditions; minimum tolerance population fecundity (MTPF) ensures natural fluctuations of the yearclass strength when a rich yearclass appears under favourable conditions, an average yearclass - under average conditions and poor yearclasses - in years with unfavourable conditions (the ratio of numbers of 3-year-olds of average yearclass to survival rate corresponding to average conditions); critical population fecundity (CPF) when a rich yearclass can just appear under the most favourable conditions (the ratio of numbers of 3-year-olds of rich yearclass to survival rate corresponding to herring survival under the most favourable conditions). Lower than critical population fecundity stipulates appearance of poor yearclasses and results in a prolonged depression of spawning stock.

The GPF level is the highest one. It corresponds to 15.7 mill.t of spawning stock biomass. The MTPF level is maintained with 6.9 mill.t. The CPF level shows agreement with 0.6 mill.t of spawning stock biomass (Table 7). Analysis

Table 4. Component ratio and population fecundity of Atlanto-Scandian herring in the 1950- and 1959-yearclasses

Year	Population fecundity of spawning stock, eggs x 10^{12}	Yearclass		Component ratio in the yearclass, %			Population fecundity of components in the yearclass, eggs x 10^{12}		
		per cent of spawning stock	population fecundity, eggs x 10^{12}	southern	northern	Barents Sea	southern	northern	Barents Sea
The 1950-yearclass									
1954	1007.3	14.8	67.6	42.1	57.9	-	27.3	40.3	-
1955	1421.6	14.6	122.2	36.4	62.1	1.5	47.0	74.1	1.1
1956	995.1	46.6	386.8	12.4	73.1	14.5	58.6	287.2	41.0
1957	1292.3	38.1	427.5	9.2	60.4	30.4	45.9	292.3	89.3
1958	1141.2	50.2	547.1	3.7	52.4	43.9	20.4	327.4	199.3
The 1959-yearclass									
1963	202.5	61.0	77.4	10.7	89.3	-	8.1	69.3	-
1964	347.5	68.9	192.4	10.1	43.9	46.0	24.8	99.1	68.5
1965	471.3	70.5	320.5	8.0	25.8	66.2	31.7	104.1	184.7
1966	334.6	57.3	202.6	3.7	22.2	74.1	8.6	52.5	141.5

Table 5. Numbers of 3-year-olds and survival rates of Atlanto-Scandian herring of different yearclass strength to age of 3 full years

Yearclass characteristic	Year-class	Numbers of 3-year-olds spec. x 10^6	Survival rate to age of 3 full years, %	Yearclass characteristic	Year-class	Numbers of 3-year-olds spec. x 10^6	Survival rate to age of 3 full years, %
Rich	1959	21175	0.002237	Poor	1954	600	0.000060
					1955	494	0.000035
Above average	1951	7380	0.000615		1956	169	0.000017
	1960	7337	0.001021		1957	252	0.000019
	1963	8281	0.004089		1958	241	0.000021
	1964	3832	0.001102				
	Mean	6707.5	0.001707		Mean		0.000030
					1962	203	0.000046
Average	1952	3448	0.000330		1965	107	0.000023
	1953	3220	0.000346		1966	230	0.000069
	1961	2175	0.000376		1967	21	0.000012
					1968	10	0.000027
	Mean	2947.7	0.000351		1969	513	0.005029
					Mean		0.000868
					1970	7	0.000104
					1971	1	0.000025
					1973	886	0.008772
					1974	575	0.006389
					1975	127	0.001144
					Mean		0.003287
					Mean for 1954-1975		0.001362

Table 6. Numbers of 3-year-olds and survival rates of herring of various components

Year	Numbers of 3-year-old herring of various components, spec. x 10^6			Survival of herring of various components to age of 3 full years, %		
	southern	northern	Barents Sea	southern	northern	Barents Sea
1951	1815.5	4287.8	1276.7	0.000151	0.000357	0.000106
1952	848.2	2003.3	596.5	0.000081	0.000191	0.000057
1953	792.1	1870.8	557.1	0.000085	0.000201	0.000060
1954	229.2	337.8	33.0	0.000023	0.000034	0.000003
1955	188.7	278.1	27.2	0.000013	0.000020	0.000002
1956	64.6	95.2	9.2	0.000006	0.000010	0.000001
1957	96.3	141.9	13.8	0.000007	0.000011	0.000001
1958	92.1	135.7	13.2	0.000008	0.000012	0.000001
1959	1715.2	8088.8	11371.0	0.000181	0.000854	0.001201
1960	594.3	2802.7	3940.0	0.000083	0.000390	0.000548
1961	535.0	1263.7	376.3	0.000093	0.000218	0.000065
1962	77.6	114.3	11.1	0.000018	0.000026	0.000002
1963	2037.1	4811.3	1432.6	0.001006	0.002376	0.000708
1964	942.7	2226.4	662.9	0.000271	0.000641	0.000191
1965	40.9	60.2	5.9	0.000009	0.000013	0.000001
1966	87.9	129.5	12.6	0.000026	0.000039	0.000004
1967	8.0	11.8	1.2	0.000004	0.000007	0.000001
1968	3.8	5.6	0.6	0.000010	0.000015	0.000002
1969	196.0	288.8	28.2	0.001921	0.002831	0.000276
1970	2.7	3.9	0.4	0.000039	0.000056	0.000006
1971	0.38	0.56	0.06	0.000010	0.000014	0.000015
1973	338.5	498.8	48.7	0.003352	0.004939	0.000482
1974	219.6	323.7	31.6	0.002440	0.003597	0.000351
1975	48.5	71.5	7.0	0.000437	0.000644	0.000063

Table 7. Population fecundity levels and biomasses of spawning stock and separate components of Atlanto-Scandian herring

Population fecundity levels	Population fecundity, eggs x 10^{12}	Biomass, mill.t
	Spawning stock	
GPF	1911.0	15.7
MTPF	839.8	6.9
CPF	76.5	0.6
CPF for 1951-1959	299.4	2.7
CPF for 1960-1969	133.5	1.1
CPF for 1970-1975	76.5	0.6
	Southern component	
GPF	1684.2	14.0
MTPF	906.4	7.6
CPF	40.2	0.3
CPF for 1951-1959	748.6	6.1
CPF for 1960-1969	70.2	0.6
CPF for 1970-1975	40.2	0.3
	Northern component	
GPF	1766.1	14.4
MTPF	856.3	7.0
CPF	71.5	0.6
CPF for 1951-1959	415.5	3.5
CPF for 1960-1969	124.8	1.1
CPF for 1970-1975	71.5	0.6
	Barents Sea component	
GPF	3046.8	28.4
MTPF	850.0	7.5
CPF	152.3	1.3
CPF for 1951-1959	152.3	1.4
CPF for 1960-1969	257.5	2.3
CPF for 1970-1975	380.8	2.9

of each component contribution into population fecundity showed that the CPF value of specimens of southern and northern components corresponded to spawning stock biomass of 0.3 mill.t in the first case and 0.6 mill.t in the second one. These data comply with the fact that in 1983 the spawning stock consisted of specimens of poor 1969-1980-yearclasses from southern and northern components alone and its biomass reached 0.6 mill.t. Favourable conditions for egg and larval development resulted this year in the appearance of the rich yearclass. The CPF of the Barents Sea component was much higher. Such amount of eggs can be laid by the stock with 1.3 mill.t of biomass, consisting of the Barents Sea specimens (Table 7).

Depending on the numbers, age composition of spawning stock, component ratio, abiotic conditions in the 1950-1970s the survival rates in the most favourable years are different for each ten-year period. In this connection the critical stock consisting of the Barents Sea herring must be different in these three ten-year periods. In 1988 the spawning stock biomass 80% of which consisted of the Barents Sea specimens (Seliverstova, 1990) reached 1.35 mill.t (Anon., 1990), the value twice as small as estimated critical spawning stock (2.9 mill.t) ensuring the appearance of the rich yearclass under the most favourable conditions in the 1970s (Table 7).

The spawning stock with the biomass of 0.3-1.3 mill.t guaranteeing the emergence of the rich yearclass under the most favourable conditions will keep to the present herring range - a narrow coastal zone of Norway - and will only migrate to spawning grounds. To restore the range of the 1950s-early 1960s the spawning stock biomass should make up 6.9-7.5 mill.t which corresponds to the MTPF level of 850-906x10^{12} eggs (Table 7).

Estimated yearclass strength (by numbers of 3-year-olds) with the use of various survival rates and population fecundity levels showed that 5 rich, 2 average and 2 poor yearclasses can appear from the spawning stock biomass of 6.9 mill.t. The probability of appearance of mainly poor yearclasses increases with the population fecundity decrease.

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Population Dynamics

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Identification of Causes of Recruitment Variation in the Herring Stock of Sitka Sound, Alaska: Preliminary Results

A. Zebdi
University of Alaska Fairbanks
Juneau, Alaska

ABSTRACT

To examine whether interannual variability in the recruitment of Sitka Sound herring is related to physical changes in the marine environment, a set of time-series of different environmental variables was analyzed in conjunction with recruitment indices. Seasonal and larger cycles are extracted from the raw data as well as different time-series anomalies. The existence of cycles in the environmental variables can be considered as a possible cause of fluctuations in herring populations.

The different environmental variables are highly correlated, primarily because of seasonality or direct effect on one-another. Some of these variables are correlated with the recruitment indices and in particular in the pre-spawning months which effect can only be related to an effect on the spawners.

The results presented during the symposium being just speculations about possible consequences of the observed physical variability on Sitka Sound herring stock, they certainly need further consideration at this point.

INTRODUCTION

Large fluctuations exist in the abundance of different populations of fish. Those variations have been monitored for a long time by different authors and are recorded in catch data in almost all fisheries. A number of hypotheses on the control of this phenomenon exist. Several elements and factors can be considered as directly involved in the determination of fish population abundance. The effect of fishing, and natural mortality, with a consideration of starvation, predation, and biotic and abiotic causes can be involved in the process. Paleosedimentary records show that there is a high magnitude of natural fluctuations when no fishing occurred (Lasker, 1985). Physical factors are elements to be considered in their effects on population abundance: they can have a localized origin (storms, upwellings, winds), be widespread oceanographic events (El-Niño), or a combination of both.

Herring has a highly variable recruitment (e.g. Anthony and Fogarty, 1985), and the variability cannot be explained by a stock- recruitment model alone. The relationship between variability and oceanographic and meteorological factors seems likely, but not obvious. In many pelagic fish species the survival of larvae depends on transport from spawning to nursery areas (Bartsch and al., 1989). Larval transport and retention hypotheses were expanded into the "member/vagrant hypothesis" (Sinclair, 1988). In this hypothesis, population size is determined by the extent of cohesive rearing areas of larvae. Retention in those areas is accomplished through vertical migration of larvae, and/or oceanographic features that contribute to successful retention (fronts, gyres). The effect is reflected in recruitment variation, as would interannual variation in conditions within retention areas. This hypothesis does not eliminate other processes (feeding success, predation, etc) as possible contributing causes of recruitment variation (Sinclair, 1988).

The Sitka Sound herring stock is a typical case of interannual variation in recruitment and is well documented. A set of historical data (catch-at-age) is available for the study of those variations. Climatological and oceanographical data are also available, and since they are taken directly in Sitka Sound (figure 1) make the study site a preferential one.

There is a long history of attempts to correlate fish abundance with indices of the physical environment. Historical data analyses provide one tool that may deliver useful insight into the processes resulting in recruitment variation. The Pacific herring is a valuable resource in the coastal waters of Alaska, and because of its economic importance there is pressing need to identify the dominant factors influencing its population fluctuations. Development of a capability to forecast herring abundance with some degree of reliability is very important for fisheries management decisions.

The Sitka Sound Herring Project that looks into different aspects of the interaction between environment and herring population has three major parts:

1. Herring larvae studies: to map the horizontal and vertical distributions of larvae and determine patterns of larval transport and location of possible retention areas.

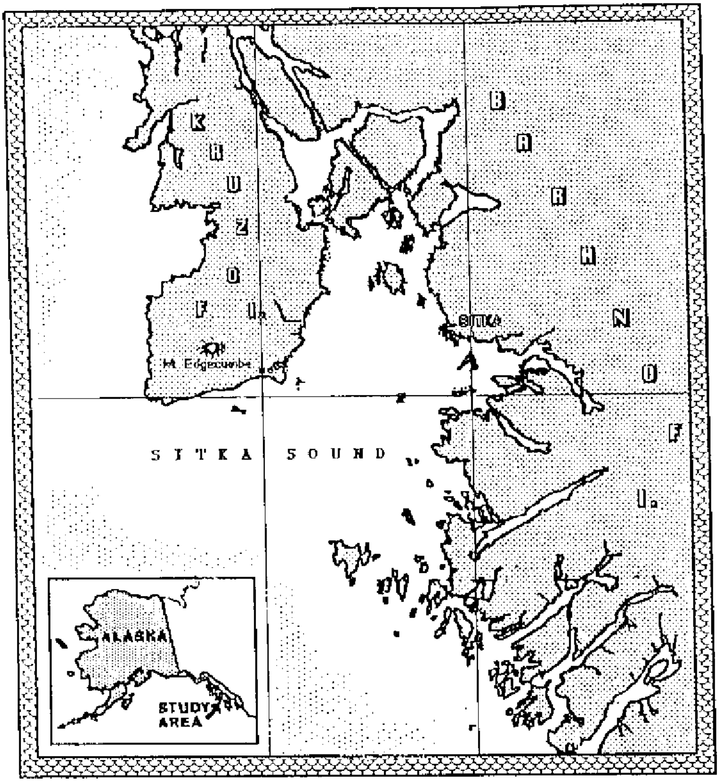

Figure 1: Sitka Sound study area in Southeast Alaska. Note the position of the city of Sitka where most of the environmental variables were measured.

2. Physical Oceanographic studies: to describe the hydrographic structure and current systems of Sitka Sound during the period when the larvae are present.

3. Historical Data Analyses: that examine the correlations between indices of recruitment and time-series of environmental variables.

This last part that is the main body of my Master's thesis work consists of the following:

a. Analysis of the different time-series of the physical variables available;

b. Defining the environmental variability that can be relevant to herring recruitment;

c. Establishing a coherent relationship between recruitment indices and environmental changes;

d.Developing a recruitment hypothesis in the light of the results obtained.

So far, I have started to look at some of the variables collected and some still need to be analyzed.

ENVIRONMENTAL VARIABLES

The number of variables to be used depends first on availability of the data in a usable form and secondly, on the time frame covered by the measures. The first approach has been to collect the data most of which were not updated and start the analysis while updating it (table 1).

1. Air Temperature, Barometric Pressure and Precipitation are the variables whose time series cover the largest period of time (table 1). The measures were taken at the Federal Aviation Administration (FAA) station at the Airport of Sitka on Japonski Island, situated right inside the Sound on the spawning grounds. In spite of the long period of time covered by these time-series some analyses cannot be performed without "shrinking" them considerably because of the gaps they contain.

2. Sea Surface Temperature (SST), Sea Surface Salinity (SSS) and Sea Level Height (SLH) available for shorter time periods, are collected at the Coast Guard dock in Sitka Sound. These shorter time-series make it more difficult to extract any cycles with certainty.

3. A series of monthly indices of intensity of large-scale, wind-induced coastal upwelling at a selected location directly off Sitka (57° N, 137° W) is another environmental variable considered. The indices are based on calculations of offshore Ekman surface wind transport derived from monthly mean surface atmospheric pressure data (Bakun, 1973).

4. The North-Eastern Pacific Pressure Index (NEPPI) is calculated as a difference between Sea Level Pressure (SLP) at 40° N, 120° W (near Reno in Nevada) and the SLP at 50° N, 170° W (in the North Eastern Pacific). The North Pacific winter SLP appears to have some relation to the Southern Oscillation (SO) and oceanic temperatures in the tropics. In particular El-Nino/Southern Oscillation (ENSO) episodes are generally coincident with strong North Pacific SLP patterns (Emery and Hamilton, 1985). This relationship can be important to us because the North Pacific atmospheric surface circulation was found to be strongly correlated with the anomalies of both SST and SLH. If the SST and SLH in the Northeast Pacific are indeed largely controlled by the regional atmospheric forcing, then tropical influences could make themselves felt in the extra-tropical ocean via atmospheric link.

Table 1. Physical variables used for the preliminary study and the period covered by the data at the time of first acquisition of the data sets available.

Variables	Period covered
Air Temperature	1867-1984
Air Pressure	1881-1978
Fresh Water Disch.	-- --[2]
NEPPI	1946-1988
Precipitation	1842-1984
Sea Level Height	1938-1985
Sea Surf. Salin.	1944-1964[1]
Sea Surf. Tempe.	1943-1983
Surface Winds	-- --[2]
Upwelling Index	1946-1988

[1] Sea Surface Salinity is the only variable that cannot be updated, and is no longer measured since 1964.

[2] Fresh Water Discharge and Surface Winds data were not usable at the time of the Symposium because of the format.

5. The other variables to be considered in this project are: Surface wind and Coastal Freshwater Discharge. The data for these variables have not yet been compiled in a usable form.

BIOLOGICAL VARIABLE

The biological variable used as Recruitment index is the log-normal transformation of the recruitment estimates (age 3) obtained by Dr. J. Collie (this symposium) using catch-age analysis. The model used for abundance estimates is an adaptation of the program GENCAGE (Funk and Sandone, 1990) to be used for Sitka Sound herring stock. Another possible Recruitment index to be considered is the proportion Recruits per Spawners, or its log normal transformation. (figure 4)

DATA ANALYSIS

The main statistical package used for this analysis is S (Success, Bell Laboratories) on the main Frame (VAX/VMS 8600) of the University of Alaska Southeast (Juneau campus). Some other software was used on PC's for completion and for some graphics e.g.: Lotus_123, Lotus_Freelance, and Mc Paint.

The raw data were plotted to have a general view on the variability, trends or cycles that could possibly be detected graphically and also to check for outliers. Relatively large amounts of variability exists in the raw data as one would expect from these types of variables. No clear trend over time can be detected apart from Sea Level Height that shows a general decrease in the graph of the raw data. No explanation has been suggested.

To look further into the data and try to determine the different possible cycles existing, the variability was first eliminated by taking the mean for every month over a long period of time. This gives us the seasonal cycles. They are very similar in accordance or opposition of phase, with very high correlation coefficients (of the order of 0.8 for some pairs of variables such as Air and Sea Surface Temperature).

When seasonal cycles are taken out of the data by calculating the yearly means, long period cycles can be detected as in the case of SSS where a four-year cycle can be seen. However, this observation needs more consideration because of the short period covered by this time-series of only twenty years. SST might also be cyclic, with longer cycles. It seems as if there was a 20-year cycle though it is not as obvious as the four-year cycle observed in the case of SSS; but, again, this SST time-series of 40 years is not sufficient to extract with certainty a cycle of this length. Because of the strong correlation existing between SST and AT, and since AT time-series covers a much longer period, a cyclic pattern could be detected more easily. I proceeded in a time-series decomposition of AT data. A large scale cycle of about 19 years appears clearly in the decomposition. This cycle seems to be the same as the one found in the solar surface activity records also reflected in the 18.6-year tidal cycle. (figure 2)

In finding the correlations between the different physical variables two problems are encountered. The first is to identify with certainty cause and effect relationships from short data records, especially when there is no lagged effect of one variable on the other to be noticed at the scale at which the measures were used (monthly means). The second is to determine the degree of confidence intervals to be chosen to determine correlation significances.

The correlations between the different variables (cross-correlations) without seasonality were obtained using the anomalies or deviations from the monthly means. Cross-correlation coefficients with positive and negative lags were calculated so the driving variables could be determined but the results are not usable at this point.

The most important part of the project is to find correlations between the physical variables and the recruitment indices as defined above. Taking into consideration that the variables may be acting on the first year of life of the herring larvae, the data which are the log transformation of the recruitment estimates were lagged for three years and correlation coefficients were calculated for one year, which corresponds to the first year of life of the recruits. The correlations corresponded thus to the prespawning months, the larval stage until metamorphosis, and the first months of the juvenile stage. The correlation coefficients obtained were plotted against time (12 months) (figure 3a-b). This was done for all the variables.

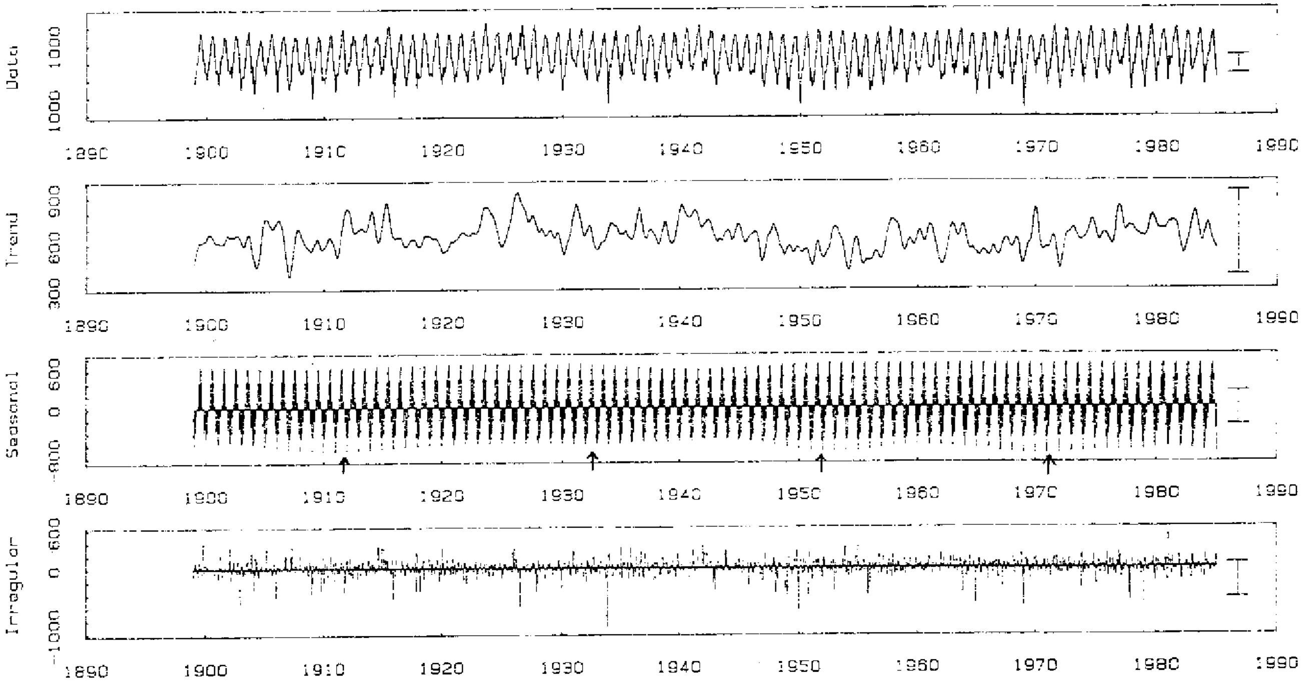

Figure 2. Time-series decomposition of Air Temperature data that shows the existence of a cycle of about 20 years.

RESULTS

The partial results obtained at this point can be summarized as follows:

1. Existence of cycles in the physical variables that can be relevant to herring recruitment data obtained from the Population Dynamics studies. The example in this is the 4-year cycle found in the Sea Surface Salinity. Unfortunately this variable is no longer taken and the set of data available does not overlap with the catch-at-age data collected from the fishery. So in spite of the existence of this cycle it is impossible to anticipate any relationship between this cycle and the recruitment indices changes over time. It cannot be checked for possible correlation.

A 20-year cycle in Air Temperature data is present and could be relevant to herring abundance fluctuations if more biological data were available; the catch data covers 19 years only! Once again such a cycle for herring cannot be verified.

2. Cross-correlations between physical variables show many high "r" values. The results, by looking at "r" values without considering them for statistical significance, are very intuitive. Air Temperature is positively correlated with SST, Air Pressure with SLH and Precipitation with SSS. (Table 2)

Table 2. Cross-correlation matrix for the different variables anomalies without lag.

	AT	AP	NEP	PRE	SLH	SSS	SST
AP	-.10	1.00					
NEP	.18	-.01	1.00				
PRE	.14	-.00	.02	1.00			
SLH	.40	-.77	.07	.07	1.00		
SSS	-.29	-.11	.02	-.50	.04	1.00	
SST	.55	-.06	.05	.04	.29	-.02	1.00
UPW	-.09	.40	0.02	.11	-.43	-.18	-.07

3. When we compare the fluctuations in herring recruitment abundance between the different stocks in the Northeastern Pacific such as Sitka Sound, Prince William Sound and British Columbia (presented in this symposium), the same variations seem to be affecting all the stocks. Such similarities between stocks, if ever controlled by any physical variables, imply a large scale effect rather than a localized one.

4. The correlations between physical variables and recruitment indices show a particular pattern when "r" values are plotted against time. The highest correlation coefficients are expressed in the prespawning months, then a relatively high correlation during the spawning and hatching time and finally another peak in "r" values when the larvae leave the Sound around the beginning of Fall. The values we are considering right now could be seen as

low and might be due only to spurious correlation. This needs to be checked, but the element to notice is the similarity in the shape of the curves for some variables (figure 3).

DISCUSSION

The preliminary results presented during this symposium represent the first approach to a more in depth investigation on the Causes of Recruitment Variation in the Herring Stock of Sitka Sound. Discussing the results at this point would be in the realm of thoughts and conjectures.

Herring is the best known fish in the Clupeoid family but still instigates a lot of questions and motivates many studies. The role it plays in the fisheries industry and the fluctuations it showed since historic times are the main reasons for such a vivid interest. A wide-spread idea is that a good year class is first determined by the larval survival for which the ocean must provide, obviously, nutritious food of the right size and present in sufficient quantity during the initial feeding of a larva. The optimum conditions for a larvae survival would then, be determined by a certain number of factors affecting either directly or indirectly the initial feeding. This is probably why the larval and juvenile stages and how they are affected by the environment seem to be gaining the attention of many researchers.

Many studies of this type looked at different environmental variables and ended up with pieces of information that could be true in one case and wrong for another one. Tanasichuk and Ware (1987), studied the effect of sea temperature and stock biomass on size-specific ovary weight and fecundity at spawning on herring. They stated that sea temperature may be responsible for some differences in egg size and fecundity (total egg number per female) among various stocks of Atlantic and Pacific herring. Another interesting study, was done by Stocker et al. (1985) and used a multiplicative, environmental-dependent Ricker spawn-recruitment model to identify significant environmental variables. The model suggests a significant relationship between temperature and spawning success with an optimal temperature during larval stages resulting in maximum production of recruits. Mysak (1986) described the oceanic and atmospheric observations, physical mechanisms, and theories associated with El-Nino-Southern Oscillation (ENSO) warming episodes in the tropical Pacific, and critically examined the means by which these anomalous events are believed to produce unusual conditions in the Northeast Pacific. He notices however that not all tropical ENSO episodes have noticeable effect at higher latitudes. Also , because of more anomalous local atmospheric forcing, significant warming, strong coastal currents, and high sea levels along the West coast of North America can occur in years during which there are no tropical ENSO episodes. He also examined the possible impacts of ENSO-induced changes and of other interannual fluctuations in the Northeast Pacific on various fisheries. He mentioned among others the increase in the Pacific herring recruitment. The parameters that are the most highly correlated between ENSO events and Northeast Pacific are:

Sea level records which contain many large peaks in common;

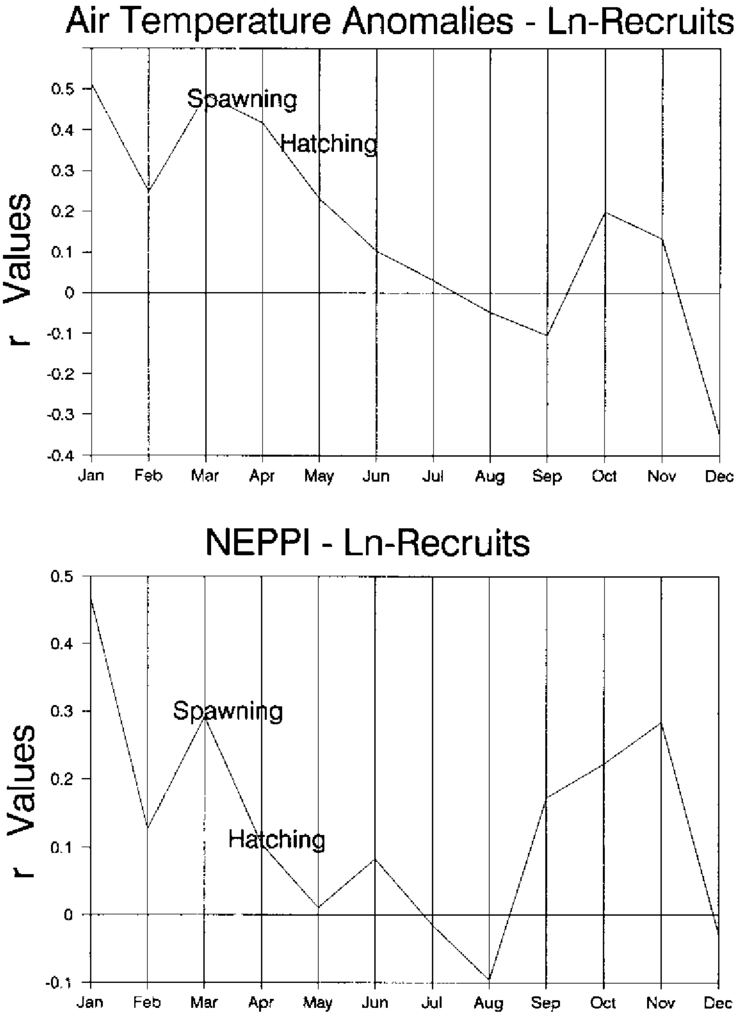

Figure 3a: Correlations between different environmental variables and Recruitment indices. R values are plotted against time for the first year of life of the herring larvae, including the prespawning months.

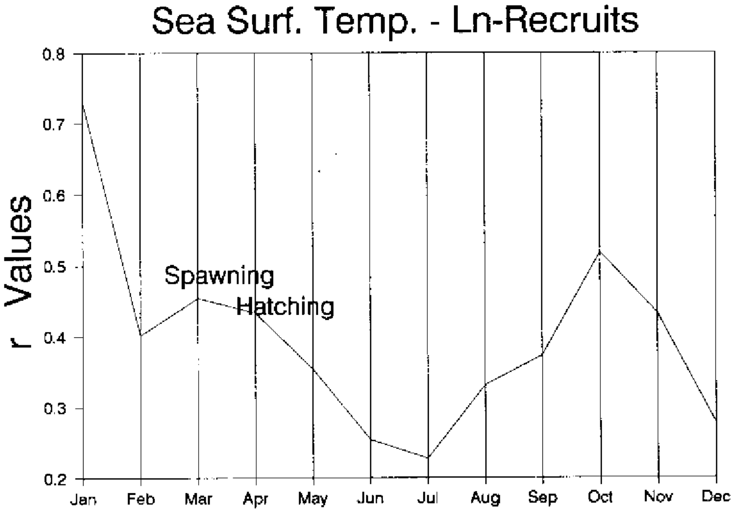

Figure 3b: Correlations between different environmental variables and Recruitment indices.
Sea Surface Temperature gives the highest correlations for the prespawning months and the curve has the same overall shape.

Sea surface temperature. There are marked interannual fluctuations within the time series taken from stations along the West coast of North America, some of which correspond to ENSO events;

Atmospheric pressure, rainfall and air temperature in the North Pacific which are inversely correlated with the ENSO events.

Those and other environmental variables, such as currents, and parametric measures of stability, turbulence, and turbidity, are believed to have a significant impact on fish survival, growth, and migration timing and routes in the Northeast Pacific. A range of other abiotic environmental variations which may produce the large interannual fluctuations that are observed in Pacific herring recruitment and year-class strength, can be suspected. These extend from individual storms and freshets which would affect survival of cohorts in an inlet to large-scale interannual events such as ENSO which cause changes in the circulation in the Gulf of Alaska.

Larval transport seems to be a common denominator for clupeoid survival, agreed upon in all the literature. It may be an effective way of sweeping relatively helpless clupeoid larvae into unfavorable areas or conversely of moving them to areas where they can find optimal survival conditions.

A statistical approach to the problem can be a good way to deal with such a large number of variables, but the difficulty is to choose the right assumptions to start with for looking to correlations. In the case of this study, the main element considered were that:

Physical variables with large-scale changes are the most likely to be affecting recruitment because of similar changes in different stocks of herring in the Northeast Pacific. (This should not prevent us from considering more localized effects that could have more detrimental consequences when the anomaly is out of range.)

Larval transport to a more or less favorable nursery will always be considered as an element to weigh and to relate to oceanic and meteorological changes. This leads to the general assumption that it is during larval stage of the life cycle of herring that the effect of the physical environment is the most felt. There is partial evidence that it could be even before being spawned that the larvae are affected by the environment. The high correlation coefficients values for the prespawning months may suggest an effect on the spawners that is governing the recruitment.

Conjugated effect of some variables could explain more of the variability than the same variables taken one by one. The multivariate analysis is then the most appropriate approach. The transformations to be used are however difficult to guess.

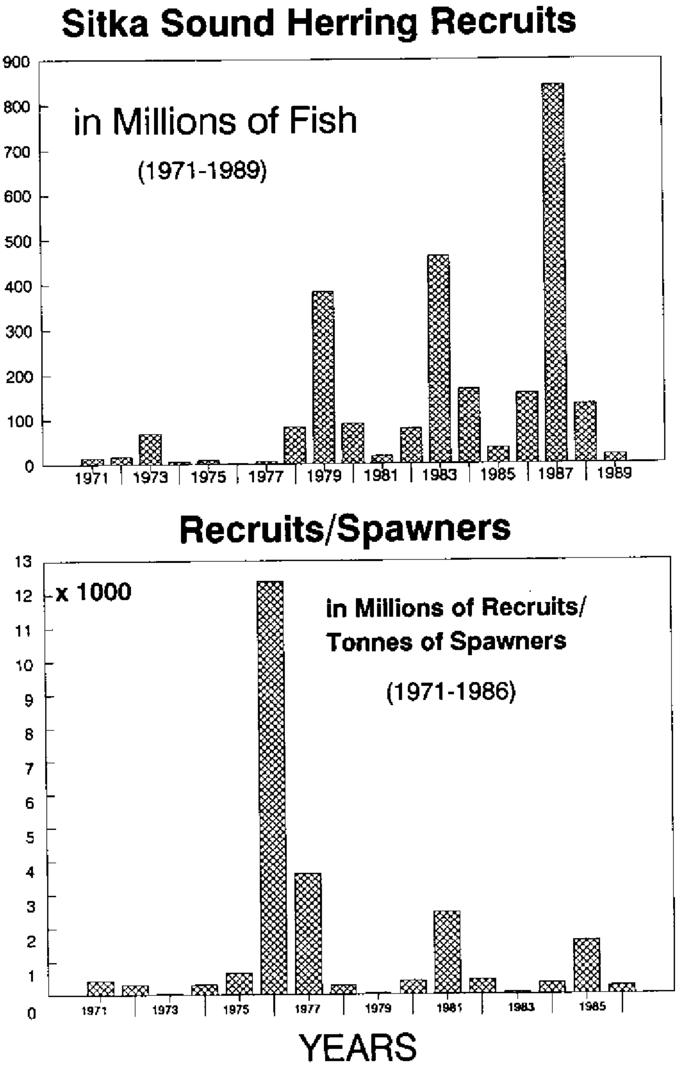

Figure 4: Herring Recruitment Estimates and Recruits/Spawners for Sitka Sound Stock from the transformed Program GENCAGE using catch-age analysis. The Recruitment Indices used are the Log-normal transformation of these data.

CONCLUSION

Recruitment success for herring larvae can be linked to many physical and biological conditions. Anomalous conditions can enhance or inhibit survival and depend upon the combined effect of the most influential factors. Those effect can act in an antagonistic way which makes the conclusions for any study very uncertain.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Population Dynamics of the White Sea Herring Stocks

E.A. Krixunov
Moscow State University
Moscow, USSR

ABSTRACT

There are three main herring populations in White Sea: Onega Bay herring, Kandalaksha Bay herring and the Dvina. There were obtained an estimates of mortality and growth parameters in the different herring populations and was made reconstruction of the abundance and biomass of mature fishes. The investigation of the stock-recruitment relationships shows that the Ricker model is more appropriate to dicribing a surviving process of young fish (less than one year old).

Simulation model used to analyse of dynamics herring populations are discrete-age compounding the modified stock-recruitment and dynamics pool equations. The model behavior shown that the population systems attain the equilibrium state under constant environmental conditions (constant parameters of models). There was shown an important role of a variable fishing mortality in year-to-year changes in herring catch.

Herrings are the most abundant fish in the White Sea. Annual general commercial herring catches in the last 10 years totalled about 1200 metric tons. The White Sea herring population structure is quite complicated. Small estuary forms are considered to be associated with fyord and sea forms. As a rule estuary small herrings are not individually mentioned in fishery statistics, which account for its association with large populations units such as fyord populations in the Onega, Kandalaksha and Dvina Bays (Figure 1). The annual catches of these herrings in the last 20 years varied from 150 to 1400 tons for the Onega population,

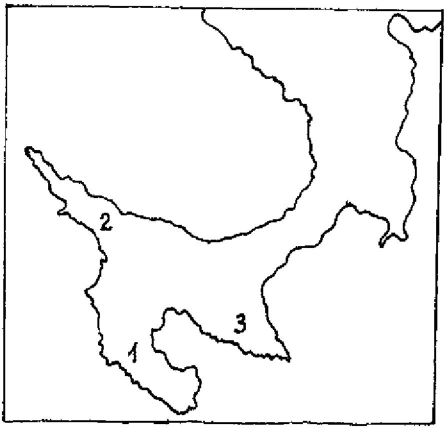

Figure 1. The White Sea. 1,2,3 - The Onega, Kandalaksha and Kandalaksha Bays

from 25 to 430 for Kandalaksha and from 80 to 620 for Dvina. Herring of the White Sea Bays are small in sizes regarding sea forms and differ from each other by growth rates, maturation rates, age structure and time of spawning. The Kandalaksha herring spawns early (from late April to early May) then comes the Onega and Dvina ones (from middle May to June). A few population signs are presented in table 1. Herring fishing proceeds when fish concentrations occur, in spring (before spawning), autumn and winter.

Table 1 (by Tambovcev, 1957,1962 et all.)

population	Maximum ages	Maximum length	Length in catch	Fecundity * 1000	Maturing ages
Onega	7	22	12-14	2.3-21.4	2-3
Kandalaksha	8	25	12-15	4.0-13.1	2-3
Dvina	7	21	11-13	2.2- 9.0	2-3

There are the results of our study of the population dynamics of White Sea herring based on the analysis of a scientific survey and catch statistics from different periods. The statistics on Onega herring involve a longer single discovery period from 1934 to 1986. The data of Kandalaksha herring relates to the period from 1959 to 1987 and that on Dvina herring - from 1964 to 1986.

The original data includes catch-at-age, statistics, fecundity estimates, information on the length and weight compositions of annual yields and to nonstandarized effort information. This data was used to identify of the parameters of herring growth and mortality equations The estimates of the natural mortality coefficients were obtained according to empirical regression of Pauly (1980). Values of total mortality rates were obtained by an analysis of the slope of a catch curves right limbs. The relative catchability-at-age coefficients were obtained by consequent dissolving an equations:

$$q_1/q_2 \cdot [\exp(M + F(\frac{q_1 + q_2}{2}))] = p_1/p_2$$

$$q_3 \cdot \exp(M + F(\frac{q_3}{2} + \frac{1}{2})) = p_3/p_4 \quad ,$$

where q_i - relative catchability coefficients, p_i - ratio of i-age class in catch. As considered a full catchability occures in ages older than 3 years ($q_{4\ldots}$ = 1).

The main estimates of growth and mortality parameters are given in Table 2

Table 2

Parameters	Onega	Kandalaksha	Dvina
W_∞	415.6	322.8	219.3
k	0.064	0.086	0.119
t_0	-4.1	-3.95	-1.95
M	0.216	0.228	0.273
Z	1.190	1.832	0.967
q_1	0.038	0.012	0.027
q_2	0.248	0.152	0.378
q_3	0.548	0.381	0.712
$q_{4-\infty}$	1.0	1.0	1.0

There are no strong differences among the main growth and mortality parameters of different bay herring. The catch-at-age statistics was used to reconstruct the abundance and fishing mortality rates by virtual population analysis (VPA). Mean values of mortality parameters were

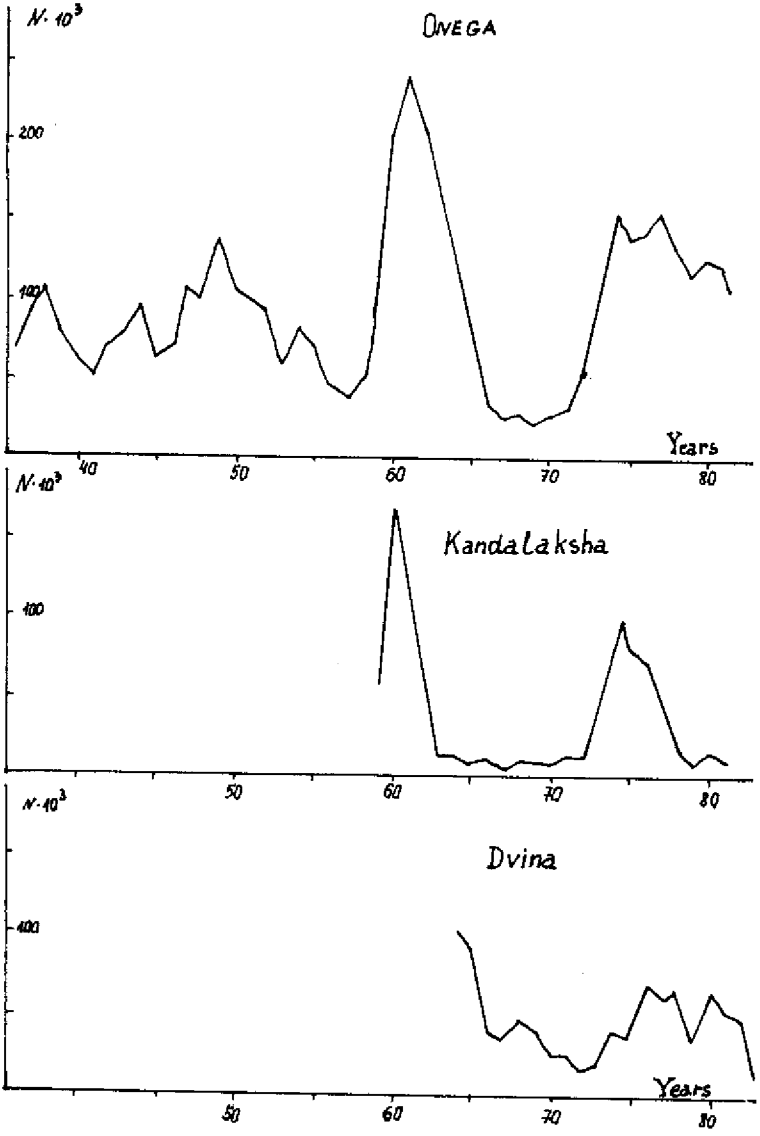

Figure 2. The dynamics of total numbers of three different herring populations

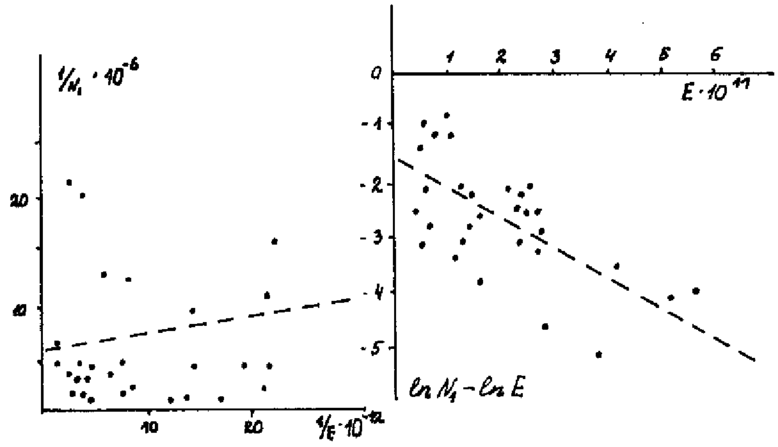

Figure 3. Fitting the Ricker and Beverton-Holt recruitmenr models for Onega population empirical points.

used as inputs in first step realizing of VPA procedure The tuning of the VPA procedure was carried out by meaning of the values of fishing mortality rates among adult full captured fish (As rule, ones not less than 3 years old). The dynamics of the reconstructed abundance of herring stocks are shown in Figure.2. The upper curve describes the dynamics of the total number of Onega bay herring, the medium curve represents the abundance Kandalaksha herring and the lower - the Dvina These curves demonstrate the common trend in the population changes of White Sea herring in the last 20 years. To explain this phenomenon it is nessesary to understand the recruitment process.

Because the herring fishery is directed on matur fishes a fishing pattern was used to calculate the number of spawning fish of each herring population. It was thought that the recruitment ratio among younger fish was the same as the ratio of it's fishing mortality coefficients to terminal ones. The assessments of the number of herring spawners was used to calculate populations fecundity, as

$$E = \sum^{i} N_i \cdot \overline{W}_i \cdot F$$

where W_i - is the mean weight of i-age fish, F - is a relative (per 1 mass gramm) fecundity.

The survival parameters of herring during the first years of life was estimated by using of the alternative recruitment models (Ricker and Beverton - Holt equations)

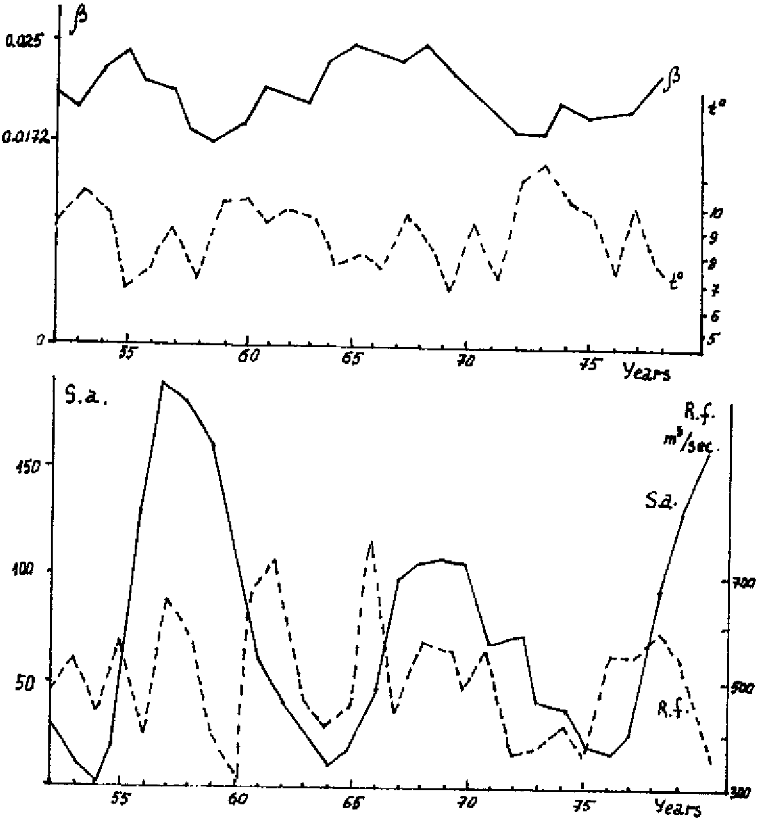

Figure 4. Dynamics of density-independent mortality (β) of young Onega herrin, and some environmental factors in 1952-1978. (t- temperature, s.a.- sun's activity, r.f - river flow mass)

The result of the investigation show that the Ricker equation is the more appropriate for discribing the survival process of young herring. The scatters of calculating points and the line of regressions Ricker's and Beverton-Holt recruitment models after lineation show in Figure 3.

There are not great differences between the mean values of the density-independent mortality coefficiens of three herring populations. It's estimates varies from $1.84\ 10^{-2}$ to $2.08\ 10^{-2}\ \text{day}^{-1}$. The differences in density-dependent mortality parameter are thought to reflect changes in the living capacity from bay to bay. These changes are illustrated by differences in location of curves domes.

The scattering of points on the stock-recruitment plot probably to reflects both estimation errors and the natural variability of recruitment parameters. In the short time interval is more likely that density-independent mortality is more sensitive to environmental effects than density-dependent parameter. Therefore, it may be suggested that annual variations of recruitment parameters are related mainly to the dynamics of density-independent mortality coefficients (β). The values of population's fecundity and corresponding abundance of first year class allow us to reconstruct the dynamics β.

The obtained dynamics of density-independent mortality of young Onega herring are shown in Figure 4. The curves of spring water temperature dynamics and that on the sun's activity and river flow mass are also shown. There are clear correlations between density-independent mortalities and spring-summer water temperature. A decrease of young herring mortality took place in years the spring water temperature increased up to 9°C or more. The young herring is known to be stable in respect of small temperature fluctuatins. Therefore only a strong temperature anomaly leads to a change in herring survival pattern. Therefore the rate of correlaton between density-independent mortality and temperature is quite low: these estimates are 0.42, 0.40, 0.43 for Onega, Dvina and Kandalaksha herring, respectively. A common tendency in the recruitment dynamics of White Sea herring is due to the a conjunction in water temperature and sun activity dynamics common for the different regions of Sea.

The simulation study of the population dynamics of herring was done to obtain information about the nature of year-to-year population changes.

The model elaborated is discrete-time and discrete-age. Description of herring recruitment processes includes the following system of equation for number ($N(t)$), and average weight ($\bar{W}(t)$ of fish in the first year of life:

$$\begin{cases} \dfrac{dN(t)}{dt} = -(\alpha\cdot E + \beta)\cdot N(t) \\ \dfrac{dW(t)}{dt} = \dfrac{\gamma/N(t)}{1 + 1/\delta\cdot\gamma/N(t)} \end{cases} \qquad (1)$$

Here α - is the compensatory reaction parameter, β - is the dens.-ind. mortality coefficient, γ - the parameter reflected inn the amount of food used by young fish for it's growth, δ - the parameter represented a maximum daily increment of body weight. System (1) leads to follow description of number and weight dynamic of young fishes:

$$N(t) = E\cdot\exp(-(\alpha\cdot E + \beta)\cdot t$$

$$W(t) = \delta t + \frac{1}{\alpha\cdot E + \beta}\cdot\ln\left[\frac{\gamma/\delta + E\cdot\exp(-(\alpha\cdot E + \beta)\cdot t}{\gamma/\delta + E}\right] + W_o$$

The parameter estimates are presented in Table 3.

Table 3.

Population	α	β	γ	δ
Onega	$1.53\cdot10^{-14}$	0.0208	$8.21\cdot10^{8}$	0.058
Kandalaksha	$6.47\cdot10^{-14}$	0.0183	$3.28\cdot10^{8}$	0.042
Dvina	$4.97\cdot10^{-14}$	0.0194	$6.45\cdot10^{8}$	0.033

An equations of the dynamics pool model were used for describing the weight and number change of adult fish. As distinct from the classic dynamic pool model, the states of each year's class of fish in our model are described by an equation of body mass distribution that is thought to be normal. The abundance of recruits in a spawning stock was defined as:

$$R_i = \Phi[1/\sigma\cdot(W_i - W_m)]$$

where Φ -is a symbol of the standarized normal function, W_i and σ - represents distribution parameters, and W_m - minimum weight of maturation.

Environmental effects are one factor of population dynamics. It is known that density-dependent regulation can lead to auto-oscillation waves in population dynamics. The modelling study allows us to simulate population system behavior in a constant environment. The obtained results are given in Figure 5. These results show that under constant environmental conditions all herring populations are stable. Perturbation of any model parameter leads to prolonged

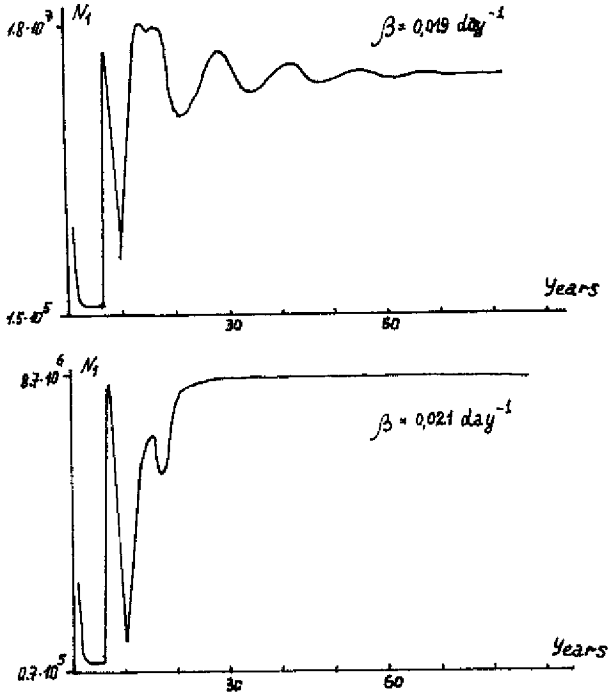

Figure 5. The simulation model behavior (recruitment) in constant parameters.

transient processes. The duration of these processes is about 25-30 years. It is likely that the real population dynamics of herring are formed by composition of a transient process parts following one another due to unpredictible disturbance in environmental conditions.

Sustainble yield curves were obtained, which are given in Figure 6. The model estimates of the fishing mortality coefficient - provided maximum catch are less than the real mean values. A comparison between yield estimates obtained by the simulation and modified dynamics pool model shows an underestimated yield in the latter case.

The results of reconstruction abundance and herring fishing mortality coefficients show the high variability of the exploitation rate. This variability, as well as

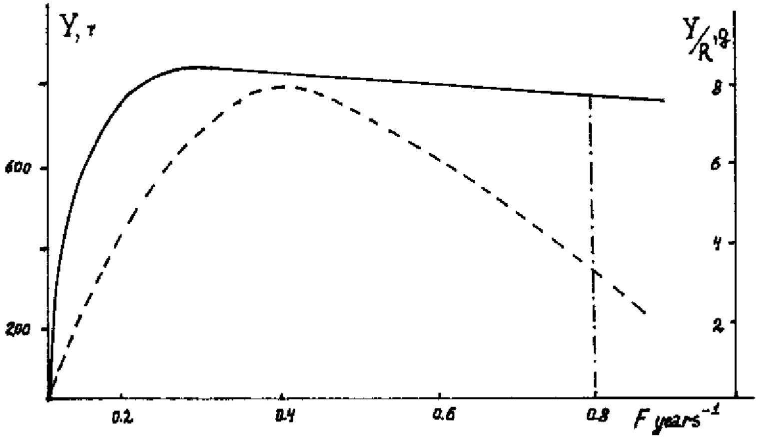

Figure 6. The Onega Bay herring sustainable yeald curve obtained by the simulation (1) and dynamics pool (2) models.

recruitment dynamics, can play an important role in year-to-year changes of herring stock size and yields. Model experiments were carried out to reconstruct dynamics of herring yield under separate and combined accounting of the real fishing and recruitment patterns. The results of these experiments are presented in Figure 7. Both variable model inputs provided yield dynamics deviating from the real as much as 27, 53 and 39%% for Kandalaksha, Onega and Dvina herring respectively. Accurate year-to-tear yield change simulation is not possible if one of these inputs is ignored. There isa lack of knowledge concerning factors affecting fishing mortality dynamics. This may change even when the fishing effort remains constant. Therefore obtaining reliable forecast is problematic.

ACKNOWLEDGMENT

Author would like to thank drs V.Pohiluk and S.Frolov who presented biological data on population structure, weight and length composition of herring catch. Author also grateful to dr T.Kuga, as well student in my postgraduate course for helping in prepare the papers text

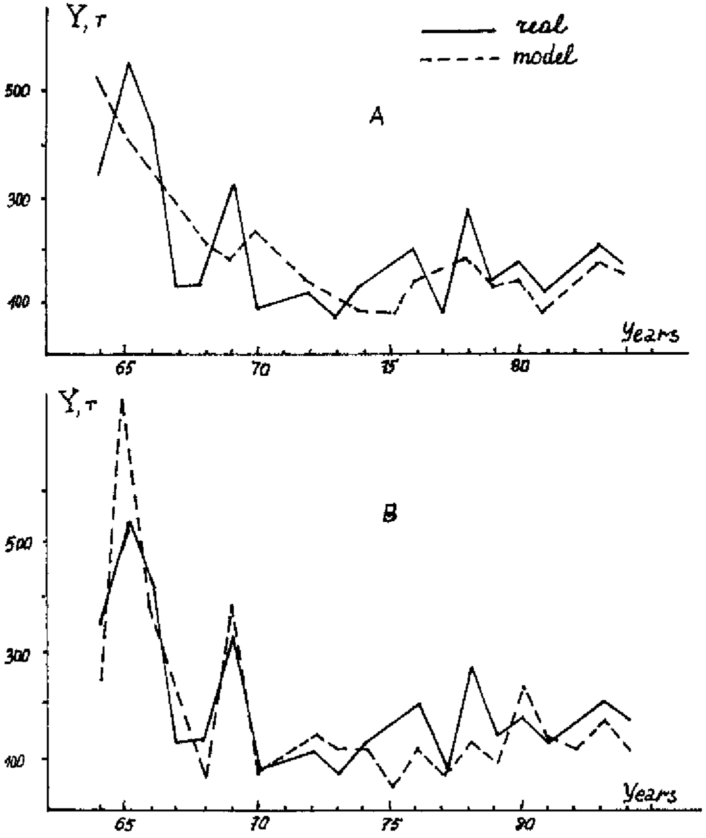

Figure 7. Simulation of the Dvina herring yield dynamics. A – under accounting real recruitment pattern. B – under accounting real recruitment and fishing patterns.

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Forecasting Pacific Herring (*Clupea harengus pallasi*) Recruitment from Spawner Abundance and Environmental Information

J.F. Schweigert and D.J. Noakes
Department of Fisheries and Oceans
Nanaimo, British Columbia, Canada

ABSTRACT

A series of seven forecasting models were fit to combinations of environmental time series data and spawner abundance estimates to forecast Pacific herring recruitment estimates determined from an escapement model. Historical data (27 or 30 years) were used to make one-step (year) ahead recruitment forecasts for the period 1981-1988. Forecasting accuracy for each model was evaluated by five performance measures: residual mean square error, mean and median absolute deviations, and mean and median percent errors. A nonparametric kernel estimation procedure applied to spawner abundance and recruitment data proved to be the best predictor of recruitment for 3 of five herring stock groupings. A Ricker environment model provided the best predictions for the other two stock groupings. Only the nonparametric model performed significantly better than the long term mean of observed recruitments. The Ricker stock-recruitment and stock-recruitment environment models performed somewhat better than the mean. Possible reasons for the poor performance of the other methods are discussed. Further evaluation of combinations of forecasts by these methods are required prior to routine implementation for stock assessment.

INTRODUCTION

Accurate forecasting of recruitment to fish stocks is crucial to the successful management of these resources. This is especially true for short-lived pelagic species such as Pacific herring *(Clupea harengus pallasi)* where recruits or first time spawners may comprise from 10 to over 50 percent of the total spawning run. In these species recruitment is the major factor determining the fluctuations in population abundance from year to year and area to area. Attempts to understand the importance of spawner abundance and environmental influences on recruitment and population fluctuations in fishes date back to the early part of this century (Burkenroad 1948, Bell and Pruter 1958). Ricker (1954) formalized the relationship between spawner

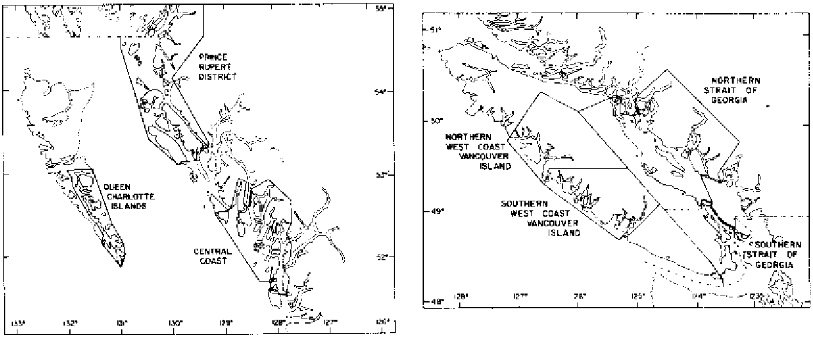

Fig. 1. Stock assessment regions or stock groupings for northern and southern British Columbia.

abundance and recruitment. Subsequently, a myriad of papers have developed additional techniques and formulae in an effort to provide improved forecasts of population fluctuations (Sinclair et al. 1988).

Management of Pacific herring stocks in British Columbia is based on two analytical models which are used to assess the escapement from the current year's fishery and forecast the abundance of spawning populations for the coming year (Haist and Schweigert 1990). Forecasts of the number of recruits to the spawning stocks are based on the historically observed recruitment time series. It is clear from this historical time series that herring recruitment is highly variable and the mean of the observed series is probably not a good predictor of future recruitment in most cases. Hence, any biological or statistical models which could provide a better understanding of the factors determining Pacific herring recruitment would be of significant value in improving management recommendations for these stocks. Stocker and Noakes (1988) endeavoured to identify the best forecasting model from an array of models including time series, Ricker stock-recruitment, and Ricker stock-recruitment environment models for the historical recruitment time series generated from an age-structured model.

In this study we describe the results of analyses that applied the following forecasting methods to the escapement model recruitment series: time series, Ricker, Ricker-environment, discriminant function, and nonparametric kernel estimation procedures. The models attempt to forecast recruitment observed in spawning runs rather than in the entire cohort, which includes sexually immature fish.

METHODS

DATA BASE

The data utilized in this study consisted of estimated numbers of 3 yr old herring observed in the spawning runs, from 1951 through 1988, to the five largest spawning stocks on the British Columbia coast (Fig. 1): south-eastern Queen Charlotte Islands, Prince Rupert District, central coast, northern Strait of Georgia, and southern west coast of Vancouver Island (Haist and Schweigert 1990). The total spawning population estimate was the number of age 3 and older fish in the spawning runs from 1951 to 1985. Hence, the models based on environmental data alone contained

38 data points while those requiring spawning population size data only contained 35 observations.

The time series, discriminant function, and Ricker stock-recruitment-environment models used environmental information such as ocean surface temperature and salinity, Ekman transport, total annual river discharge, and sea level. These data were obtained from the observing stations closest to the spawning grounds from 1948 through 1985 (Table 1). Secondary environmental series were used occasionally if the series for the primary site was incomplete.

Table 1. Environmental variable data sources (1948-1985) used in the analyses for five herring stock groupings. SST - sea surface temperature, SSS - sea surface salinity, EK - Ekman transport, SL - sea level, DIS - river discharge. Subscripts refer to quarterly averages throughout.

Stock Grouping	Environmental Variables
Queen Charlotte Islands	SST - Langara Island
	SSS - Langara Island
	EK - 54°N 134°W
	SL - Prince Rupert
	DIS - Skeena River
Prince Rupert District	SST - Langara Island
	SSS - Langara Island
	EK - 54°N 134°W
	SL - Prince Rupert
	DIS - Skeena River
Central Coast	SST - Pine Island
	SSS - Pine Island
	EK - 51°N 131°W
	SL - Prince Rupert
	DIS - Bella Coola River
Strait of Georgia	SST - Entrance Island
	SSS - Entrance Island
	EK - 48°N 125°W
	SL - Tofino
	DIS - Fraser River
W. Coast Vancouver Is.	SST - Amphitrite Point
	SSS - Amphitrite Point
	EK - 48°N 125°W
	SL - Tofino
	DIS - Fraser River

Stocker and Noakes (1988) used an exploratory correlations approach to identify environmental variables which were significantly correlated with recruitment during particular months of the year. For this study, we decided that most biological processes mediated by environmental factors probably operate on either a shorter or longer time frame than one month. It is impractical to investigate effects on a daily or weekly time frame at this time. Instead, environmental data were summarized into quarterly averages which are more consistant with annual events in the herring life cycle. For example, during the first quarter spawners are either migrating inshore or schooled up near the spawning areas; during the second quarter larvae are hatching and metamorphosing; during the third quarter juveniles are schooling up and growing rapidly; and by the fourth quarter juveniles are beginning to migrate offshore. We felt that the quarterly means for environmental variables might better reflect the impact of particular factors on ultimate recruitment.

TIME SERIES MODELS

The general transfer function noise model (TFN) or times series model consists of two components: a dynamic component and a stochastic component. The dynamic component models the interaction between recruitment at time *t*, and any covariate spawning stock size or environmental series in the overall model. The stochastic noise component characterizes the error remaining in the data when the effects of the covariate series have been accounted for. Hence, for *m* covariate series, the TFN model is given by:

$$(y_t-\mu_y) = \sum_{i=1}^{m} \omega_i (B) \left[\delta_i (B)\right]^{-1} B^{b_i} (x_{ti}-\mu_{xi}) + \Theta (B) \left[\phi (B)\right]^{-1} \sigma \epsilon_t \qquad (1)$$

where t is discrete time, y_t is the response or output variable, x_{ti} is the value of the i^{th} covariate series at time t, ε_t is the error term or model residual (usually assumed to be normal and independently distributed with mean zero and variance one), and σ is the standard deviation of the model residuals. The transfer function components of the model,

$$\omega_i(B)\left[\delta_i(B)\right]^{-1} B^{b_i} \tag{2}$$

are represented in terms of the finite order polynomials

$$\omega_i(B) = \omega_{0i} - \omega_{1i}B - \omega_{2i}B^2 - \ . \ . \ . \ - \omega_{u_i i}B^{u_i} \tag{3}$$

and

$$\delta_i(B) = 1 - \delta_{1i}B - \delta_{2i}B^2 - \ . \ . \ . \ - \delta_{r_i i}B^{r_i}, \tag{4}$$

where $\omega_{0i}, \omega_{1i}, \ . \ . \ . \ , \omega_{u_i i}$ and $\delta_{1i}, \delta_{2i}, \ . \ . \ . \ , \delta_{r_i i}$ (i = 1, 2, ..., m) are the parameters to be estimated, u_i and r_i are the orders of the polynomials $\omega_i(B)$ and $\delta_i(B)$, repectively, and B is the backward shift operator such that $B_{y_t} = y_{t-1}$ and $B^n y_t = y_{t-n}$, where n is a positive integer. The term B^{b_i} is used to account for any delay in response associated with the i^{th} covariate series. The input covariate series are additional time series related to the response variable, recruitment, in some manner.

The stochastic noise component of the model in equation 1, $\Theta(B)[\phi(B)]^{-1}\sigma\varepsilon_t$, models the autocorrelation structure of the data. This term includes a moving average component of order q (MA(q)), $\Theta(B)$, and an autoregressive operator of order p (AR(p)), $\phi(B)$, given by:

$$\Theta(B) = 1 - \Theta_1 B - \Theta_2 B^2 - \ldots - \Theta_q B^q \tag{5}$$

and

$$\phi(B) = 1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p \tag{6}$$

respectively. The combined term is referred to as an ARMA(p,q) process. An AR process indicates that the observations at time t are related linearly to observations prior to time t. For an MA process, the variable y_t is related to the previous errors. Mixtures of AR and MA processes provide a means to describe the autocorrelation structures in particular time series.

An important step from a modelling perspective is determining which of the two terms to include in the TFN model, (i.e. should the TFN model only include the transfer component and a random error term, only the stochastic noise component or both components). Cross correlation analyses were performed to determine which covariate series to include in the model. Plots of the autocorrelation function (ACF) and the partial ACF were used to identify orders for the AR and MA operators. Model residuals were examined to ensure they were approximately normally distributed and not significantly correlated. We used the Akaike information criterion to choose the best of several competing models which all satisfied the selection criteria.

DISCRIMINANT FUNCTION MODELS

Discriminant analysis is a multivariate statistical technique which attempts to find a linear combination of the predictor variables that show a large difference in the group means for the response variable (Lachenbruch 1975). In other words, it develops a discriminant criterion or discriminant function to classify each observation in the data set into one of the several groups of interest. In the case of recruitment forecasting, it is almost as important to be able to predict whether recruitment will be good or poor as to be able to forecast the expected number of new recruits to a spawning stock. Hence, the objective of this analysis was to separate out years of good, average, and poor recruitments based on the environmental time series or the number of adult spawners with a discriminant function. Each recruitment time series was ranked from lowest to highest and split into thirds. The associated environmental variables for each observation were used to develop discriminant functions with which to classify data for the forecast year into one of the three groups. Discriminant analyses were conducted for each stock based on the environmental variables alone (DFE) and for environmental variables plus spawner abundance (DFSE). Then, forecasts of the expected recruitment for the coming season were made by summing the relative probability of poor, average, or good recruitment times the historical average size of the respective recruitments:

$$\hat{R}_t = \sum_{i=1}^{3} P_{it} \bar{R}_i \tag{7}$$

where $\hat{R}_t$ is the recruitment estimate for the forecast year, P_{it} is the probability that the recruitment for the forecast year will be poor, average, or good and $\bar{R}_i$ is the average of the poorest third, middle third, or best third recruitments observed in the historical time series.

NONPARAMETRIC MODELS

An assortment of nonparametric regression and data interpretation schemes are available for forecasting problems (see Noakes 1989). Their goal is to capture local characteristics of the data while incorporating a degree of global smoothness. The degree of smoothing is determined by combining statistical fit with a penalty function relating to the relative roughness of the fitted surface. The degree of smoothing determines how closely the surface or curve fits local data variation, i.e. increased smoothing will provide a more linear fit to the data set. The model used to generate forecasts of herring recruitment in this analysis is based on a kernel estimator. The kernel estimator determines the joint probability density function for historical recruitment and spawning stock abundance. The estimated density functions are then used to estimate recruitment conditional on the spawning stock abundance in the birth year of the recruiting year class.

For a simple univariate case with n independent observations, x_i, $i = 1, 2, \ldots, n$ and common but unknown density $f(x)$, which we estimate by $\hat{f}(x;h)$ based on the kernel $k(\bullet)$ and smoothing parameter h such that:

$$\hat{f}(x;h) = \frac{1}{nh} \sum_{i=1}^{n} k \left(\frac{x - x_i}{h} \right) \tag{8}$$

where $k(\bullet)$ is a probability density function such as the normal. The kernel is a function used to weight the contribution of data points, x_i, to the estimated density at the prediction point. The choice of the kernel is not as important as the choice of the smoothing parameter, h, for obtaining reasonable estimates of $f(x)$. For a Gaussian kernel the estimate becomes:

$$\hat{f}(x;h) = \frac{1}{nh} \sum_{i=1}^{n} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-(x - x_i)^2}{2h^2}\right) \tag{9}$$

The smoothing parameter determines how smooth the estimate of $f(x)$ is so that choosing too large a value for h results in oversmoothing while too small a value produces an estimate of $f(x)$ with too many peaks. We use a jack-knife based modified likelihood approach to choose the appropriate value of h (see Noakes (1989) for details). A multivariate extension of equation 6 determines $f(\mathbf{x})$ $\{\mathbf{x}=(x_1,x_2)\}$, the joint density for historical recruitment (x_1) and spawning stock size (x_2). The forecasted recruitment is then determined by finding the maximum estimated density, $\hat{f}(\mathbf{x})$, with respect to recruitment, x_1, given the current spawning stock size $x_2 = S_{t-3}$:

$$\hat{R}_t = \max_{X_1} \hat{f}(x \mid X_2 = S_{t-3}) \tag{10}$$

where $\hat{R}_t$ is the recruitment forecast and X_2 is the spawning stock abundance, S_{t-3}, in the year generating recruitment R_t. While it is theoretically possible to extend this procedure to include multiple covariates, data limitations in this study restricted the usefulness of this approach to the bivariate case (Silverman 1986). Given this practical constraint, we chose only to consider the relationship between stock size and recruitment.

RICKER S/R AND ENVIRONMENT MODELS

The final two series of models examined to forecast herring recruitment using spawner abundance and environmental data are those suggested by Ricker (1954, 1975). We estimated the number of age 3 recruits from the number of spawners 3 years earlier by:

$$R_t = \alpha S_{t-3} \exp(-\beta S_{t-3} + \varepsilon_t) \tag{11}$$

where R and S are as defined above, α and β are spawner-recruit parameters, and ε_t is a normally distributed random variable with mean 0 and variance σ^2. The model was fit to the data series by regressing the logarithm transform of the ratio of R/S against S.

Similarly, we fit a series of RICENV models to the estimates of parental abundance and environmental variables using a SAS procedure which minimizes the Mallows criterion (C_p) and usually maximizes R^2, the multiple correlation coefficient (SAS 1988). The models were of the form:

$$R_t = \alpha S_{t-3} \exp(-\beta S_{t-3} + \gamma_i X_{i,t-3} + \varepsilon_t) \qquad (12)$$

where $X_{i,t-3}$ is a vector of environmental variables, and γ_i is a vector of parameters for each environmental variable in the model. We did the analysis on 27 to 35 data points as described below and chose the model with the environmental variables that were most consistantly significant for the 8 sets of analyses.

MODEL EVALUATION

Selecting the best model for forecasting recruitment must include a component to deal with the management cost associated with forecasting error as discussed by Stocker and Noakes (1988). They considered five symmetric, monotonically increasing cost functions to compare models: the residual mean squared error (RMSE), the mean absolute deviation (MAD), median absolute deviation (median AD), mean absolute percent error (MAPE), and the median absolute percent error (median APE).

To evaluate the relative performance of the four classes of forecasting models we fit each model for each of the five stocks to the first 30 years of the data series, generated a one-step (year) ahead forecast, refit the model to the 31 points, reforecasted, etc. The models which incorporated spawner abundance used a time series 3 years shorter than those based solely on environmental data due to the 3 year lag in recruitment to the fishery. We used the average of the historical time series as the standard against which to compare forecasts. The resulting performance measures for each model were averaged over the 8 years:

$$RMSE = \frac{1}{8} \sum_{t=1981}^{1988} (R_t - \hat{R}_t)^2 \qquad (13)$$

where R_t is the observed recruitment and $\hat{R}_t$ is the predicted recruitment for each model. The models were then ranked on the basis of the five criteria, and an overall rank sum calculated for each stock.

RESULTS

TIME SERIES ANALYSIS

The best transfer function noise or ARMA model determined for each herring stock group is shown in Table 2. Observed recruitments for the period 1981-1988 are shown in Table 3 with the corresponding estimates for each of the seven forecasting methods.

The environmental time series did not correlate significantly with the Queen Charlotte Islands recruitment series so the historical average of recruitment estimates was used for model evaluation for this stock.

The Prince Rupert District environmental time series was significantly correlated with the recruitment series based on a TFN model incorporating the estimated Ekman transport at 54°N 134°W during the first 2 quarters of the year (Table 2). This model accounted for about 51 percent of the total variation in recruitment.

The central coast recruitment data were modelled with a transfer function that included Ekman transport at 51°N 131°W during the first quarter of the year and the Bella Coola River total annual discharge (Table 2, Fig. 2). This model explained 47 percent of the recruitment variation for this stock grouping.

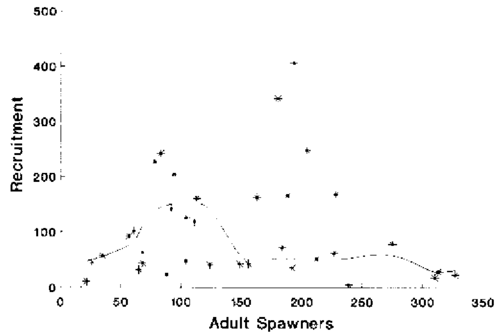

Fig. 2. Time series of herring recruitment (solid line), Ekman transport (dashed line) and river discharge (dotted line) for the central coast, 1951-1988.

The Strait of Georgia environmental series accounted for only 32 percent of the variation in recruitment. The TFN model developed for this stock included the Ekman transport at 48°N 125°W during the second quarter of the year and the sea level at Tofino in the fourth quarter of the year (Table 2).

The herring stock grouping on the south west coast of Vancouver Island could not be fit significantly with any TFN models. Instead, we used a simple ARMA model with a 3 year recruitment lag to make recruitment forecasts for this stock (Table 2).

DISCRIMINANT FUNCTION MODELS

The discriminant functions used in the forecasting process were fitted to all 17 (DFE) or 18 (DFSE) variables for each stock grouping (4 environmental variables x 4 quarters plus annual river discharge and spawner abundance). We did not make any attempt to utilize significant subsets of variables identified with a stepwise procedure. Logistically this was too cumbersome to pursue at this time. Unfortunately, this meant that most parameter estimates were underdetermined as we were fitting the models using only 27 to 38 data points. This analysis was disappointing as very few of the discriminant functions were statistically significant based on Wilk's λ. Examination of the parameter weightings for the discriminant functions revealed only subtle differences between poor, average, and good recruitment groups. Plots of the canonical variates frequently indicated that average recruitments were quite distinct from the good or poor ones but it was difficult to distinguish between poor and good recruitments (Fig. 3). Adding spawner

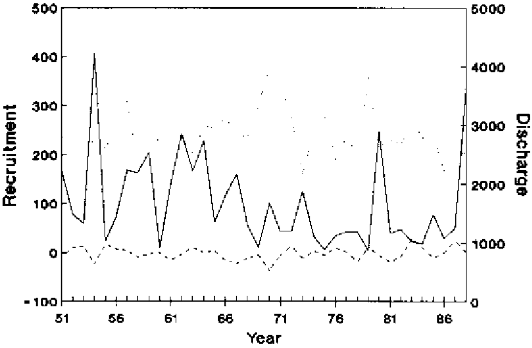

Fig. 3. Canonical variates for environmental variables indicating poor (⊛), average (*), and good (o) recruitments for the central coast, 1951-1988.

Table 2. Forecasting models derived from time series analysis (Tranfer function noise) and regression analysis (Ricker-enviroment) for five herring stocks.

Stock Grouping and Model Type	Prediction models
Transfer Function	
Queen Charlotte Islands	Mean - no significant TFN model
Prince Rupert Distict	$\ln R_t = TF(EK_1) + TF(EK_2) + \sigma^2/2$
Central Coast	$\ln R_t = TF(EK_2) + TF(DIS) + \sigma^2/2$
Strait of Georgia	$\ln R_t = TF(EK_2) + TF(SL_4) + \sigma^2/2$
W. Coast of Vancouver Is.	$\ln R_t = \phi_3 R_{t-3} + \mu_R(1 - \phi_3) + \sigma^2/2$
Ricker-environment	
Queen Charlotte Islands	$\ln\,(R_t/S_{t-3}) = \alpha + \beta S_{t-3} + SSS_3 + SL_3$
Prince Rupert Distict	$\ln\,(R_t/S_{t-3}) = \alpha + \beta S_{t-3} + EK_1 + EK_2 + EK_4 + SL_3 + DIS$
Central Coast	$\ln\,(R_t/S_{t-3}) = \alpha + \beta S_{t-3} + SSS_1 + EK_2$
Strait of Georgia	$\ln\,(R_t/S_{t-3}) = \alpha + \beta S_{t-3} + SSS_2 + SSS_3$
W. Coast of Vancouver Is.	$\ln\,(R_t/S_{t-3}) = \alpha + \beta S_{t-3} + SST_4 + SL_2$

abundance to the environmental series did not substantially affect model fit but did result in significantly different forecasts for some years in most stocks (Table 3). It appears that one should attempt to refit these models using the environmental variables identified as important for forecasting recruitment by one of the other methods.

NONPARAMETRIC MODELS

The Gaussian kernel nonparametric estimation procedure (NPAR) used in this analysis produces results reminiscent of the usual Ricker S/R function (Fig. 4). In this case, we have plotted the peak values of the kernel function, $f(x)$, from the three dimensional surface relating recruitment and spawner abundance. These estimates are very similar to a freehand line drawn through the bivariate plot of adult abundance and recruitment data. Recruitment estimates are presented in Table 3. There are no readily comparable performance statistics for this model but confidence intervals for the forecasts are very wide (i.e. for Queen Charlotte Islands in 1981 the recruitment estimate is 44 with 90 percent confidence intervals of 4 to 296).

RICKER S/R AND ENVIRONMENT MODELS

The recruitment forecasts for the Ricker and Ricker-environment (RICENV) models are shown in Table 3. In the Queen Charlotte Islands the Ricker model accounted for at best 32 percent of the total variation in recruitment while the RICENV model with SSS_3 and SL_3 accounted for a maximum of 51 percent of recruitment variation (Table 2). For the Prince Rupert District the Ricker models explained at most 3 percent of the recruitment variation while the RICENV models with EK_1, EK_2, EK_4, SL_3, and DIS accounted for almost 68 percent of variation in recruitment (Table 2).

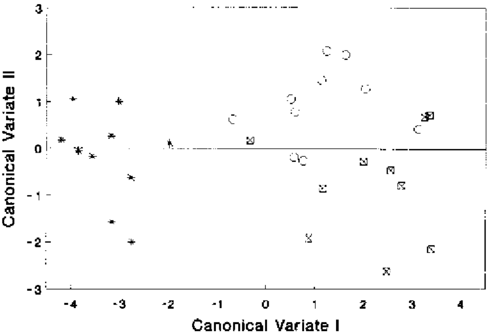

Fig. 4. Recruitment time series and curve of predicted values from the NPAR model for the central coast, 1951-1988.

The Ricker model for the central coast herring stock groups explained 47 percent of recruitment variation. The RICENV models with SSS_1 and EK_2 accounted for up to 61 percent of total recruitment variability (Table 2). Strait of Georgia Ricker models explained almost 55 percent of total recruitment variation while the RICENV models with SSS_2 and SSS_3 explained up to 65 percent of variation in recruitment. Finally, the Ricker models for the southern west coast of Vancouver Island explain as much as 51 percent of the variance in recruitment. The RICENV models with SST_4 and SL_2 explain up to 62 percent of recruitment variability (Table 2).

MODEL EVALUATION

The performance measures for all the forecasting models are presented in Table 4. For the Queen Charlotte Islands all methods tend to overpredict recruitment and none do particularly well at capturing the inherently high degree of recruitment variability characteristic of this stock (Table 3). Clearly the best model for this stock is the RICENV model followed by the DFE model. The recruitment forecasts for the Prince Rupert District are variable. The best model for this stock grouping is the NPAR model followed again by the DFE model. The central coast recruitment forecasts are generally high for almost all models. This reflects in part the historical pattern of recruitments which appears to have been much higher than the levels observed during the past decade. However, the exceptionally strong recruitment in 1988 was only reflected in the estimates for the two discriminant function models (Table 3). The best forecasting model for the central coast seems to be the RICENV model followed closely by the Ricker S/R, TFN, and NPAR models (Table 4). The Strait of Georgia is characterized by a fairly stable recruitment pattern with occasional exceptional recruitment. This pattern is reflected by most of the forecasting methods. Again, only the discriminant function models (DFE and DFSE) correctly forecast the strong 1986 recruitment. However, they overestimate the poorer 1984 recruitment, as do all the other methods (Table 3). The best forecasts for this stock are generated by the NPAR model followed closely by the Ricker and RICENV models. Recruitments to the west coast of Vancouver Island are also generally stable, although more variable than for Georgia Strait. Estimates by the discriminant analysis models (DFE and DFSE) are much too high while forecasts from the other models are all similar. The best forecasts were again generated by the NPAR model, followed by the Ricker and RICENV models (Table 4). Summarizing the results across the five stocks: the best performer is clearly the NPAR model, followed by the Ricker S/R and RICENV models which performed only somewhat better than the long term mean (Table 4).

Table 3. One-step (year) ahead recruitment forecasts from seven methods which use either stock abundance or environmental variables or both for five Pacific herring stock groupings.

				Environment Only		Spawners Only		Spawners and Environment	
Stock Grouping	Forecast Year	Observed Recruits	Mean Recruits	TFN	DFE	NPAR	Ricker S/R	DFSE	RICENV
Queen Charlotte Islands	1981	7	45	45	25	44	46	26	20
	1982	6	44	44	18	45	35	31	12
	1983	7	43	43	68	7	15	104	24
	1984	68	42	42	63	57	17	81	13
	1985	20	43	43	15	45	32	25	33
	1986	1	42	42	8	43	36	22	10
	1987	10	41	41	6	43	23	6	4
	1988	45	40	40	90	42	29	95	92
Prince Rupert District	1981	22	81	65	13	20	27	12	45
	1982	29	79	82	41	21	43	38	18
	1983	46	78	13	44	53	66	36	12
	1984	102	77	11	169	64	156	172	494
	1985	26	78	175	14	42	58	14	10
	1986	35	76	12	23	52	69	165	74
	1987	135	75	119	15	72	66	16	34
	1988	108	77	34	158	92	77	163	218
Central Coast	1981	40	72	24	31	151	93	31	74
	1982	47	107	102	169	151	89	169	108
	1983	23	105	33	189	31	47	189	22
	1984	18	102	11	213	24	42	213	55
	1985	78	100	32	70	68	44	70	78
	1986	29	99	56	195	28	38	195	31
	1987	51	97	32	27	51	64	27	14
	1988	343	96	16	192	51	73	192	63
Strait of Georgia	1981	125	176	176	156	119	105	116	129
	1982	202	174	105	73	197	93	287	140
	1983	123	175	174	85	142	122	227	217
	1984	77	173	137	188	91	177	239	191
	1985	116	171	52	129	126	99	129	129
	1986	323	169	113	279	94	171	279	175
	1987	108	173	165	73	96	157	73	105
	1988	144	172	250	283	175	166	283	131
West Coast of Vancouver Is.	1981	91	95	35	173	83	71	156	82
	1982	28	95	35	165	86	56	106	34
	1983	31	93	26	128	30	42	167	30
	1984	68	91	36	109	78	48	171	37
	1985	118	90	34	34	92	86	32	90
	1986	113	91	19	125	101	87	127	134
	1987	45	91	36	81	88	85	118	119
	1988	188	90	40	47	184	57	52	66

DISCUSSION

The main objective of this study was to develop a forecasting model which could provide more accurate estimates of 3 yr-old recruits than simply calculating historical averages of observed recruitments. The total rank sum for all five stock groupings indicates that three methods performed better than the mean: the NPAR model, the Ricker S/R model, and the RICENV model. The five performance measures we examined produced similar rankings within stocks although there are striking exceptions for all stocks. Usually the model with the lowest RMSE was also the one which had the lowest rank sum for that stock although for the Prince Rupert District and central coast this statistic was similar for the three best forecasting methods.

An explanation for the poor performance of the transfer function noise model and for the discriminant function models is not readily apparent. These models are all solely dependent on environmental time series. It is possible that the data used in these models is not an accurate reflection of the environmental conditions to which the pre-recruit herring are exposed. Complete time series of environmental data are available for a limited number of areas which are not always near the herring spawning and rearing areas. In fact, no significant time series model was found for the Queen Charlotte Islands. The recording stations for this area are quite distant from the spawning grounds. The results for this stock group may also reflect incomplete spawn survey coverage until the 1960's which would negatively impact recruitment estimates. As suggested earlier, the discriminant function models may perform better if they are restricted to using a few 'significant' environmental variables rather than the whole array of information.

The models which performed better than the mean of the historical recruitments are all based on an estimate of spawning stock abundance although one, the RICENV model, incorporates environmental variables. This suggests that environmental factors may not be as important in determining recruitment in some stocks as the number of fish which are allowed to spawn. However, another possibility is that for some stocks there may be a critical time period during which environmental factors impact on pre-recruit survival. Because we used quarterly averages of the environmental variables some of the signals for these effects may be damped out of the data. Interestingly, it is only the two stocks which experience the greatest fluctuations in recruitment for which we see any significant environmental effects. These results are in contrast to those of Stocker and Noakes (1988) who found that RICENV and TFN models with an index of spawner abundance performed best in forecasting recruitment estimates from an age-structured assessment model. Unfortunately, the environmental variables used in their study are not directly comparable to those in this study making direct model comparisons impossible. However, they found temperature to be a significant factor in determining recruitment success for most stocks. An earlier study by Stocker et al. (1985) had also found temperature and Fraser River discharge to correlate significantly with recruitment of herring in Georgia Strait. In the current study only for the west coast of Vancouver Island stock were temperature effects significantly related to recruitment. It is also interesting to note that the forecasts by Stocker and Noakes (1988) were all biased to overprediction which they interpreted as being due to a period of low recruitments. We did not experience these effects in the current study although the two time series are not entirely concurrent. A re-evaluation of their models using so me of the methods identified in this study may lead to better forecasts of their recruitment series as well.

We found some similarities in the environmental variables the TFN and RICENV

Table 4. Summary of the recruitment forecasting errors from seven forecasting models for five herring stock groupings based on eight one-step (year) ahead forecasts.

	Performance	Mean		TFN		DFE		NPAR		Ricker S/R		DFSE		RICENV	
Stock Grouping	Statistic	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank	Mean	Rank
Queen Charlotte Islands	RMSE	1007	5	1007	5	791	2	812	3	853	4	1693	6	752	1
	MAD	30	6	30	6	20	1	24	3	25	4	29	5	21	2
	Median AD	33	6	33	6	31	5	29	4	22	3	20	2	13	1
	MAPE	771	6	771	6	257	2	726	5	592	4	536	3	182	1
	Median APE	412	6	412	6	150	3	227	5	122	2	191	4	102	1
	Rank Sum		29		29		13		20		17		20		6
Prince Rupert District	RMSE	2072	3	5311	6	2738	4	791	1	1430	2	4926	5	22443	7
	MAD	44	4	60	6	35	3	21	1	32	2	52	5	91	7
	Median AD	45	6	48	7	12	1	16	2	31	3	33	4	36	5
	MAPE	91	7	81	6	8	2	1	1	38	3	40	4	57	5
	Median APE	93	7	39	5	19	3	12	2	46	6	5	1	32	4
	Rank Sum		27		30		13		7		16		19		28
Central Coast	RMSE	10864	3	14196	6	13324	4	13575	5	10004	1	16443	7	10752	2
	MAD	80	5	63	3	88	6	66	4	59	2	105	7	56	1
	Median AD	65	5	23	2	85	6	9	1	29	3	136	7	35	4
	MAPE	165	5	2	1	265	6	58	4	49	3	314	7	34	2
	Median APE	109	6	38	3	46	4	17	2	60	5	125	7	3	1
	Rank Sum		24		15		26		16		14		35		10
Strait of Georgia	RMSE	5882	1	10111	7	9051	6	6783	4	6070	3	8377	5	5993	2
	MAD	66	4	87	7	77	6	41	1	59	3	74	5	56	2
	Median AD	53	4	62	5	64	6	13	1	35	2	64	7	37	3
	MAPE	34	6	15	4	8	3	3	1	7	2	49	7	19	5
	Median APE	42	7	41	6	7	3	3	2	8	4	27	5	0	1
	Rank Sum		22		29		24		9		14		29		13
West coast of Vancouver Island	RMSE	2733	2	5264	5	8120	6	777	1	2771	3	8854	7	2833	4
	MAD	44	4	54	5	79	6	20	1	38	3	86	7	36	2
	Median AD	37	4	44	5	83	7	11	1	27	3	82	6	24	2
	MAPE	61	5	44	4	112	6	34	3	6	1	121	7	7	2
	Median APE	19	3	54	5	70	6	3	1	22	4	111	7	7	2
	Rank Sum		18		24		31		7		14		34		12
	Overall		91		98		94		39		58		117		63

identified as significant determinants of recruitment. Both methods found salinity and Ekman transport to be important factors affecting recruitment to most of the herring stocks. Ekman transport and salinity are indicators of the intensity of upwelling and salinity is also related to zooplankton abundance. Although it is uncertain how these factors operate, it seems possible that the timing and intensity of upwelling may mediate food availability for pre-recruit herring and thereby impact recruitment to the spawning populations.

Given the series of acceptable recruitment forecasting models developed in this study one can ask the question of how to best incorporate this new information into the fisheries management scheme. For British Columbia herring, we determine quotas on the basis of a weighted run forecast from two assessment models (Haist and Schweigert 1990). Hence, it would be important to evaluate the types of forecasting error associated with each model. In other words, are there biases in one or the other model for a particular stock? Does one model consistantly over or under predict recruitment? If so, what is the cost in terms of long term catch and stock stability and viability of adopting these models instead of the current approach for managing the fishery? These effects should be evaluated prior to basing management decisions on any of these forecasting models.

Another consideration not dealt with in this study is the possibility of improving forecasting accuracy by combining the forecasts from a series of models, as suggested by Newbold and Granger (1974). Noakes et al. (1990) have recently shown that for some salmon stocks it was possible to achieve better prediction accuracy by using a simple linear combination of equally weighted recruitment forecasts from pairs of the best individual prediction models. It appears that since different forecasting models are based on different assumptions and data they may address different aspects of the forecasting problem. Therefore, a combined forecast may incorporate the particular strengths of the different models to produce a better overall forecast. An evaluation of various combinations of forecasting models should be investigated prior to adopting any individual forecasting model for managing Pacific herring stocks in British Columbia.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

An Evaluation of the Precision and Accuracy of B.C. Herring Stock Forecasts Using an Age-structured Model

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V. Haist
Department of Fisheries and Oceans
Nanaimo, British Columbia, Canada

ABSTRACT

This paper presents the results of retrospective stock assesments conducted with an age-structured model for British Columbia herring stocks. Stock reconstructions, conducted for each year from 1981 to 1990, showed persistent trends to over- or under-estimate abundance when natural mortality was fixed at .45 in the analysis. When the natural mortality rate was estimated simultaneously with other model parameters these persistent trends were eliminated or significantly reduced. Generally, the natural mortality rate was estimated as less than .45 for northern B.C. stocks and greater than .45 for southern B.C. stocks.

A bootstrap method for estimating confidence limits on stock forecasts is presented. An evaluation of the method over the period 1981 to 1989 suggests the method produces consistent estimates when natural mortality is estimated rather than fixed, and when a prior distribution for the availability of 3-year-olds in the final year is included. The 95% confidence limits on forecasts of 4-year-old biomass are approximately -58% and +135% of the forecast while the limits on age 5 and older biomass are ±30% of the forecast.

INTRODUCTION

Since 1971 the major herring fisheries in British Columbia have been for a roe product. The fisheries occur on the spawning grounds where the fish are in dense schools which are highly aggregated. Therefore the fishery must be highly regulated to ensure overfishing does not occur. During the initial years of the roe-fishery, catch levels were determined on the fishing grounds by estimating stock abundance in each local area. Fish in excess of a specified spawning requirement were deemed available for the fishery. Since 1983, herring fisheries have been managed with a fixed quota system. With this system catch levels are determined prior to the season based on stock forecasts. With the advent of the fixed quota management system the requirement for consistent and accurate stock assessment and forecasting models was accentuated.

Two independent models have been developed and are currently used in the annual herring assessment process. These are: an escapement model, which uses spawn survey data to estimate annual spawning biomass; and an age-structured model which uses catch and age composition information to reconstruct stock abundance. It is anticipated that spawn surveys would provide relatively accurate, although not necessarily precise, estimates of spawning abundance. Stock estimates from the age-structured model are likely more precise, however, not necessarily accurate. Currently stock forecasts from the two models are weighted equally to obtain a combined stock forecast. There is a need to evaluate both models for the precision and accuracy of their forecasts to determine a more appropriate and objective weighting system.

This paper presents the results of an evaluation of the precision and accuracy of stock forecasts from the age-structured model. One component of the evaluation is a retrospective analysis where stock assessments are conducted for each year from 1981 to 1989 and stock trends compared with those from the 1990 assessments. The second component of the analysis is an evaluation of a bootstrap procedure for estimating confidence limits on stock forecasts. For each year from 1981 to 1989 the bootstrap procedure is used to generate a distribution of stock forecasts for the following year. These distributions of stock forecasts are compared with stock estimates obtained from both the following year assessments and the 1990 assessments.

AGE-STRUCTURED MODEL

An age-structured model, based on the error structure suggested by Fournier and Archibald (1982), has been used to assess B.C. herring stocks since 1982. The model has undergone numerous revisions to make it more consistent with the life history of herring and the fisheries which are analyzed. The current version incorporates auxiliary information in the form of spawn index data, separates catch and age-composition data by gear type, and includes availability parameters to model partial recruitment to the spawning stocks. Model parameters are estimated simultaneously using a maximum likelihood method. The model has been described in detail elsewhere (Haist and

Schweigert 1990); only those features which are relevant to this analysis are described here.

Two types of fishing gear are commonly used in B.C. herring fisheries. Of these, seine nets are assumed to be non-selective while gillnets are selective for larger, older fish. Herring fisheries have primarily concentrated on spawning fish or fish migrating to spawning grounds, so the relative availability of age classes to the non-selective gear should be equivalent to the partial recruitment of age classes to the spawning stock. The age-structured model explicitly separates availability (partial recruitment) and gear selectivity. Seine and gillnet fisheries are temporally separate so catch and age-composition data are partitioned into fishing periods, separating data for the different gears. Three fishing periods are modelled. The first period encompasses all catch prior to the spring roe-herring fisheries. This includes all the reduction fishery catches prior to 1968 and the winter food and bait fisheries since 1970. The second fishing period includes all seine roe-herring catch and the third period includes all gillnet roe-herring catch.

Let T_{ij} be the total number of fish in age class j at the beginning of season i, and λ_{ij} be the proportion of age j fish which are available to the fishery. Then N_{ij1}, the total number of age class j fish which are available at the start of period 1 in season i is given by:

$$N_{ij1} = \lambda_{ij} T_{ij} \qquad 1$$

To model the fishing process a form of catch equations which model fishing and natural mortality as continuous processes over time period r, is used:

$$C_{ijr} = \frac{F_{ijr}}{F_{ijr} + M_r}\left(1 - \exp\left(-F_{ijr} - M_r\right)\right)N_{ijr}$$

and, for $r < p$

$$N_{ijr+1} = N_{ijr}\exp\left(-F_{ijr} - M_r\right)$$

where C_{ijr} is the catch of age class j in season i for period r,

F_{ijr} is the fishing mortality of age class j in season i for period r,

M_r is the natural mortality for period r,

N_{ijr} is the number of fish in age class j in season i for period r,

p is the number of fishing periods ($p = 3$),

n is the number of seasons ($n = 31, 32, \ldots 40$),

k is the number of age classes ($k = 10$).

$N_{i+1,j+1,1}$ is defined by equation 1 where for $j + 1 < k$

$$T_{i+1,j+1} = N_{ijp}\exp\left(-F_{ijp} - M_p\right) + T_{ij}\left(1 - \lambda_{ij}\right)\exp\sum_r -M_r \qquad 2$$

In the model the last age class, k, accumulates all fish aged k and older.

To reduce the number of parameters to be estimated certain assumptions with respect to the availabilities and mortalities are made. The availabilities are formulated to increase with age, and for ages 4 and older they are constant between years. Because the proportion of 3-year-olds which are mature appears to vary between years (Haist and Stocker 1985) and some reduction fisheries targeted on immature 2-year-olds, the availability for these two age classes is parameterized allowing annual deviations from an average availability for the age class $(\bar{\lambda}_j)$. Availability for ages 2 and 3 for seasons 1 to n-1 (only those seasons where there is age data) is

$$\lambda_{ij} = \bar{\lambda}_j + d_{ij}$$

Deviations from the average availability are not estimated for ages 2 and 3 in the final year because there is not enough information in the data to estimate these parameters. For ages 4 to 6 and ages 2 and 3 in year n (and seasons where there is no age data)

$$\lambda_{ij} = \bar{\lambda}_j$$

For the selective fishery (i.e., the gillnet fishery) fishing mortality is separable into an age selectivity component and a fishing intensity component. Following Doubleday (1976),

$$\ln(F_{ijr}) = a_{ir} + b_{jr}$$

where a_{ir} represents the general level of fishing mortality due to fishery r in season i, and b_{jr} represents the relative vulnerability of age-class j in fishery r. For non-selective fisheries the model is

$$\ln(F_{ijr}) = a_{ir}$$

For annual stock assessments conducted to date the natural mortality rate $(M_{\bullet} = \sum_r M_r)$ has been fixed at .45 for all assessment regions. For this analysis additional stock reconstructions are conducted where the natural mortality parameter, $M_{\bullet}$, is estimated. Natural mortality during each fishing period is modelled as

$$M_1 = .90M_{\bullet}$$

$$M_2 = M_3 = .05M_{\bullet}$$

Additional components of the model structure (eg. stock-recruitment relationship, incorporation of spawn index data), assumptions about measurement and process errors, and the objective function are described in detail in Haist and Schweigert (1990). Stock reconstructions are conducted for seven assessment regions (Fig. 1) for the period 1951 to 1990. The assessment regions in northern B.C. are; Prince Rupert District (PRD), Queen Charlotte Islands (QCI), and Central Coast (CC). In southern B.C. the assessment regions are; the northern and southern Strait of Georgia (GN and GS), and the northern and southern west coast of Vancouver Island (WN and

WS). The number of parameters estimated in each stock reconstruction is dependent on the number of fisheries which have occurred in the assessment region and ranges from 171 (WN) to 212 (PRD) for the 40 year time series.

RETROSPECTIVE ANALYSIS

To evaluate the consistency of the stock reconstructions from the age-structured model a retrospective analysis is conducted. For each assessment region ten data sets comprised of 31 to 40 years of catch and age data were constructed (ie. 1951-1981, 1951-1982,... 1951-1990). The stock reconstructions represent those which would have been obtained had the current model been used to assess stock status in earlier years. It is assumed that the stock abundance estimates and other parameters obtained from the final assessment (ie. 1990) are the most accurate.

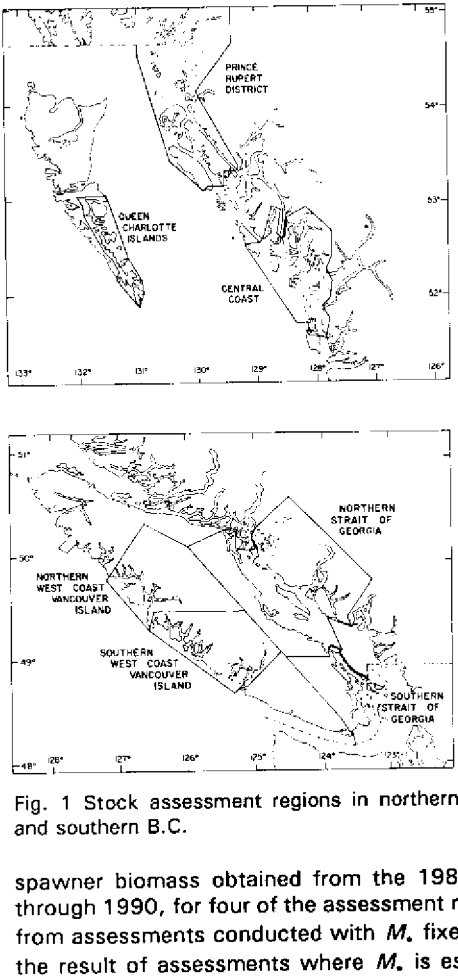

Fig. 1 Stock assessment regions in northern and southern B.C.

Figure 2 shows estimates of spawner biomass obtained from the 1982 assessment and alternate years through 1990, for four of the assessment regions. The upper figures (a) result from assessments conducted with *M.* fixed at .45. The lower figures (b) are the result of assessments where *M.* is estimated simultaneously with other parameters in the model. With *M.* fixed at .45 there are persistent trends for the model to under- or over-estimate stock abundance relative to estimates obtained from the 1990 assessment. These persistent trends are eliminated, or less severe, when *M.* is estimated in the model.

The same information, shown as the percentage discrepancy (100[(initial/final)-1]) between the initial and final stock estimates (eg. the 1981 stock estimate obtained from the 1981 stock assessment versus the 1981 stock estimate obtained from the 1990 stock assessment) are shown in Table 1 for all assessment regions. With the natural mortality rate fixed at .45 the persistent trend to underestimate stock abundance is apparent in all three northern B.C. assessment regions (QCI, PRD, CC) and one region in southern B.C.(WS). For the remaining three southern assessment regions (GN, GS, WN) the trend is reversed and stock biomass is consistently overestimated. While not eliminated

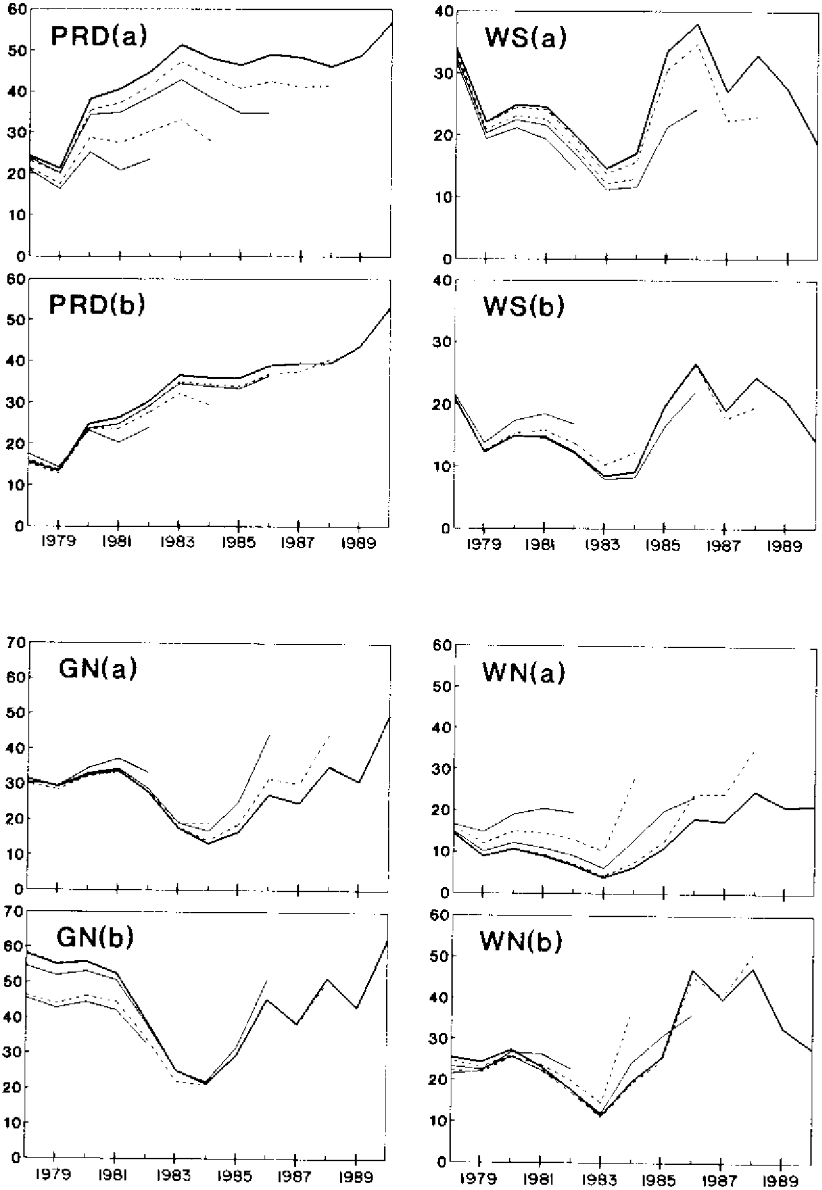

Fig. 2. Spawner biomass estimates (since 1978, in thousands of tonnes) from the 1982, 1984, 1986, 1988, and 1990 stock assessments for four assessment regions. The upper figures (a) are from assessments with M_* fixed at .45. The lower figures (b) are from assessments with M_* estimated.

Table 1. Percent difference between estimated spawner biomass obtained in initial year and in 1990 assessment.

M = .45

year	QCI	PRD	CC	GN	GS	WS	WN
1981	-1.0	-56.5	-40.6	-11.4	49.0	-28.7	134.4
1982	-9.4	-47.3	-44.4	20.3	-18.7	-28.3	187.7
1983	-12.4	-42.8	-40.3	25.3	45.8	-33.1	308.8
1984	-5.1	-41.9	-38.5	44.6	78.7	-23.8	341.0
1985	-17.7	-35.1	-38.2	84.8	54.8	-30.2	110.4
1986	-34.8	-29.0	-36.9	63.1	30.8	-36.3	29.3
1987	-16.8	-14.3	-28.4	56.6	77.1	-38.9	70.8
1988	-11.1	-10.2	-25.0	26.1	30.4	-30.3	42.8
1989	30.3	0.6	-19.9	23.4	10.9	-31.5	1.3
avg.	-8.7	-30.7	-34.7	37.0	39.9	-31.2	136.3

M estimated

year	QCI	PRD	CC	GN	GS	WS	WN
1981	4.9	-31.6	-20.1	-43.5	-19.4	39.9	9.1
1982	-3.5	-20.8	-26.1	-16.3	-50.8	35.2	28.2
1983	-10.0	-17.5	-21.1	-12.0	-20.6	23.9	60.8
1984	-4.0	-18.1	-18.5	-1.5	-1.8	33.9	88.2
1985	-16.8	-11.5	-21.4	16.7	-1.5	1.5	29.8
1986	-30.0	-6.0	-23.2	12.3	-7.7	-17.2	-23.5
1987	-14.2	6.5	-16.2	8.4	16.6	-24.1	15.9
1988	-9.4	2.5	-16.5	-2.4	-0.8	-19.3	7.0
1989	38.0	8.1	-16.5	5.5	-6.1	-30.8	-13.5
avg.	-5.0	-9.8	-20.0	-3.6	-10.2	4.8	22.5

in all cases, the persistent trends are substantially reduced in the assessments where M_* is estimated.

Table 2 shows the natural mortality rates (M_*) obtained from the stock reconstructions where this parameter is estimated in the model. Consistent with the trends in the retrospective analysis the estimated natural mortality rates are higher than .45 for those stocks which were persistently overestimated and lower than .45 for those stocks which were persistently underestimated. For the three assessment regions in northern B.C. and the northern Strait of Georgia the natural mortality estimate decreases from the 1981 through the 1990 assessments. For the two west coast of Vancouver Island assessment regions natural mortality is increasing, and in the southern

Table 2. Natural mortality rate (M) estimated in 1981 and 1990 assessments and estimated availability-at-age from 1990 assessments with M fixed and estimated.

	M estimated in year		availability-at-age				
stock	1981	1990	2	3	4	5	6
QCI	fixed		.06	.43	.62	.89	1.0
	.54	.46	.06	.43	.62	.89	1.0
PRD	fixed		.08	.38	.55	.80	1.0
	.38	.36	.10	.43	.60	.83	1.0
CC	fixed		.13	.50	.71	.95	1.0
	.43	.38	.15	.54	.74	.96	1.0
GN	fixed		.10	.71	.97	1.0	1.0
	.77	.67	.07	.58	.88	1.0	1.0
GS	fixed		.15	.73	.98	1.0	1.0
	.69	.70	.10	.65	.97	1.0	1.0
WS	fixed		.09	.72	.94	1.0	1.0
	.24	.29	.13	.77	.98	1.0	1.0
WN	fixed		.05	.72	.86	1.0	1.0
	.61	.71	.03	.57	.76	.97	1.0

Strait of Georgia there is no apparent change.

CONFIDENCE LIMITS ON STOCK FORECASTS

A bootstrap procedure (Efron and Gong 1983) has been used to estimate the standard error and calculate confidence limits on forecasts of age 4 and older fish biomass for each of the past 3 annual stock assessments (eg. Haist and Schweigert 1990). A comparison of the forecasts with the following year estimates of abundance suggested the method was appropriate for forecasting biomass of age 5 and older fish but not for 4-year-old fish. That is, substantially more than 5% of the following year estimates of 4-year-old biomass were outside the forecast 95% confidence limits. Therefore, an alternate method for calculating these confidence limits is presented and evaluated here. Additionally, the method which appears appropriate for age 5 and older biomass is evaluated for the period 1981-1990.

The bootstrap procedure involves resampling the original data sets with replacement to generate a new data matrix which has the same statistical properties as the original data sets. To resample the age-composition data a two-stage procedure is used. First random subsamples (ie. a sample obtained from one fishing vessel) are selected from the original data set, then individual fish are randomly selected from the subsample. Additionally, the total catch and spawn index data are resampled as described in Haist and Schweigert (1990). The data for each stock assessment region and retrospective year (ie. 1981-1989) were resampled 50 times and these bootstrap samples analyzed to generate 50 sets of parameter estimates.

The distribution of values obtained for a parameter from the bootstrap replicates provides an estimate of the standard error of that parameter. The standard error is consistent with the variance in the data but does not take into consideration process error in the model.

A major source of process error in the forecasts of numbers at age 4 results from uncertainty in the availability of 3-year-olds in the final year. This parameter is not estimable and is fixed at the mean 3-year-old availability, as has been described. A more appropriate procedure may be to evaluate the distribution of forecasts obtained when the final year 3-year-old availability is fixed at each of the values obtained for previous years (ie. $\lambda_{n3}=\lambda_{i3}, i=1,2,\ldots,n-1$). Because it would require significant computer time to reanalyse all data sets over all λ_{i3} an approximation to this method is implemented here.

The approximation is based on the observation that while the total abundance of the age 3 year-class in the final year is not well determined the abundance of available 3-year-olds is quite well determined. That is, with additional years of data the estimated size of this cohort may change substantially, however, the estimated number which were available to the fishery as 3-year-olds does not change much. Therefore the distribution of T_{n3} obtained by evaluating

$$T_{n3}=N_{n31}/\lambda'$$

for $\lambda'=\lambda_{i3}, i=1,2,\ldots,n-1$, and N_{n31} as estimated in the analysis may provide an appropriate probability distribution for this parameter. To obtain a distribution of forecast age 4 abundance $(T_{n+1,4})$ T_{n3} is replaced by N_{31}/λ_{i3} in equation 2,

$$T_{n+1,4}=N_{n33}\exp(-F_{n33}-M_3)+N_{31}/\lambda_{i3}(1-\lambda_{i3})\exp\sum_{r}-M_r$$

and a $T_{n+1,4}$ calculated for each λ_{i3}. This generates n-1 predictions of age 4 abundance for each bootstrap replicate. For comparison, forecasts are also generated with the age 3 availability fixed in the final year $(\lambda_{n3}=\bar{\lambda}_3)$. The forecast biomass is obtained by multiplying the forecast numbers-at-age by the average weight-at-age.

Efron (1982) suggests a percentile method for calculating confidence intervals for a parameter based on the bootstrap distribution of that parameter. That is, the 95% confidence interval is that interval which contains the central 95% of the bootstrap distribution. However, a large number of bootstrap replications

Table 3. Proportion of stock estimates greater of less than forecast 95% confidence limits. * indicates the proportion is significantly different than .05. N = 63 (7 assessment regions, 9 forecast years)

	stock assessment	
	following year	1990
forecast age 5+ biomass		
M fixed	.143*	.603*
M estimated	.063	.254*
forecast age 4 biomass		
availability fixed	.222*	.317*
availability resampled	.048	.079

are required to get reasonable accuracy in the tails of the distribution. Because each bootstrap replicate is composed of n-1 predictions of age 4 biomass there are an adequate number of observations to use the percentile method to calculate confidence limits on age 4 forecasts. However, there are only 50 bootstrap predictions of age 5 and older biomass. Fortunately, these are approximately normally distributed so the confidence limits for this group are based on the standard error, assuming a normal distribution.

Table 3 shows the proportion of stock estimates, obtained from the following year assessments and from the 1990 assessments, which are either greater or less than the forecast 95% confidence limits on the forecasts. Theoretically, 5% should be outside these limits, given the procedure for estimating the limits is appropriate. Results for forecast age 5 and older biomass are shown for assessments conducted with $M_{\cdot}$ fixed at .45 and $M_{\cdot}$ estimated in the analysis. Significantly more than 5% of the confidence ranges do not include the following year or 1990 assessment estimates for the assessments with fixed $M_{\cdot}$. With $M_{\cdot}$ estimated, the following year stock estimates are consistent with the forecast confidence range, however the 1990 stock estimates are still outside the confidence range more often than is expected.

The results pertaining to forecasts of age 4 biomass which are presented in Table 3 are from the assessments where $M_{\cdot}$ is estimated. The confidence limits which are obtained from the bootstrap procedure with 3 year-old availability fixed in the final year are not consistent with later estimates of the size of this year class. However, when availability is evaluated over the A_{i3} the resulting confidence limits on age 4 biomass are consistent with both the following year and 1990 estimates.

Figure 3 shows the size of the 95% confidence limits on stock forecasts. Each pair of points in the figure represents the confidence limits on one of the stock forecasts, where the forecast is indicated by the line. The 95% confidence limits on forecasts of age 4 biomass, which are asymmetrical, average -58% and +135% of the forecast. The 95% limits on forecasts of age 5 and older biomass average plus/minus 30% of the forecast. The size of the confidence limits on forecasts of the total adult stock is dependant on the relative proportion of age 4 and age 5 and older fish in the forecast, but averages -40% and +68% of the forecast.

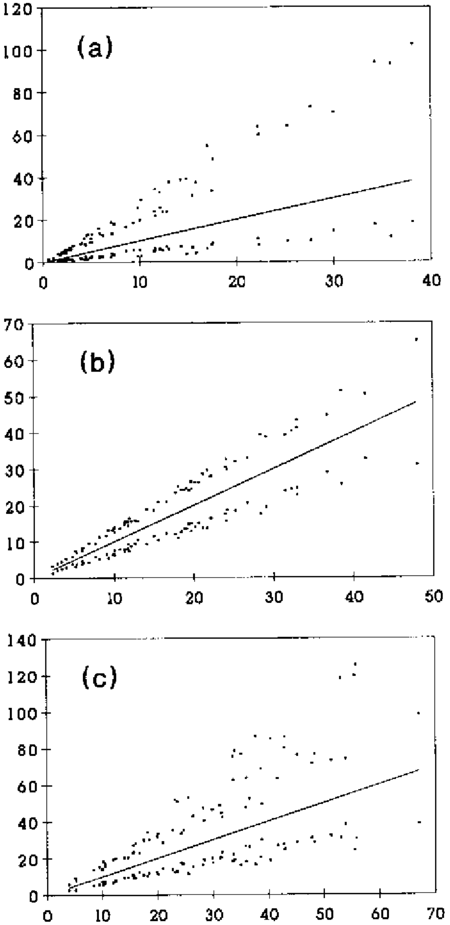

Fig. 3. 95% confidence limits on stock forecasts (represented by line, in thousand tonnes). (a) forecasts of 4-year old biomass, (b) forecasts of age 5+ biomass, and (c) total (4+) biomass.

DISCUSSION

Results presented in this manuscript suggest that natural mortality rates vary substantially between B.C. herring stocks. With the exception of the southern west coast of Vancouver Island, natural mortality rates are higher for the southern stocks than the northern ones. Similarly there appears to be a north-south cline in availability-, or maturation-, at-age.

A few previous studies have reported estimates of natural mortality for various B.C. herring stocks. These studies were based on age-composition data, either alone, or in conjunction with effort data. Where age-specific mortality rates were calculated they increased significantly with age. Tester (1955) estimated the annual natural mortality rates for southern Strait of Georgia (GS) herring increased from 40% (M=.51) for age 4 fish to 59% (M=.89) for age 7 fish. Taylor (1964) estimated the annual natural mortality rate increased from 32% (M=.39) for age 5 fish to 59% (M=.89) for age 9 fish in the Queen Charlotte Islands (QCI). These results are not inconsistent with the age-independent natural mortality rates (which largely reflect the dominant ages 3 through 6) estimated in this study (M=.70 for GS; M=.46 for QCI). Because the estimation of age-specific natural mortality rates is highly confounded with the estimation of age-specific availabilities there was no attempt to estimate age-specific mortality in this analysis.

The estimated natural mortality rate (M = .29) for the southern west coast of Vancouver Island (WS) is an anomaly. That is, the estimates for the three other south coast herring stocks are similar, and considerably higher (M = .67 to .71). There is no reason to believe there are any mortality factors which are unique to this stock. It is possible that there is a net migration into this stock, which leads to the mortality rate being underestimated. The WS spawning area is geographically closest to the oversummering grounds (La Perouse Bank) inhabited by both the Strait of Georgia and west coast Vancouver Island herring stocks and may therefore be the recipient of considerable immigration.

Natural mortality rates have been estimated for Barkley Sound herring (the major component of the WS stock) by Taylor (1964) and Schweigert and Hourston (1980). Taylor estimated the annual mortality rate to be about 60% (M = .92) based on age-composition data from the early 1900's when fishing was negligible. Schweigert and Hourston estimated M at .36 for the same stock, based on age-composition and effort data for the period 1954 through 1967. It is possible that the natural mortality rate has changed considerably during this century.

Estimates of natural mortality appear to be fairly well determined in these analyses. This statement is based on the overall improvements in model fit when natural mortality was estimated in the analyses and also the consistency of mortality estimates between stocks (with the exception of WS). This is probably the result of reasonably long time series of data which contain good contrast. That is, prior to 1967 fishing mortalities were high and since 1970 they have been low.

For both the retrospective analysis and the evaluation of confidence limits from the bootstrap procedure it was assumed that the 1990 assessment results provide an accurate account of the history of the stocks. While this is likely not true, it does provide a basis for comparing the results of the various assessments. Consistent stock forecasts and confidence limits were not attained when the natural mortality rate was fixed. With the natural mortality rate estimated in the model confidence limits on age 5 and older biomass were consistent with the following year stock estimates however, they were not consistent with the 1990 assessment. This could result from incorrect estimates of the variance of model or data errors or from systematic deviations from the model assumptions.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Cohort Analysis of Pacific Herring in the Togiak District, Alaska, 1980–90

T.T. Baker
Alaska Department of Fish and Game
Anchorage, Alaska

Contribution PP-029 of the Alaska Department of Fish and Game, Division of Fisheries, Juneau

ABSTRACT

A cohort analysis model was developed to estimate biomass for a spawning population of Pacific herring *Clupea harengus pallasi* in the Togiak District, Alaska. This biomass-based model incorporated catch, natural mortality, availability (recruitment), and growth. The model required independent estimates of instantaneous natural mortality, availability, growth, and a starting biomass estimate. Natural mortality was estimated based on the following: (1) life history parameters, (2) historical natural mortality, (3) catch curve analysis, and (3) aerial survey biomass-at-age data. The sensitivity of the model was compared with five different estimates of natural mortality, three estimates of availability, and two different independent estimates of starting biomass. The biomass-based model performed similarly to a model based on numbers of fish. The biomass-based cohort analysis model produced different estimates than the aerial survey biomass estimates in the Togiak District. The biomass-based cohort analysis can be easily used on other herring populations or manipulated and applied to other fish populations. In addition, this biomass-based model can be easily extended to more sophisticated age-structured stock assessment models, such as separable cohort analysis or catch-at-age analysis.

KEY WORDS: Cohort analysis, natural mortality, recruitment, availability, growth, spawning biomass, aerial surveys, Pacific herring, *Clupea harengus pallasi*, Togiak District, Alaska.

INTRODUCTION

The effective management of commercially exploited fish stocks has become highly dependent upon the accurate assessment of stock size or abundance. This has been especially true of the management of Pacific herring *Clupea harengus pallasi* stocks in the eastern Pacific Ocean. This dependence has required that a tremendous amount of time and effort be directed toward development of stock assessment techniques for eastern Pacific herring stocks. The stock assessment techniques applied to herring can be split into direct and indirect assessment techniques. Direct assessment techniques include spawn deposition surveys (Hourston *et al.* 1972; Trumble *et al.* 1977; Humphreys and Hourston 1978; Blankenbeckler 1980, 1987; Spratt 1981; Blankenbeckler and Larson 1982, 1985, 1987; Biggs and Funk 1988), hydroacoustic surveys (Thorne 1977a, 1977b; Lemberg 1978; Blankenbeckler 1980; Thorne *et al.* 1982), aerial surveys (Lebida and Whitmore 1985; Brady 1987), and tagging studies (Stevenson 1954; Taylor 1964, 1973; Haegele *et al.* 1983). Indirect age-structured assessment (ASA) methodologies (Megrey 1989) include cohort analysis (Schweigert and Hourston 1980; Hourston and Schweigert 1980; Walters *et al.* 1982; Wespestad 1982), and catch-age analysis (Funk and Sandone 1990). The distinguishing feature of herring stock assessment in the eastern Pacific Ocean has been the dependence on direct observations of biomass to estimate abundance (Trumble and Humphreys 1985).

The Togiak District in Bristol Bay, Alaska, supports the largest spawning population of herring in the state (Figure 1). The primary stock assessment tool for herring in the Togiak District has been observation of biomass from aerial surveys (Lebida and Whitmore 1985). During late April and May herring move into the Togiak District from their over-wintering grounds near the Pribilof Islands to spawn along the shoreline (Shaboneev 1965). During this time aerial surveys are flown daily. This period also coincides with the primary harvest of the Togiak herring stock. Two commercial (purse seine and gill net) fisheries harvest herring just prior to spawning for their sac roe. After spawning is completed, these herring move southward along the Alaska Peninsula where they concentrate in the vicinity of Unalaska Island during the summer and then return to their over-wintering grounds in the fall (Shaboneev 1965; Rumyantsev and Darda 1970). Lesser catches are taken during the summer months in the Dutch Harbor Food and Bait fishery and as bycatch in the domestic pollock and cod trawl fisheries in the eastern Bering Sea.

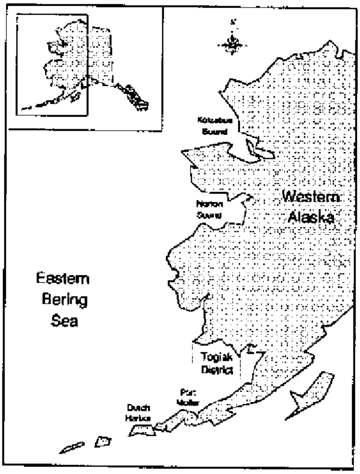

Figure 1. Map of the Togiak District, Alaska and eastern Bering Sea.

In this paper, a biomass-based cohort analysis is presented that was used to estimate the spawning biomass of herring in the Togiak District, Alaska, from 1980 through 1990. The development of the cohort analysis model is presented that takes into account catch, natural mortality, growth, and availability (recruitment). The components required to run the model and the estimation of each component are described. The results of the biomass-based cohort analysis are compared to a cohort analysis based on numbers of fish. In addition, a series of natural mortality, availability, and starting biomass estimates are used in the biomass-based model. These components can have large effects on cohort analysis models (Bradford and Peterman 1989; Vetter 1988).

COHORT ANALYSIS MODEL

The biomass-based cohort analysis developed here is modified from Zhang and Sullivan (1988) and starts with the relationship describing survivorship of a number of fish (N),

$$N_{a+1,y+1} = N_{a,y}e^{-(F_{a,y} + M_a)} \quad . \qquad (1)$$

where $N_{a,y}$ and $N_{a+1,y+1}$ are the number of age *a* and *a+1* fish in year *y* and *y+1* that and $F_{a,y}$ are the instantaneous rates of fishing mortality for age *a* fish in year *y* and M_a is the average instantaneous rate of natural mortality.

Zhang and Sullivan (1988) modify equation (1) with an equation describing exponential growth in weight ($W_{a,y}$) of a fish at age *a* in year *y*:

$$W_{a+1,y+1} = W_{a,y}e^{G_a} \quad ; \qquad (2)$$

where, G_a is the average instantaneous rate of growth (Ricker 1975). The components of equations (1) and (2) are multiplied together which results in the following description of change in biomass at age ($B_{a,y}$) with time:

$$B_{a+1,y+1} = B_{a,y}e^{-(F_{a,y} + M_a - G_a)} \quad . \qquad (3)$$

It was at this stage that I modified equation (3) with an equation that includes availability or partial recruitment to describe the spawning biomass:

$$B_{a+1,y+1} = B_{a,y}e^{A_a} \quad ; \qquad (4)$$

where, A_a is the average instantaneous availability or partial recruitment rate of age a fish from year y to year y+1. Availability was defined as the proportion of a cohort that migrates to spawn in any given year and therefore will be available to the inshore sac roe fisheries. Sexual maturity of herring was thought to coincide with participation in the spawning migration (Wespestad 1982).

Equation (4) is combined with equation (3) which results in a description of the change in recruited biomass with time that accounts

Spawn deposition surveys have been the most common means of stock assessment from California to Central Alaska (Trumble *et al.* 1977; Humphreys and Hourston 1978; Blankenbeckler 1980; Spratt 1981; Biggs and Funk 1988). Herring deposit their eggs on vegetation found in intertidal and subtidal areas of bays, inlets, and estuaries. Several techniques have been developed to estimate the spawning biomass of herring from number of herring eggs deposited in an area (Trumble *et al.* 1977; Humphreys and Hourston 1978; Blankenbeckler 1980; Spratt 1981; Biggs and Funk 1988). In addition to spawn deposition surveys, hydroacoustic surveys have also been used in Southeast Alaska (Blankenbeckler 1980) and Washington (Lemberg 1978). In Washington, herring in the Strait of Georgia, concentrate in an offshore holding area, move inshore to spawn, and then disperse. Hydroacoustic surveys conducted during April and May each year provide biomass estimates of the spawning migration (Lemberg 1978). In Southeast Alaska hydroacoustic surveys were conducted in areas where herring were known to concentrate on overwintering grounds (Blankenbeckler 1980).

Observations of herring biomass by aerial surveys or overflights have been the most common means of biomass assessment in western Alaska (Fried 1983). Herring are unique in that they form small groups or schools and move into nearshore areas along the coast from several days to several weeks prior to spawning each year. These nearshore areas are surveyed daily from small aircraft to determine location, number, and size of the herring schools in an area. Biomass estimates are derived by converting surface area estimates of herring schools into tonnes of herring (Brady 1987; Lebida and Whitmore 1985). However, there have been problems associated with stock assessment of herring from aerial surveys. The biomass estimates from aerial surveys are highly variable and may be biased for the following reasons: (1) herring schools may not be fully visible from the air, (2) the proportion of the schools that are visible is constantly changing due to weather and water clarity, and (3) the movement and residence time of herring schools on the spawning grounds are unknown. Hydroacoustic surveys have not been used extensively in western Alaska because of the shallow water depths associated with the large continental shelf. Spawning ground surveys have not been applied because of the large expansive spawning grounds and their remoteness (Barton and Wespestad 1980). In addition, spawn deposition surveys are not feasible in many areas of western Alaska due to limited water clarity and exposure to open ocean.

Because of the problems associated with biomass estimates from direct assessment techniques, other means were sought to assess the herring stocks in western Alaska (Wespestad 1982). The most likely alternatives were age-structured stock assessment (ASA) methodologies. Wespestad (1982) conducted a preliminary cohort analysis of the combined Bering Sea herring stocks, and Funk and Sandone (1990) applied a modified cohort analysis and more sophisticated catch-age analysis to the herring stock in Prince William Sound, Alaska. Cohort analysis has also been a primary stock assessment tool for herring populations in British Columbia (Haist *et al.* 1985, 1986; Hourston and Schweigert 1980), and the Northwest Atlantic (Jacobsson 1985). Sampling to determine the age composition of the commercial catches of herring throughout Alaska has been conducted since the inception of the sac roe fisheries in the late 1960's and early 1970's (Baker et al. 1990; Sandone and Brannian 1988; Sandone et al. 1988). These time series of catch-at-age observations would allow the application of ASA methodologies.

for fishing mortality, natural mortality, growth, and availability (recruitment):

$$B_{a+1,y+1} = [B_{a,y}e^{-(F_{a,y} + M_a - G_a)}]e^{A_{a+1}} \quad . \tag{5}$$

Equation (5) is reformulated as follows:

$$B_{a+1,y+1} = B_{a,y}e^{-(F_{a,y} + M_a - G_a - A_{a+1})} \quad . \tag{6}$$

Using equation (6), a simple model is formulated based on Pope's (1972) cohort analysis and the assumption that catch was taken at the beginning of the year over a short period of time (as is the case in herring sac roe fisheries in Togiak District from 1980–1990):

$$B_{a,y} = [B_{a+1,y+1}e^{M_a - G_a - A_{a+1}} + C_{a,y}]e^{A_a} \quad . \tag{7}$$

Equation (7) can be used to reconstruct the spawning biomass one year earlier in age and time. The data required for the procedure are (1) catch (in tonnes) of age *a* fish in year *y* ($C_{a,y}$) for all the years, (2) mean body weight of age *a* fish in year *y* ($W_{a,y}$) for all ages from some or all years, (3) age-specific natural mortality (M_a) for all ages, (4) instantaneous availability (A_a) for all ages during some or all years, and (5) a starting estimate of biomass for all ages. Estimates of the terminal fishing mortalities ($F_{a,ymax}$) can be used to estimate a starting biomass, if one is not available.

CATCH STATISTICS

Herring catch by the purse seine and gill net sac roe fisheries were obtained from fish tickets collected from commercial fishermen, tenders, and processors. Sandone and Brannian (1988) tabulated catch statistics for herring sac roe fisheries from 1980 to 1984 in the Togiak District by gear type and section from computer summaries of the Alaska Department of Fish and Game fish ticket database. They also tabulated catch statistics for 1985 to 1987 by gear type and section from annual management reports to the Board of Fisheries. Catch statistics were provided by Brannian and Rowell (1989) for 1988, and Rowell and Brannian (1989) for 1989.

AERIAL SURVEY BIOMASS ESTIMATES

Biomass estimates from aerial surveys were combined across time and area for an estimate of the total spawning biomass for any year. Estimates of spawning herring in the Togiak District from 1980 to 1989 were taken from Rowell and Brannian (1989). The 1990 spawning biomass estimate was provided by K.A. Rowell (Alaska Department of Fish and Game, Anchorage, personal communication). Herring escaping the commercial harvest were estimated by subtracting the combined purse seine and gill net harvest from the total spawning biomass for each year.

AGE COMPOSITION AND MEAN WEIGHT AT AGE

Samples collected during the commercial sac roe fisheries and from other areas of significant biomass sightings in the Togiak District were used to estimate age composition and mean weight by age group. Estimates of age composition were applied to the total spawning biomass and catch to produce estimates of biomass and catch by age group. The mean weight of each age group of herring was used to convert the catch and biomass into the number of herring in each age group.

GROWTH

Schnute's general growth model was used to develop an age-weight relationship for herring in the Togiak District (Schnute 1981). Mean weight of each group was collected during 1980 to 1989 from the Togiak commercial purse seine fishery. The purse seine data were thought to be the most representative of the herring in the Togiak District.

I used Schnute's General growth model to find the model that best fit the age-weight for Togiak herring from 1980 to 1989. Schnute's model is a general model that incorporates many historical growth models (i.e., von Bertalanffy, Gompertz, linear) as submodels (Schnute 1981). The most parsimonious model has the fewest statistically significant parameters and the smallest residual sum of squares. I obtained parameter estimates by minimizing the residual sum of squares with a non-linear least squares estimation program that used a modified Marquardt algorithm. The most parsimonious model was a Gompertz growth model:

$$W_a = W_\infty e^{-e^{-g(a-a_0)}} \quad ; \qquad (8)$$

where W_a was the estimated weight at age a, W_∞ was a parameter of asymptotic weight and equal to 515 g, g was a relative growth parameter and equal to 0.264, and a_0 was a initial age parameter and equal to 4.63 years. The model had 107 degrees of freedom, a sum of squares equal to 75,947, and R^2 equal to 0.941 (Figure 2).

The Gompertz model was then used to calculate an mean W_a for herring ages 3–17 (Figure 2). The instantaneous growth rate ($G_{a,y}$) was then approximated as

$$G_{a,y} = \log_e[W_{a+1,y+1}/W_{a,y}], \qquad (9)$$

using W_a that were calculated from the Gompertz growth model. An average G_a was estimated for all years. Mean weights could have been used instead of the estimates of Wa from the Gompertz model. However, the Gompetrz model provided smoothed estimates of weight by age group and also provided estimates of weight for age classes where little data had been collected.

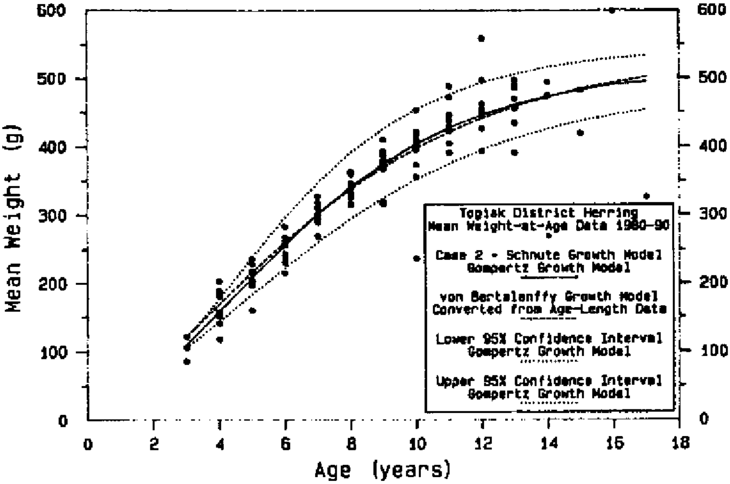

Figure 2. Mean weight by age group for Pacific herring sampled from the purse seine sac roe fishery in Togiak District, 1980-89. The most parsimonious growth for the mean weight by age group was a gompertz growth model. The gompertz growth model is compared to a von Bertalanffy growth model that was estimated and converted from age-length data.

A von Bertalanffy growth model was used to develop an age-length relationship for herring in the Togiak District as:

$$L_a = L_\infty[1-e^{-k(a-a_0)}] \tag{10}$$

where L_a was the estimated length of fish at age *a*, L_∞ was a parameter of asymptotic length, and k was a relative growth parameter. Mean length by age group from the Togiak purse seine fishery were estimated from data collected from 1980 to 1989. This data was thought to be the most representative of the herring in the Togiak District. Parameter estimates were obtained by minimizing the residual sum of squares with a non-linear least squares estimation program that used a modified Marquardt algorithm. The parameter estimates were L_∞ = 33.4 cm, k = 0.200, and a_0 = 1.853 years (107 degrees of freedom, sum of squares = 6,009, and R^2 = 0.941; Figure 2). The parameters L_∞ and *k* were used later to provide independent estimates of natural mortality.

NATURAL MORTALITY AND AVAILABILITY (RECRUITMENT)

The cohort analysis model required estimates of instantaneous rates of natural mortality (M_a) and availability (A_a). Availability was defined as the proportion of a cohort that migrates to spawn in any given year and therefore will be available to the inshore sac roe fisheries. For all non-fully recruited age classes, both natural mortality and availability were assumed to have an effect on the population. However, there was no way to separate the two components. Therefore, natural mortality was set equal to zero and availability was assumed to include both components. For all fully recruited age classes, availability was equal to zero. A fully recruited age class will have an annual availability rate of 1 and instantaneous availability rate of 0 ($e^0 = 1$).

Estimating natural mortality and availability has proven extremely difficult in the past (Vetter 1988). The current methods for estimating natural mortality all have strong limitations or disadvantages (Vetter 1988). Because of these limitations, natural mortality and availability were estimated using a number of different methods. In addition, historical estimates of natural mortality were reviewed for herring in Alaska and British Columbia to provide a range of estimates that could be used and compared with cohort analysis (Table 1). The estimates used fell into four categories (1) natural mortality based on life history, (2) historical natural mortality and availability, (3) natural mortality and availability based on catch curve analysis, and (4) natural mortality and availability based on biomass by age group (from aerial survey estimates).

Table 1. Summary of the methods used to estimate instantaneous rates of natural mortality (M_a) and availability (A_a) for Pacific herring in the Togiak District, Alaska.

Mortality Source or Method	Data Required or Used	Location	Natural Estimates
Based on Life History			
Alverson and Carney (1975)	k, age at maximum biomass		0.196 - 0.490
Gunderson (1980)	gonadal index		0.465 - 0.790
Gunderson and Dygert (1988)	gonadal somatic index		0.450 - 0.618
Hoenig (1983)	maximum age		0.178 - 0.417
Pauly (1980)	k, $L\infty$, mean water temperature		0.178 - 0.392
Historical Natural Mortality (used in other Studies)			
Beverton (1963)	early literature	British Columbia	0.400 - 0.600
Funk and Sandone (1990)	recent literature	Prince Wm. Sound	0.350 - 0.450
Haist et al. (1985, 1986)		British Columbia	0.450
Ricker (1975)	age distribution	British Columbia	0.450
Schweigert and Hourston (1980)		Barkley Sound, B.C.	0.360
Tester (1955)	age distributions, effort	Vancouver Island	0.400 - 0.850
Wespestad (1982)	growth data from Shaboneev (1965)	Bering Sea	0.390
Natural Mortality and Availability based on Catch	Togiak District sac roe catch-at-age data (1980-89)	Togiak District	M_a = 0.082 - 1.795 for ages 8-17 A_a=-4.468--0.108 forages3-7
Natural Mortality and Availability based on Aerial Survey Estimates	Togiak District aerial survey biomass-at-age estimates (1980-89)	Togiak District	M_a = 0.054 - 1.902 for ages 8-17 A_a=-2.047--0.151 forages3-7

Natural Mortality based on Life History

Alverson and Carney (1975) presented a relationship where natural mortality (M) was estimated as

$$M = \frac{3k}{e^{ka_{mb}} - 1}; \qquad (11)$$

where *k* is the coefficient from the von Bertalanffy growth model and a_{mb} is the age at which biomass is maximized. Alverson and Carney (1975) noted that for a wide range of fish populations, cohorts maximize their biomass at an age approximately one-fourth of the maximum observed age. Assuming that maximum observed age for herring in the Togiak District was 17 (Kathy Rowell, Alaska Department of Fish and Game, 333 Raspberry Road, Anchorage, Alaska, personal communication), herring would maximize their biomass at age 4 or 5 based on Alverson and Carney (1975). However, in looking at the catch and biomass by age group from 1980 to 1989, catch and biomass were actually maximized on the average at age 7. Because of the difference, M was estimated for ages 4 to 7, assuming *k* = 0.200. Natural mortality ranged from 0.196 to 0.490 (Table 1) with M = 0.196 when a_{mb} = age 7, 0.259 when a_{mb} = age 6, 0.349 when a_{mb} = age 5, and 0.490 when a_{mb} = age 4.

Gunderson (1980) investigated relationships between natural mortality and body size, age at maturation, longevity, and energy devoted to gonad development for a large number fish species. Gunderson (1980) found that the ratio of gonad weight to body weight of females could be used to predict natural mortality as

$$M = 4.64GI - 0.370; \qquad (12)$$

where GI was the ratio of gonad weight to body weight of mature females. The GI for herring sampled from the purse seine catch in the Togiak District in 1988 was 0.22. However, the average GI ranged with age from 0.17 to 0.25 for individual herring. Natural mortality ranged from 0.465 when GI = 0.17 to 0.790 when GI = 0.25. Natural mortality was 0.651 when GI = 0.22.

Gunderson and Dygert (1988) developed a new relationship that related natural mortality to the wet gonadal somatic index (WGSI) as follows:

$$M = 0.03 + 1.68WGSI; \qquad (13)$$

where WGSI was the ratio of the gonad weight to the somatic body weight. The somatic body weight was the body weight minus the combined weight of the gonads and stomach contents. The WGSI for herring sampled from the commercial purse seine catch in the Togiak District in 1988 was estimated to be 0.29 assuming that the stomachs of herring sampled were empty. The WGSI ranged from 0.25 up to 0.35. Natural mortality estimates ranged from 0.450 when WGSI = 0.25 up to 0.618 when WGSI = 0.35 with M = 0.517 when WGSI = 0.29.

The estimates provided by Gunderson (1980) and Gunderson and Dygert (1988) for Togiak herring were probably high. Funk and Sandone (1990) found that the GI for herring in Prince William Sound, Alaska was approximately 0.22, and Gunderson and Dygert (1988) calculated a WGSI of approximately 0.29 for herring sampled in a commercial purse seine fishery in Washington. These numbers were similar to values calculated for Togiak District herring. Herring spawning in the Togiak District have been longer lived than the herring in Washington and Prince William Sound. Gunderson (1980) reported that adding longevity to equation (12) explained little additional variability. However, these relationships were developed from a number of fish species. In the case of herring, a factor reflecting longevity would probably lower the estimates of M for herring in the Togiak District.

Hoenig (1983) developed a relationship between instantaneous total mortality (Z) and maximum age (a_{max}) for 84 fish stocks (herring and other marine fish stocks) as

$$\log_e(Z) = 1.945 - 1.225\log_e(a_{max}). \qquad (14)$$

For herring in the Togiak District, maximum observed age ranged from 10 in 1980 up to 17 in 1989 and 1990. Total mortality ranged from 0.178 when $a_{max} = 20$ to 0.417 when $a_{max} = 10$, with $M = 0.217$ when $a_{max} = 17$ (Table 1). These estimates were maximum estimates because natural mortality is always less than or equal to total mortality.

Pauly (1980) developed a multiple regression equation to estimate M as

$$\log(M) = -0.066-0.279L_\infty+0.6543\log(k)+0.4634\log(C), \qquad (15)$$

where L_∞ was the asymptotic length in centimeters from the von Bertalanffy growth model, *k* was the von Bertalanffy growth coefficient and C was the mean annual water temperature in degrees celsius. Pauly (1980) applied the model to 175 marine fish stocks obtaining an $R^2 = 0.718$. Pauly (1980) noted that the estimates of M for clupeids were high. He suggested that his model did not take into account the schooling behavior of clupeids which would probably reduce predation, and therefore, his model would overestimate M. Herring that spawn in the Togiak District are known to migrate through different areas in the Bering Sea during the year. Because of this, the herring probably encountered water temperatures ranging from 2 °C up to 10 °C and averaging approximately 4 °C. Using this range of water temperature and assuming $L_\infty = 33.4$ cm and $k = 0.200$, M ranged from 0.178 when C = 2°C to 0.392 when C = 10°C, with M = 0.245 when C = 4°C.

Historical Natural Mortality and Availability

A literature review resulted in numerous estimates of natural mortality for herring populations, primarily in Alaska and British Columbia. Beverton (1963) concluded that M was between 0.400 and 0.600 after reviewing early literature values for Pacific herring (Table 1). Funk and Sandone (1990) reviewed current literature and used a schedule of age-specific estimates of natural mortality, with M = 0.450 at age 8, for their catch-age analysis of herring in Prince William Sound. Haist et al. (1985, 1986) used M = 0.450 for their age structured model of all herring stocks in British Columbia. Ricker (1975) estimated M to be 0.450 based on a catch curve of a lightly fished herring stock in the Queen Charlotte Islands (Table 1). Schweigert and Hourston (1980) used M = 0.36 for their cohort analysis of herring stocks in Barkley Sound, British Columbia. Tester (1955) estimated M based on catch, age-composition, and effort data from herring stocks near Vancouver Island. He found that M was highly age dependent, with M being age-specific and ranging from 0.400 for younger ages up to 0.85 for older ages. Wespestad (1982) estimated M = 0.39 using the Alverson and Carney (1975) method and combined growth data for eastern Bering Sea herring spawning stocks collected by Shaboneev (1965). Wespestad (1982) also estimated age-specific estimates of M from catch data of herring in the Bering Sea that ranged from 0.015 for age 4 to 0.700 for age 11.

Sexual maturity of herring in the Togiak District was thought to coincide with participation in the inshore spawning migration (Fried and Wespestad 1985). Although some herring reach sexual maturity at age 2, most do not mature until age 3–5 (Fried and Wespestad 1985). Fried and Wespestad (1985) used a reported maturity schedule for offshore herring catches in the Bering Sea from 1959 to 1977 (Wespestad 1982) to estimate an availability schedule for herring in the Togiak District (Table 2).

Table 2. Estimates of mean weight at age (W_a in grams), instantaneous rates of growth (G_a), natural mortality (M_a) and availability (A_a) used in the biomass-based cohort analysis model of Pacific herring in the Togiak District, Alaska.

			Wespestad (1982)		Togiak District Catch by Age Data		Togiak District Biomass by Age Data		Life History/ Historical Estimates	
Age	W_a	G_a	M_a	A_a	M_a	A_a	M_a	A_a	M_a	M_a
3	110	0.357	0.150	-0.844	0.000	-5.081	0.000	-2.047	0.250	0.350
4	158	0.274	0.150	-0.151	0.000	-0.679	0.000	-0.767	0.250	0.350
5	208	0.211	0.180	-0.030	0.000	-0.489	0.000	-0.562	0.250	0.350
6	256	0.162	0.230	0.000	0.000	-0.298	0.000	-0.357	0.250	0.350
7	301	0.124	0.290	0.000	0.000	-0.108	0.000	-0.151	0.250	0.350
8	341	0.095	0.360	0.000	0.082	0.000	0.054	0.000	0.250	0.350
9	375	0.073	0.450	0.000	0.273	0.000	0.259	0.000	0.250	0.350
10	404	0.056	0.570	0.000	0.463	0.000	0.465	0.000	0.250	0.350
11	427	0.043	0.700	0.000	0.653	0.000	0.670	0.000	0.250	0.350
12	446	0.033	0.700	0.000	0.844	0.000	0.875	0.000	0.250	0.350
13	461	0.025	0.700	0.000	1.034	0.000	1.080	0.000	0.250	0.350
14	473	0.020	0.700	0.000	1.224	0.000	1.286	0.000	0.250	0.350
15	482	0.015	0.700	0.000	1.415	0.000	1.491	0.000	0.250	0.350
16	490	0.012	0.700	0.000	1.605	0.000	1.696	0.000	0.250	0.350
17	495	0.000	0.700	0.000	1.795	0.000	1.902	0.000	0.250	0.350

Natural Mortality and Availability based on Catch Curve Analysis

Natural mortality (M_a) and availability (A_a) were estimated from the average age composition of the sac roe catch in the Togiak District from 1980 to 1989. Total mortality at age (Z_a) was first estimated for ages 3 to 14, as follows:

$$\hat{Z}_a = -\log_e(P_{a+1}/P_a), \qquad (16)$$

where, P_a and P_{a+1} were the average proportion of herring age *a* and *a+1* in the sac roe catch in Togiak District from 1980 to 1989. A linear trend was evident in the relationship between Z_a and age for ages 4 through 14 (Figure 3). Therefore, age was regressed against $-\log(P_{a+1}/P_a)$ for ages 4 through 14 (Figure 3). Average mortality was then estimated for ages 4–14 from the resulting linear regression where $Z_a = -1.217 + 0.190a$; with 9 degrees of freedom and $R^2 = 0.656$. Because of the large

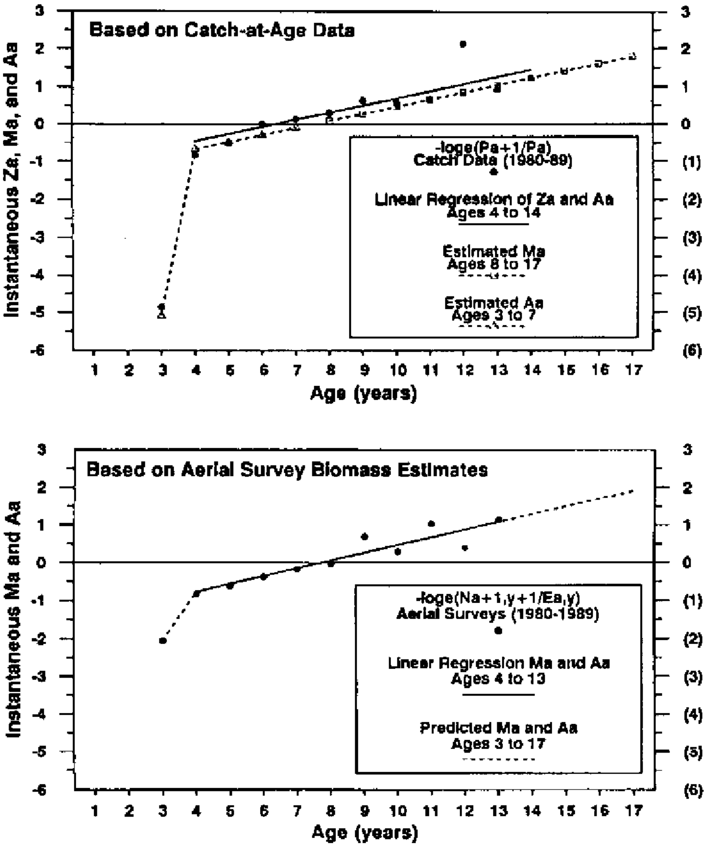

Figure 3. Estimates of natural mortality from catch and biomass at age data from the Togiak District, 1980-89. In the top graph, total mortality was estimated by a linear regression of $(-\log_e[P_{a+1}/P_a])$, where P_a and P_{a+1} was the average proportion of herring age *a* and *a*+1 in the catch from 1980-89. Natural mortality was then estimated by subtracting $F_a = 0.22314$, which equates to a catch of 20% of the total spawning biomass. In the bottom graph, natural mortality was estimated by a linear regression of $(-\log_e[N_{a+1,y+1}/E_{a,y})$, where $N_{a+1,y+1}$ was the aerial survey biomass estimate of herring age *a*+1 and *y*+1 and $E_{a,y}$ was the age *a* herring that escaped the harvest in year *y*.

resulting residual for age 3 herring, Z_a for age-3 herring was assumed to be equal to the 1980-89 average Z_a. In addition, the relationship was extrapolated to estimate Z_a for ages 15, 16, and 17.

Based upon the catch data, it appeared herring fully recruited to the spawning population at age-8. Therefore, it was assumed that only mortality affected age 8 and older herring. In contrast, for herring age 3-7, both recruitment and mortality, had an effect, and there was no way to separate the two components. For this reason, availability (A_a) takes into account recruitment and natural mortality for non-fully recruited age classes. Availability was set equal to zero for all fully recruited age classes, and M_a was set equal to zero for all non-fully recruited age classes.

With this in mind, M_a was estimated for ages 8-17 herring by subtracting fishing mortality from Z_a estimated by linear regression (Table 2). Herring in the Togiak District were managed for a harvest equal to 20% of the total spawning biomass, resulting in $F_a = -\ln(1-0.200) = 0.22314$. For ages 3-7, A_a was estimated by subtracting $F_a = 0.22314$ from Z_a (Table 2).

Natural Mortality and Availability based on Aerial Survey Biomass Estimates

The number of age *a* herring in the spawning population in year *y* ($N_{a,y}$) was estimated as

$$N_{a,y} = B_{a,y}/\bar{W}_{a,y}. \qquad (17)$$

The number of age *a* herring escaping the harvest became

$$E_{a,y} = N_{a,y} - C_{a,y}. \qquad (18)$$

Age-specific natural mortality in year *y* ($M_{a,y}$) was estimated as

$$M_{a,y} = -\log_e(N_{a+1,y+1}/E_{a,y}). \qquad (19)$$

This relationship assumes catch was taken over a short period. Fishing time for herring in the Togiak District for herring has declined from 26 d in 1981 to less than 3 d in recent years.An average M_a was calculated across all years. A linear trend was evident for ages 4-13. A linear regression was fit to ages 4-13, where $M_a = -1.588 + 0.205a$ with 8 degrees of freedom and $R^2 = 0.854$ (Figure 3). As with catch data, the aerial survey biomass estimates showed that herring in Togiak District were fully recruited at age 8. From this, M_a was estimated for herring ages 8-14 from the linear regression, and the relationship was extrapolated to estimate M_a for ages 14-17. The linear regression was also used to estimate A_a for herring ages 4-7 (Table 2; Figure 3). Because of the large residual for age-3 herring, A_a was set equal to the average M_a across all years for this age group.

MODEL APPLICATION

The biomass-based cohort analysis model (equation 7) was used to reconstruct the spawning biomass of herring in the Togiak District, Alaska. Biomass estimates from the model were compared using five estimates of M_a, three estimates of A_a, two starting biomass estimates, and one set of estimates of G_a (Table 2). Three of the five estimates of M_a and the three estimates of A_a used in the analysis were from (1) Wespestad (1982), (2) catch curve analysis, and (3) aerial survey biomass-at-age data. The two remaining estimates of M_a were set equal to 0.250 and 0.350. These two estimates represented the range of natural mortality based upon life history and historical estimates for herring from other areas. The set of estimates for G_a were calculated from equations (8) and (9) and were considered the average G_a from 1980 to 1989.

A number based cohort analysis model was first compared to a biomass-based model using three different estimates of M_a and A_a (Figure 4). The starting biomass was the 1989 aerial survey biomass estimate. The number based model,

$$N_{a,y} = [N_{a+1,y+1}e^{M_a - A_{a+1,y+1}} + C'_{a,y}]e^{A_{a,y}}, \qquad (20)$$

was similar to the biomass-based model (equation 7). The only differences between the models was that in the number-based model, $N_{a,y}$ was estimated by $B_{a,y}/W_{a,y}$ (equation 17), $C'_{a,y}$ was the harvest in numbers of fish, and G_a was not included. The resulting estimates from the cohort analysis model (in numbers of fish) were then converted back to biomass by $N_{a,y}$ x $W_{a,y}$. The two models produced almost identical biomass estimates for the three different estimates of M_a and A_a (Figure 4).

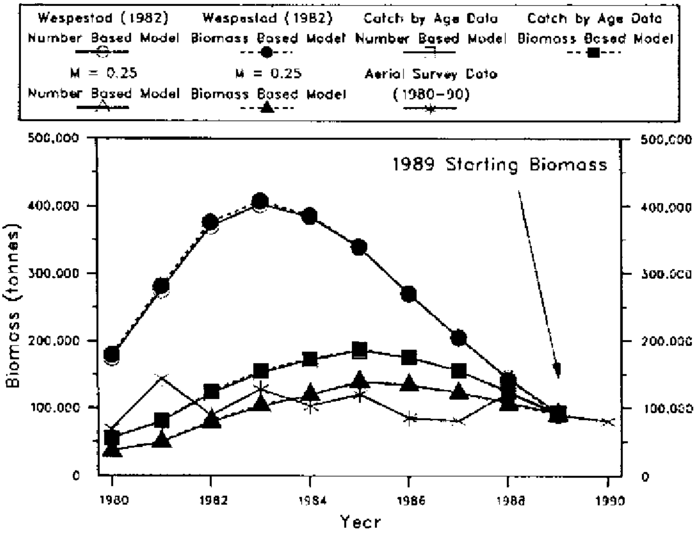

Figure 4. Comparison of biomass estimates from number and biomass-based cohort analysis models using three different instantaneous rates of natural mortality (M_a) and availability (A_a). The starting biomass used was the 1989 aerial survey biomass estimate.

I next compared the five estimates of M_a assuming $A_a = 0$ (Figure 5). The estimates were compared using both 1989 (top graph) and 1990 (bottom graph) aerial survey estimates as the starting biomass. By setting $A_a = 0$, the model equated to a cohort analysis model with no availability parameter. All the estimates produced dome-shaped biomass estimates. The M_a estimates taken from Wespestad (1982) with fixed $M = 0.350$ providing

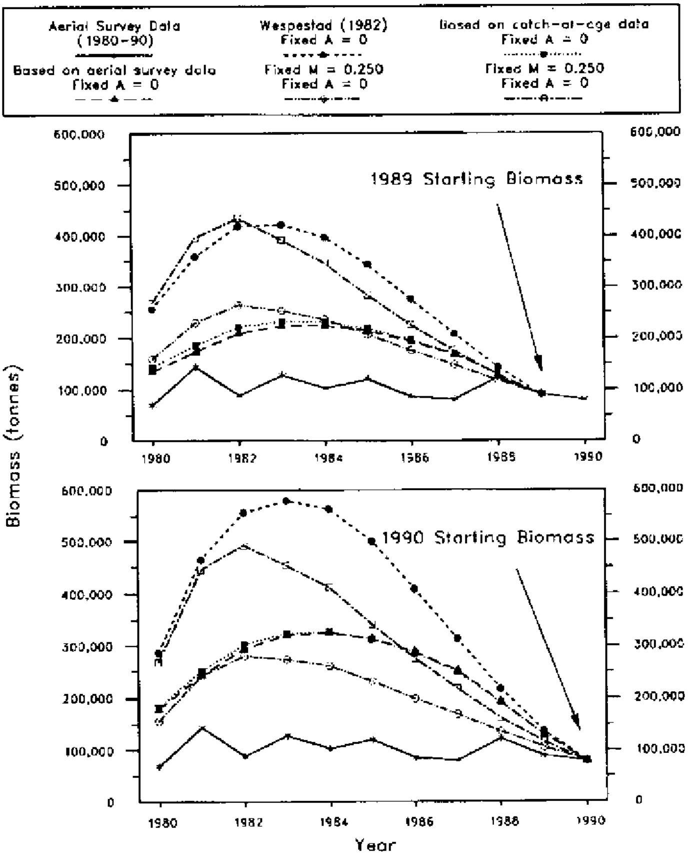

Figure 5. Comparison of biomass estimates from a biomass-based cohort analysis model using five different instantaneous rates of natural mortality (M_a). Availability (A_a) was set equal to zero. The starting biomass used in the top graph was the 1989 aerial survey biomass estimate. The starting biomass used in the bottom graph was the 1990 aerial survey biomass estimate.

the largest biomass estimates, followed by M based on catch curve analysis and aerial survey data (these two provided almost identical estimates). Fixed M = 0.250 produced the smallest estimates.

The three estimates of A_a were compared for fixed M_a = 0.250 (Figure 6). Again, the estimates were compared with the starting biomass equal to

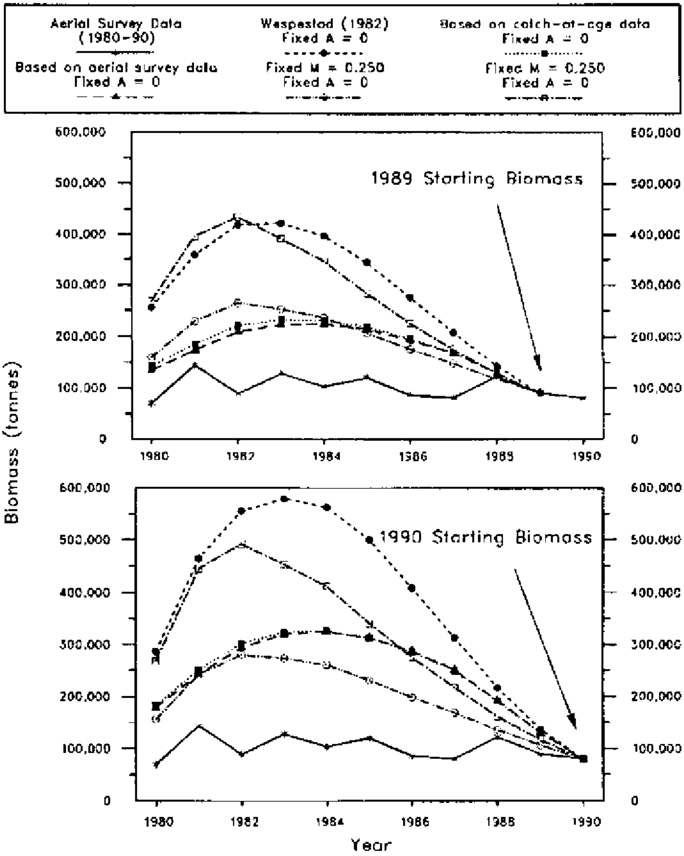

Figure 6. Comparison of biomass estimates from a biomass-based cohort analysis model using three different instantaneous rates of availability (A_a). Natural mortality was set equal to 0.250. The starting biomass used in the top graph was the 1989 aerial survey biomass estimate. The starting biomass used in the bottom graph was the 1990 aerial survey biomass estimate.

the 1989 and 1990 aerial survey estimates. As expected, A_a = 0 produced the highest biomass estimates, followed by the A_a from Wespestad (1982),

A_a from the catch curve analysis, and the aerial survey data, which provided the lowest estimates. The estimates of A_a from the catch by age group data and aerial survey data also provided similar biomass estimates.

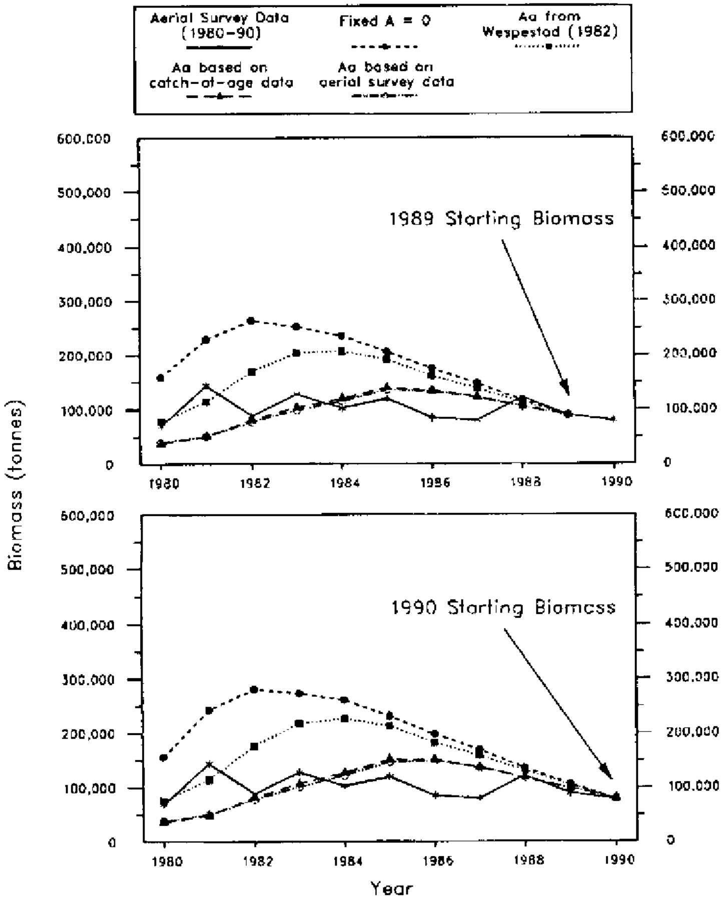

Figure 7. Comparison of biomass estimates from a biomass-based cohort analysis model using five different instantaneous rates of natural mortality (M_a) and availability (A_a). The starting biomass used in the top graph was the 1989 aerial survey biomass estimate. The starting biomass used in the bottom graph was the 1990 aerial survey biomass estimate.

Finally, five estimates of M_a and A_a were compared with the 1989 and 1990 aerial survey estimates used as the starting biomass (Figure 7). The estimates of A_a used with fixed $M_a = 0.250$ and 0.350 were estimated from the catch by age group data. All five of the estimates provided dome-shaped biomass estimates across years. The estimates taken from Wespestad (1982) provided the largest biomass estimates followed by those from the catch by age group data and aerial survey data. The biomass estimates from the catch by age group data and aerial survey data provided almost identical estimates. The biomass estimates with fixed M_a were the smallest.

Biomass estimates from the catch-at-age data, aerial survey data, and fixed $M = 0.250$ and 0.350 were similar to the aerial survey estimates when the starting biomass was the 1989 aerial survey estimate. However, only when M was fixed were the biomass estimates from the cohort analysis similar to the aerial survey estimates. The biomass estimates using M_a and A_a from Wespestad (1982) were much larger than the other biomass estimates and the aerial survey estimates. The basic trend of the cohort analysis models as compared to the aerial survey estimates was different. The aerial survey estimates were more variable with a flat trend compared to the dome-shaped cohort analysis models (Figure 6).

DISCUSSION

The four major factors affecting fish populations are natural mortality, fishing mortality, recruitment, and growth. A biomass-based cohort analysis model was presented that incorporates all four of these factors in a fairly simplistic fashion. Zhang and Sullivan (1988) first incorporated growth and recommended that growth should be incorporated into cohort analysis models when catch is given in biomass and management decisions are made in terms of biomass. I have taken their model one step further by incorporating availability directly into the model as Zhang and Sullivan (1988) did with growth. Availability was incorporated in the model on an exponential basis. However, a proportion (varying by age) could be easily be substituted everywhere exponential availability was used. Expressing availability as an exponent allows availability to be directly subtracted and added from natural mortality and makes the model easier to follow.

Why not just include availability with natural mortality in one parameter? Looking at equation (7), one can see natural mortality is added in the cohort analysis, while availability is subtracted. This makes biological sense in that one component is adding to the population while the other one is taking away from it. It should also be remembered that the biomass-based model, as developed here, can be easily manipulated and extended to more sophisticated approaches; e.g., separable cohort analysis (Doubleday 1976) or catch-at-age analysis (Deriso et al. 1985).

One of the main objectives of this study was to compare the estimates from the cohort analysis with the aerial survey estimates. In comparing the estimates from these two methods, there should be cause for concern if the biomass estimates from the cohort analysis models are assumed to be correct. The larger dome shape of the estimates from the cohort analysis compared to the lower flat trend of the aerial survey estimates would mean the aerial surveys were underestimating the actual herring biomass. In addition, if the basic trends in the estimates are correct, the aerial survey estimates are not even a relative index of spawning biomass. The differences would have probably been even greater had an independent estimate of starting biomass been used. The starting biomass estimates used in this study were the biomass estimates from the aerial surveys in 1989 and 1990. Because of these differences, alternative means of stock assessment should be examined in the Togiak District and other areas of Alaska where aerial surveys are presently being used as a stock assessment tool.

With this in mind, the biomass-based cohort analysis can also be easily used for herring populations in areas outside the Togiak District and can be used for most other fish populations as well. The model requires estimates of natural mortality, availability, growth, and fishing mortality or harvest. The information needed to use the model has already been collected for most Alaska herring populations. The biggest barrier in using cohort analysis will be finding independent estimates of natural mortality and availability. Probably the best approach would be to use a range of estimates for natural mortality and availability.

The second objective of this study was to determine the best estimates of natural mortality for herring in the Togiak District. Estimating natural mortality has proven to be extremely difficult in the past (Vetter 1988). The current methods for estimating natural mortality all have advantages and strong limitations or disadvantages (Vetter 1988). Because of the limitations associated with each method, I estimated natural mortality using a number of different methods. I also reviewed historical estimates of natural for herring in Alaska and British Columbia to provide a range of estimates that could be used and compared with cohort analysis (Table 1). The estimates used fell into four categories: (1) natural mortality based on life history, (2) historical natural mortality and availability, (3) natural mortality and availability based on catch curve analysis, and (4) natural mortality and availability based on biomass by age group (from aerial survey estimates). When comparing the methods, remember that natural mortality estimated from life history information produces a single estimate of natural mortality for the entire population (across all age groups). The estimate from catch curve analysis and biomass by age group data produce age-specific estimates of natural mortality.

The estimates of natural mortality from catch curve analysis and the biomass by age group data were very similar. This was to be expected because both methods were dependent upon age composition data that was representative of the herring population. The catch curve analysis was based on age composition data collected from the purse seine catch. Purse seines are considered a non-selective gear type and should be representative of the population. Both methods also produced natural mortality estimates that increased linearly with age. This is not an unexpected result. Ricker (1975) obtained catch curves for a number of fish species and found that natural mortality increased with age.

Knowing the natural mortality estimates from catch curve analysis and biomass at age data were similar, it was not unexpected to see the cohort analysis produce similar biomass estimates. However, similar biomass estimates were also produced using fixed estimates of natural mortality based on life history parameters and historical natural mortality estimates. Based on these result, any of the estimates of natural mortality could be used to estimate biomass from the cohort analysis model. However, because of the large effect that natural mortality has in age-structured stock assessment models like cohort analysis (Vetter 1988), I suggest that a number of methods still be used to estimate natural mortality and that a range of natural mortality estimates be used in the future for herring or any other fish populations.

ACKNOWLEDGEMENTS

I would like thank the many Alaska Department of Fish and Game personnel who contributed toward the collection and processing of herring age, size, sex, and abundance data used in this analysis. In particular I would like to thank Katherine A. Rowell, Jeff Skrade, Wes Bucher, Dick Russell, and Gene J. Sandone for collecting and summarizing the data. My appreciation to Linda K. Brannian, Fritz C. Funk, Katherine A. Rowell, and Robert L. Wilbur for their helpful comments and critical review of the manuscript. This manuscript is contribution PP-029 of the Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Morphological Variation of Herring in the Northern Baltic Sea

R. Parmanne
Finnish Game and Fisheries Research Institute
Helsinki, Finland

ABSTRACT

For the purpose of fisheries management in the northern Baltic Sea, an investigation was made of the possible existence of separate herring groups deviating from each other in morphology. The morphometric and meristic variation of 474 one-year-old herring was examined by multivariate methods, using thirteen morphological variables. The herring in the Bothnian Bay differ morphologically from the fish in the other parts of the northern Baltic Sea. The greatest differences were observed in the dimensions of the head and the otolith. However, no distinct morphological groups could be distinguished.

INTRODUCTION

In the 1980s, the yearly Baltic herring catch was about 400 000 tonnes. In the same period the Finnish catch was roughly 80 000 tonnes per year. There are several reports from different parts of the world that herring stocks have collapsed as a result of intensive fishing. In order to prevent this kind of development in the Baltic, all the seven states bordering on the Sea concluded the so-called Gdansk Convention in 1973, by which the International Baltic Sea Fishery Commission was founded. The Commission requests yearly scientific advice from the International Council for the Exploration of the Sea (ICES) on fisheries management. The state of the herring stocks has been assessed by areas, the agreed assessment areas being treated as distinct units.

Although the properties and distribution areas of the Baltic herring stocks have already been investigated for almost a hundred years, the number and characteristics of the possible discrete stocks have not been definitely established.

The aim of this study is to determine whether separate herring groups exist in the northern Baltic Sea, which differ from each other in morphology.

The term "group" has been used here to designate herring which are alike, and whose properties deviate from those of corresponding groups, but which are not necessarily in reproductive isolation from the other groups. Thus a population may consist of several groups.

MATERIAL AND METHODS

In the northern Baltic Sea, the proportion of autumn spawners is often less than 1 % of all the herring (Ojaveer *et al.*, 1984). Possible autumn-spawners in the material of this study have been included in the majority of spring-spawning Baltic herring.

For the morphological investigation, 1-year-old herring of the year class 1975 were collected in autumn 1976. Samples of 60-100 herring 12-16 cm in total length were taken from 17 catches made along the Finnish coast (Fig. 1). The total number of 1-year-olds in the samples was 474.

Morphometric Measurements

The morphometric measurements were made to the nearest 0.1 mm as follows (Fig. 2):

Fork length (FL): From the tip of the snout with the mouth closed to the fork of the tail fin.

Anterodorsal length (AD): From the tip of the snout to the base of the first fin ray of the raised dorsal fin.

Anteroanal length (AA): From the tip of the snout to the base of the first fin ray of the anal fin.

Head length (HL): From the tip of the snout to the posterior edge of the gill cover including the membranous edge in the measurement.

Head height (HH) at the point of contact of head and body.

Body height (BH) at the point where the height is greatest.

Eye diameter (ED) longitudinally on the left eye.

Meristic Counts

The number of soft pectoral fin rays was counted on the left fin. The first branchless spinous ray was excluded from the counting.

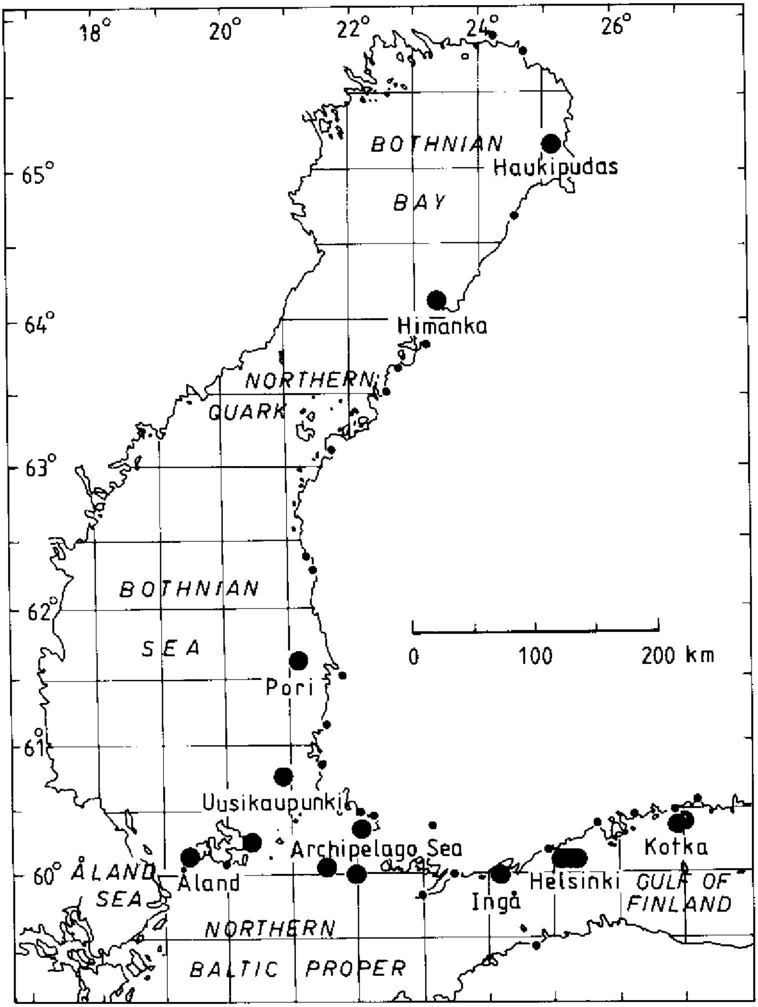

Figure 1. Sampling sites for the morphological study of one-year-old herring.

The pyloric caeca were detached from each other and counted in water against a dark background.

In the vertebral counts the urostyle was included in the number of vertebrae.

Otolith Measurements

Measurements (Fig. 2) were made on the left otolith.

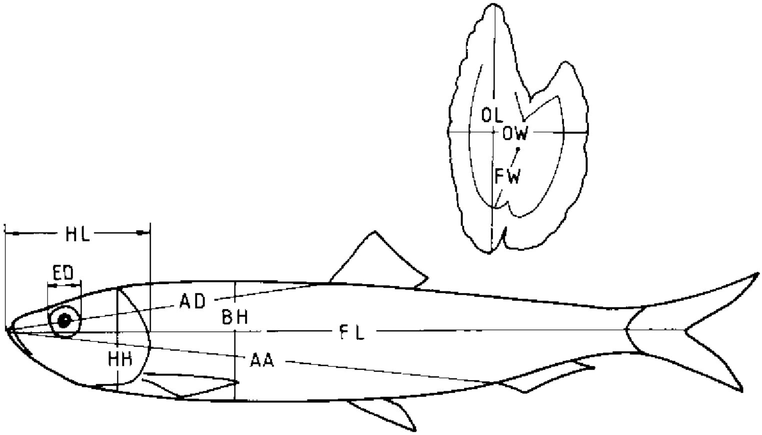

Figure 2. Morphometric measurements of one-year-old Baltic herring and its otolith. Explanations in text.

The length of the otolith (OL) was measured as the maximal distance between the rostrum and postrostrum (see Anwand, 1962-1963a).

The width of the otolith (OW) was measured perpendicularly to the length as the greatest distance between the dorsal and ventral edge of the otolith.

The width of the first growth zone (FW) was measured from the middle of the nucleus in the direction of the postrostrum to the outer edge of the first hyaline zone.

The Individual Morphological Variables

The study of the areal differences of individual morphometric variables was based on the relative values. Thus the results of the measurements are given as percentages of the fork length of the fish. The otolith width and the width of the first growth zone of the otolith are presented as percentages of the length of the otolith.

For the statistical analyses of the data, the SAS software system (SAS Institute Inc., 1985, 1987) was applied.

The hypothesis that the morphological data are samples from a normal distribution was tested by areas with the Shapiro-Wilk statistic.

As there were differences in the areal variances of the normally distributed variables, the hypothesis that the means of the variables were equal was tested pairwise by areas by the Cochran and Cox test.

As the distributions of the number of pectoral fin rays and vertebrae were not normal, the probability that the samples were taken from the same statistical population was tested pairwise by areas by the Mann-Whitney U test.

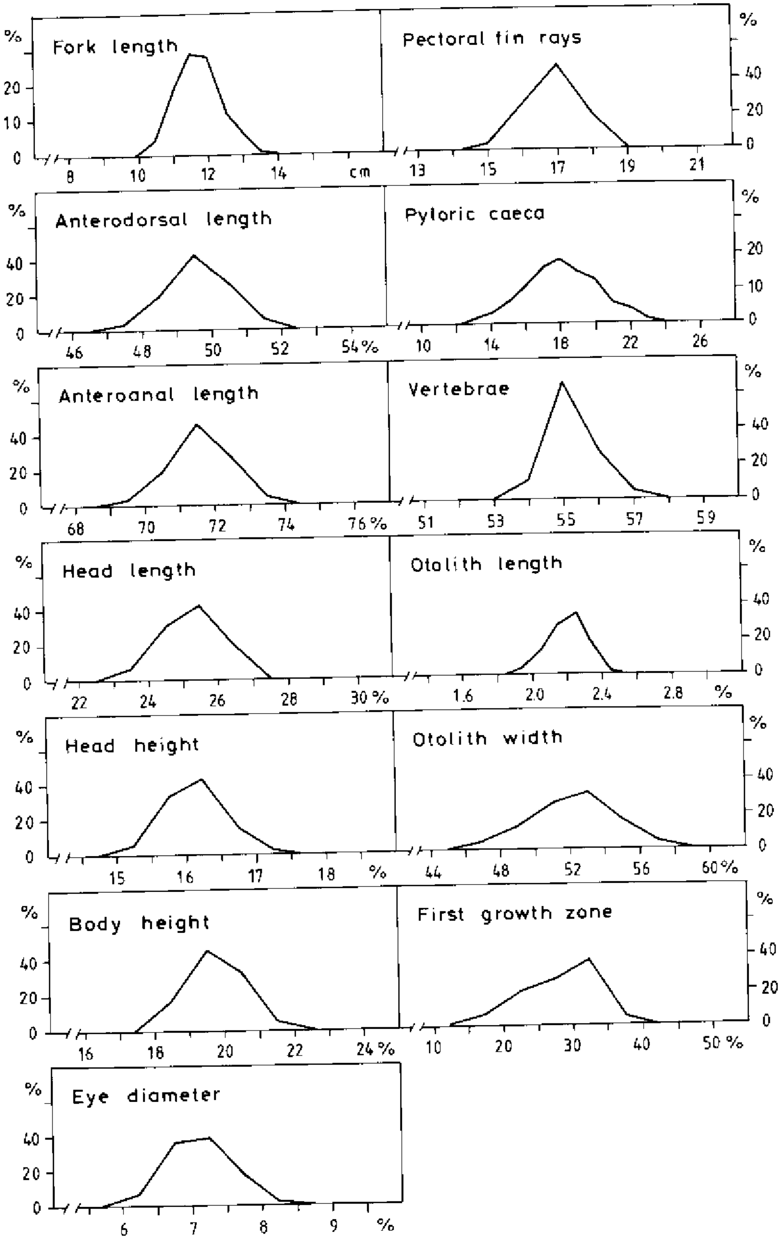

Figure 3. Distribution of the relative morphological characters of 1-year-old herring. Plastic properties are given as percentages of the fork length, except the otolith width and the width of the first growth zone, which are given as percentages of the length of the otolith. N = 472.

Multivariate Methods

The multivariate study was based on the original values of the morphometric variables.

In the multivariate procedures used, the calculations were performed according to the SAS System (SAS Institute Inc., 1987).

Multivariate analysis of variance

Differences of the original variables between the males and females were tested within the areas by the multivariate analysis of variance, the not-normally distributed variables being deleted, i.e. number of pectoral fin rays and vertebrae. The variables included in the analysis were thus the original values of:

Fork length
Anterodorsal length
Anteroanal length
Head length
Head height
Body height
Eye diameter
Number of pyloric caeca
Otolith length
Otolith width
The width of the first growth zone of the otolith

Canonical discriminant analysis

The characters of Baltic herring in different areas were studied by canonical discriminant analysis, by computing squared distances between areal means on the basis of the pooled within-class covariance matrix. As the variables in canonical discriminant analysis should have an approximately multivariate normal distribution, the not-normally distributed variables, the number of pectoral fin rays and number of vertebrae, were excluded. The variables included in the analysis were thus the same eleven as in the multivariate analysis of variance of the original variables.

Density linkage clustering method

To study the number of possible Baltic herring clusters, the density linkage clustering method with kth-nearest-neighbour density estimation was applied for varying values of k. The method is based on the agglomerative hierarchical

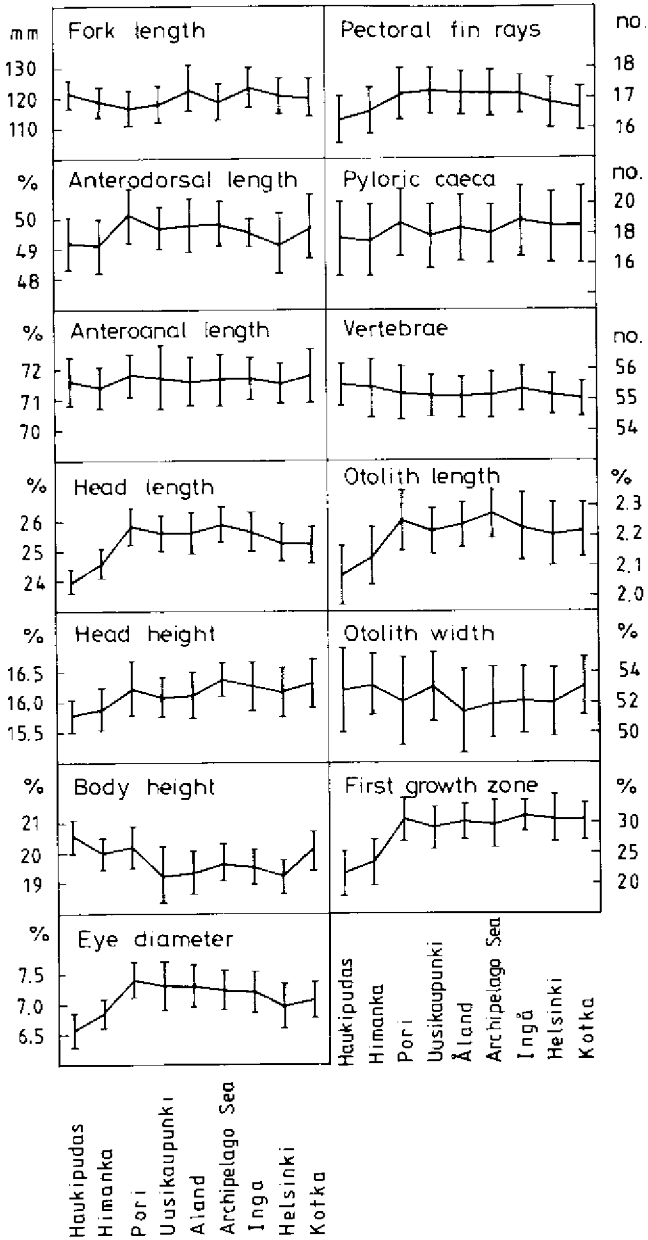

Figure 4. Mean and standard deviation of the meristic and relative morphometric characters of 1-year-old herring in the northern Baltic Sea. N = 472.

clustering procedure. Each observation begins in a cluster by itself. The two closest clusters are merged to form a new cluster, which replaces the two old clusters. In the cluster analysis, canonical variable scores of the eleven normally distributed original variables were used. The procedure was carried out separately for the Bothnian Bay and for the remainder of the northern Baltic Sea.

Principal component analysis

The variables contributing to the areal differences were investigated by applying principal component analysis separately for the Bothnian Bay and the other areas. Not-normally distributed variables, i.e. the number of pectoral fin rays and the number of vertebrae, were excluded from the analysis. The variables included were thus the original values of the eleven morphological characters used in the multivariate analysis of variance of the original variables. The principal components were computed from the correlation matrix.

RESULTS

Differences in Individual Characters between Areas

The areal study of the individual morphological variables was made on the basis of the relative morphometric characters to obtain results that were comparable between the areas and with earlier investigations. The distributions of the fork length, meristic and relative morphological variables are given in Figure 3.

The normality of the meristic and relative morphometric characters was tested in different areas by the Shapiro-Wilk statistic. With most variables the null hypothesis, that the data are samples from a normal distribution, cannot be rejected. However, the numbers of the pectoral fin rays and vertebrae differ significantly from the normal distribution.

According to the Cochran and Cox test for the normally distributed variables, and the Mann-Whitney U test for the numbers of the pectoral fin rays and vertebrae, there are several statistically significant morphological differences between the areas (Fig. 4).

Differences between Males and Females

The differences between the means of the original morphological characters of the sexes are slight (Table 1).

The greater part of the original morphometric values of the males and females are samples from a normal distribution, according to the Shapiro-Wilk statistic.

The existence of differences between the sexes in the original variables was tested by the multivariate analysis of variance after exclusion of the not-normally distributed variables, the pectoral fin rays and vertebrae. According to the analysis

Table 1. Means and standard deviations of original morphometric (in mm) and meristic characters of 1-year-old herring in the northern Baltic Sea.

	Males n = 232	Females n = 240
Fork length	119.9±6.7	119.8±6.0
Anterodorsal length	59.5±3.4	59.4±3.1
Anteroanal length	85.9±5.0	85.8±4.5
Head length	30.3±1.7	30.2±1.6
Head height	19.3±1.0	19.3±1.0
Body height	23.8±1.5	23.6±1.5
Eye diameter	8.5±0.5	8.5±0.5
Number of pectoral fin rays	16.9±0.9	16.9±0.8
Number of pyloric caeca	18.2±2.3	18.2±2.3
Number of vertebrae	55.2±0.8	55.2±0.7
Otolith length	2.64±0.18	2.63±0.17
Otolith width	1.15±0.06	1.15±0.05
The width of the first growth zone	0.63±0.11	0.62±0.12

based on the original values for eleven morphological variables, there were no consistent differences between the sexes (Table 2), and the sexes were thus treated together for further analyses.

Canonical Discriminant Analysis

According to the canonical discriminant analysis of the eleven original variables, the hypothesis that the areal means are equal can be rejected (P=0.0001).

The first canonical variable has the largest correlations with the width of the first growth zone, eye diameter and otolith length. The second canonical variable has the largest absolute correlation values with the fork length and the anteroanal length. The eigenvalues indicate that the first canonical variable accounts for 77 per cent of the variance and the two first explain 85 per cent.

The first canonical variable is a measure of the head and otolith dimensions and the second of fish size.

Besides differing from the fish in the other areas in the head and otolith dimensions (Fig. 4), the herring from the Bothnian Bay also differ from each other in the canonical discriminant analysis (Table 3, Fig. 5). The herring in the other areas are fairly similar to each other, although on the first axis the sample from Kotka slightly resembles the herring from the Bothnian Bay.

Table 2. Test of the hypothesis that sex does not affect the morphology of Baltic herring according to the multivariate analysis of variance based on the eleven original variables.

Area	F	Denominator DF	Probability
Kotka	0.577	38	0.835
Helsinki	0.781	38	0.657
Ingå	0.480	39	0.904
Archipelago Sea	1.730	38	0.104
Åland	1.568	42	0.144
Uusikaupunki	1.016	38	0.452
Pori	0.849	39	0.595
Himanka	1.561	54	0.138
Haukipudas	2.240	38	0.032
All areas	0.746	460	0.695

Due to these morphological differences, the individuals from the Bothnian Bay and from the other areas were treated separately in the further analyses.

Estimation of the Number of Possible Clusters

The number of possible herring groups in the northern Baltic Sea was not known. In the density linkage clustering method with the kth-nearest-neighbour density estimation, each value of k yields an estimate of the number of modal clusters. If the estimated number of modal clusters is constant for a wide range of the numbers of neighbours to be used for the kth-nearest neighbour density estimation, this is evidence that at least that many modes exist in the population.

According to the cluster analysis based on the canonical variable scores of the eleven normally distributed original variables, the number of modes as a function of k is as follows:

	Modes	
k	Bothnian Bay	Other areas
2	16	63
3	3	12
4	2	2
≥ 5	1	1

As the estimated number of modal clusters is not constant for any range of k values, there is no evidence of distinct clusters in the Bothnian Bay or the other areas.

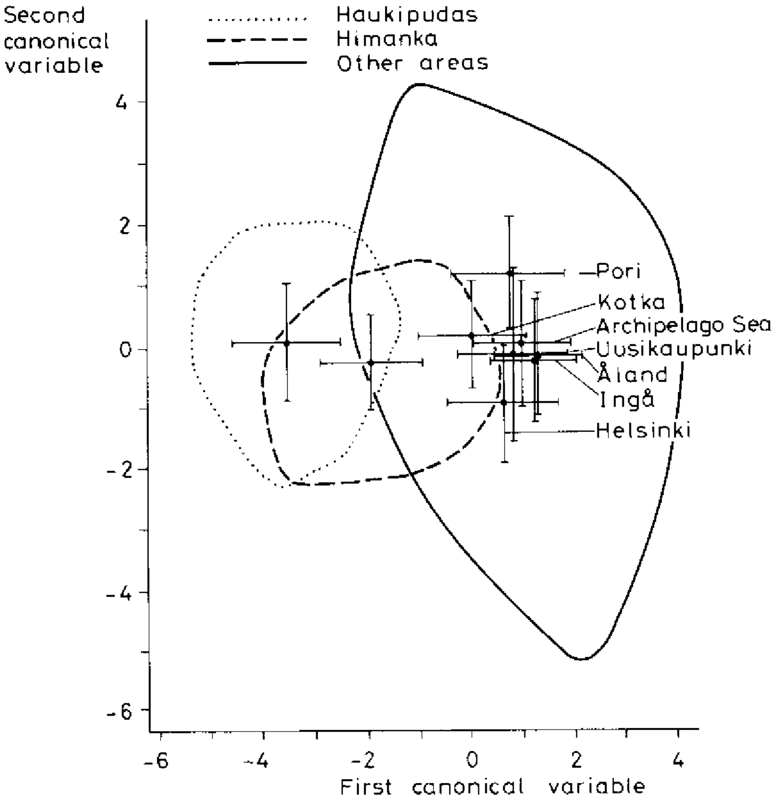

Figure 5. Score values, areal means and standard deviations of the herring specimens on the two first canonical axes of the discriminant function analysis based on eleven original morphological characters.

Morphological Differences Indicated by the Principal Component analysis

In the Bothnian Bay the eigenvalues of the principal component analysis based on the eleven original morphological characters indicate that the first component accounts for 55 % of the variance (Table 4). The two first components explain 72 % and the three first account for 82 %.

According to the correlations between the variables and principal components, the first component in the Bothnian Bay is a measure of fish size, since the first eigenvector shows the highest correlations with fork length, anteroanal length and head height (Table 4). After the general size variation of the fish has been excluded by the first principal component, the second component is a measure of otolith dimensions, having the highest correlations with the width of the first growth zone and the otolith width. The third component in practice chiefly indicates variation in the number of pyloric caeca.

Table 3. Squared distances between the areas according to the canonical discriminant analysis based on the eleven original morphological variables of Baltic herring.

	Kotka	Helsinki	Ingå	Archi-pelago Sea	Åland	Uusi-kaupunki	Pori	Himanka
Helsinki	2,943							
Ingå	2.789	2,047						
Archipelago S.	2.388	1.909	1,314					
Åland	4.571	3.251	0,846	2.279				
Uusikaupunki	3.375	2.108	1.707	1,511	1,376			
Pori	3.211	4.969	3.282	2,203	3.319	2.253		
Himanka	5,822	8.289	11.082	9.707	11,241	8.179	9.824	
Haukipudas	13.776	19.721	23.439	21.859	23,928	20.640	20.397	3.433

The score values of the two first principal components do not form distinct groups in the Bothnian Bay (Fig. 6). However, part of the herring in Haukipudas and Himanka can be separated on the basis of the second principal component, indicating differences in otolith dimensions.

In the other northern areas of the Baltic Sea the first component accounts for 62 % of the variance, the two first components explain 72 % and the three first 81 % (Table 5).

As in the Bothnian Bay, in the other northern areas the first principal component is a measure of fish size, and the second mainly of otolith dimensions (Table 5). The second and the third principal components differ in structure, however, from those of the Bothnian Bay, because in the other areas the variation in the number of pyloric caeca is also included in the second component, and the third component represents the contrast between otolith width and the number of pyloric caeca.

Table 4. The correlations, eigenvalues and the cumulative variance of the eleven original morphological variables and the first five principal components of herring in the Bothnian Bay.

	Principal components				
Variable	1	2	3	4	5
Fork length	0,958	-0.205	-0.047	-0.010	0.016
Anterodorsal length	0,904	-0.214	0.017	-0.018	0.135
Anteroanal length	0.943	-0.174	-0.041	0.018	0.010
Head length	0.931	0.192	0.008	-0.114	0.052
Head height	0.938	0.052	-0.062	0.062	0.043
Body height	0.808	-0.276	-0.087	0.282	0.008
Eye diameter	0.562	0.500	0.038	-0.608	0.123
Pyloric caeca	0.060	-0.181	0.973	0.037	0.113
Otolith length	0.697	0.485	0.049	0.339	-0.005
Otolith width	-0.388	0.726	-0.062	0.239	0.478
First growth zone width	0.282	0.791	0.182	0.084	-0.458
Eigenvalue	6.059	1.904	1.004	0.647	0.469
Cumulative variance	0.551	0.724	0.815	0.874	0.919

Table 5. The correlations, eigenvalues and the cumulative variance of the eleven original morphological variables and the first five principal components of herring in the northern Baltic Sea, excluding the Bothnian Bay.

	Principal components				
Variable	1	2	3	4	5
Fork length	0.962	-0.138	-0.071	-0.032	0.103
Anterodorsal length	0.955	-0.084	0.008	-0.007	0.064
Anteroanal length	0.953	-0.114	-0.070	-0.046	0.110
Head length	0.950	-0.006	0.131	0.044	-0.084
Head height	0.949	0.007	0.028	0.055	0.093
Body height	0.844	0.012	-0.068	-0.003	0.204
Eye diameter	0.697	0.125	0.312	0.246	-0.567
Pyloric caeca	0.196	0.519	-0.720	0.412	-0.029
Otolith length	0.827	0.179	0.256	0.086	0.140
Otolith width	-0.485	0.471	0.538	0.372	0.295
First growth zone width	0.262	0.766	0.026	-0.582	-0.065
Eigenvalue	6.772	1.164	1.005	0.723	0.517
Cumulative variance	0.616	0.721	0.813	0.878	0.926

In the northern Baltic Sea, excluding the Bothnian Bay, the mean score values of the first principal component indicate differences in the fish size between the Bothnian Sea and the more marine environment. No geographical trend can be observed on the basis of the second and third principal components. The differences in the mean principal component scores are small compared with the standard deviations (Table 6).

Thus the herring in the northern Baltic Sea, excluding the Bothnian Bay, seem to be morphologically homogeneous also on the basis of the principal component analysis.

DISCUSSION

The material studied morphologically consisted of 1-year-old herring. Although young herring are fairly stationary (Alander, 1947, Höglund, 1955, Dementjeva, 1956, Bergström, 1979, Fetter & Ojaveer, 1988), fish migrations may diminish the morphological differences between the areas.

Sexual Dimorphism

The multivariate analysis of variance did not reveal any significant differences in the morphology of males and females. This agrees with the results obtained in earlier investigations on Baltic herring (Anwand, 1962-1963d) and Atlantic herring (Anthony & Boyar, 1968, Parsons, 1973, 1975).

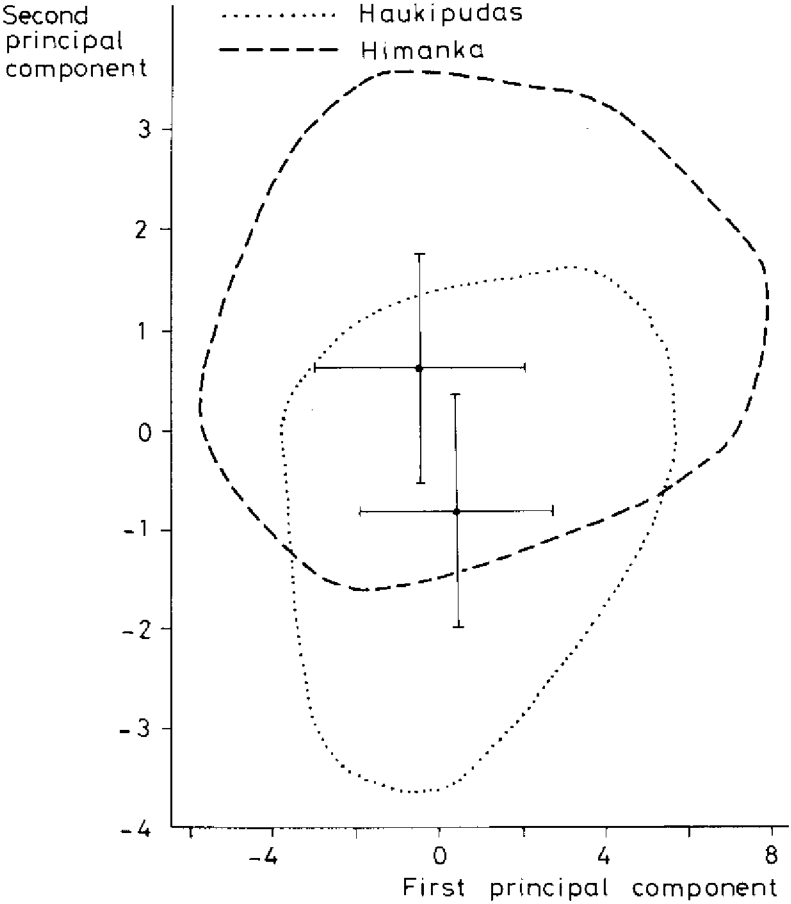

Figure 6. Score values, areal means and standard deviations of the specimens on the first two principal component axes based on the eleven original characters of herring in the Bothnian Bay.

Possible Effects of Temperature and Salinity on the Morphology of Baltic Herring

In the Baltic Sea temperature and salinity decrease from south to north. An increasing trend is evident from south to north in the anterodorsal length, head length, head height, eye diameter and otolith length. An exception to the general increasing trend is formed by the Bothnian Bay. Thus these morphometric characters are not inversely proportional to the temperature and salinity in the whole Baltic Sea area.

Table 6. Mean principal component scores and the standard deviations of the eleven original morphological variables of herring in the northern Baltic Sea, excluding the Bothnian Bay.

	Mean	Standard deviation
First principal component		
Kotka	-0.104	2.473
Helsinki	-0.198	2.251
Ingå	1.358	2.265
Archipelago Sea	-0.346	2.346
Åland	1.232	3.010
Uusikaupunki	-1.087	2.250
Pori	-0.961	2.494
Second principal component		
Kotka	0.003	1.080
Helsinki	-0.226	1.365
Ingå	0.230	1.051
Archipelago Sea	0.092	1.002
Åland	-0.102	0.828
Uusikaupunki	-0.314	0.772
Pori	0.313	1.256
Third principal component		
Kotka	-0.162	1.104
Helsinki	-0.417	1.011
Ingå	0.108	1.142
Archipelago Sea	0.302	0.828
Åland	0.198	0.841
Uusikaupunki	0.121	0.948
Pori	-0.164	0.971

The number of vertebrae generally decreased from the southern parts of the Baltic Sea to the north, but in the Bothnian Bay the number was large. Lundbeck (1930) suggested that although the number of Baltic herring vertebrae is generally small in cold water, low salinity causes a large number of vertebrae. Another possibility is a V-shaped relationship with temperature or salinity, as Tåning (1952) has suggested for temperature and the number of vertebrae in the sea trout.

The effects of temperature and salinity on the morphology of Baltic herring cannot be determined with the present material. These environmental effects should be studied in aquarium experiments.

The herring morphology in the northern parts of the Baltic Sea shows spatial differences, which are evidently connected with the temperature, salinity and other environmental factors during the early life history of herring, and are not due to genetic differences (Ryman *et al.*, 1984, Dahle & Eriksen, 1990). Many characters form a cline along the coast. Within the same area variation may also occur in the environment and thus in the herring morphology, depending on the time of spawning and on the spawning site; whether, for instance, the locality is a low-saline fast-warming inner bay, or the open sea.

In the canonical discriminant analysis, no distinct morphological groups can be observed in the northern Baltic Sea in the system of coordinates based on the first two canonical variables. This is also the result, if the canonical discriminant analysis is made by deleting the fork length and using the relative values of the morphometric variables instead of the original ones. According to the canonical discriminant analysis based on the original variables, the herring in the Bothnian Bay partly deviate from those in the other areas, and there is also some spatial differentiation within the Bothnian Bay. The first axis correlates with salinity, or some other environmental factor which changes from the Baltic proper towards the heads of the Gulfs of Bothnia and Finland.

The lack of distinct morphological groups in the northern Baltic is supported by the result of the density linkage clustering method, where there is no evidence of clusters in either the Bothnian Bay or the other parts of the northern Baltic Sea.

In the principal component analysis, the first principal component is a measure of fish size. Differences in the mesh size of the gear, or in the horizontal or vertical size distribution of the one-year-old herring during the fishing, may affect the size of the fish caught and thus the results of the analysis. The second principal component measures the morphology of the otolith. Differences in the width of the first growth zone between the individuals may arise from the fact that in all coastal areas of the northern Baltic Sea the spawning of herring may take place during several months. Early hatched larvae have a longer growth period before the formation of the first hyaline ring than larvae hatched from a late spawn.

The herring in the Bothnian Bay, especially its northern part, differ morphologically from the fish in the other parts of the northern Baltic Sea, although overlapping occurs. Within the Bothnian Bay, spatial differences in morphology are evident, but there is also overlapping. The results obtained for this and the other areas by the methods used here do not support the hypothesis that the northern part of the Baltic Sea contains distinct groups of herring separable from each other on a morphological basis.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

The Impact of Pacific Salmon on Herring Survival in the Western Bering Sea

V.I. Karpenko and V.V. Maksimenkov
Kamchatka Department of the Pacific Fisheries and Oceanography Research Institute
Petropavlovsk-Kamchatsky, USSR

Fluctuations in the abundance of salmon and herring often share a common cycle (Birman, 1985) and are stipulated for similarity of mechanisms of forming theirs generations (Karpenko, Maksimenkov, in press). In some areas these cycles are inversely and related which, to a marked degree, predation, where salmon are the predators. Juvenile salmon begin to feed upon larval herring after out-migration which coincides in time with the hatching of herring (Godfrey, 1965; Healey, 1980). During the salmon's seaward migration period, they continue to feed on juvenile herring (Prakash, 1962; Ito, 1964; Major et al, 1978). This paper is based the salmon prey on larval and juvenile herring in western Bering sea.

MATERIALS AND METHODS

Data were collected in Karaginskiy Bay of the Bering sea from 1975 through 1989. During 15 years of observations, 5000 stomachs of juvenile salmon have been examined. In 310, there have been found larval and juvenile herring. The relative amount of larval herring consumed was calculated using the following formula:

$$n = \frac{N \cdot W \cdot p \cdot q}{w},$$

where n - relative quantity of herring consumed;
W - average predator weight, mg;
p - daily ration in fractional form;
q - the herring fraction of the food mass;
N - relative predator abundance, number/set;
w - average weight of larval herring, mg.

RESULTS AND DISCUSSION

In the sea, after leaving the rivers, juvenile salmon feed on brackish water and marine crustaceans, adult and larval stages of insects, and larval fish (Karpenko, 1981, 1982). The basic diet of juvenile pink, chum and sockeye salmon is composed of crustaceans, while juvenile coho and chinook feed primarily on fish.

In coastal waters of Karaginskiy Bay, juvenile salmon are capable of feeding upon larval and juvenile herring over a long time - June through September.

Juvenile herring were first discovered in the stomachs of chinook and coho salmon in September 1977. The lenghts of the consumed fish varied between 29 mm and 40 mm. Later, juvenile herring were discovered in the stomachs of all species of the Pacific salmon in 1978-1989 (Figure 1).

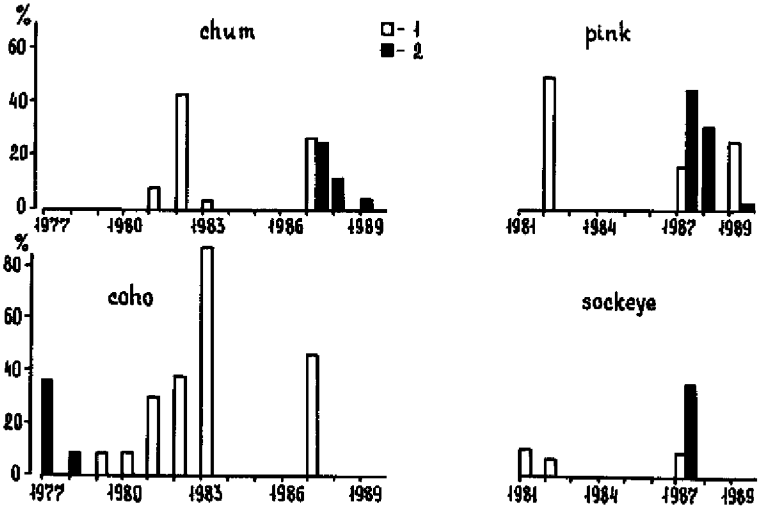

Figure 1. The herring fraction of the food mass of juvenile salmon in June-September 1977-1989.
1 - June-July; 2 - August-September.

In coastal area of Karaginskiy Bay, larval herring were first discovered in the stomachs of salmon in 1979 and were theirs stomachs in next four years. During the month of July 1981 through 1983, larval herring were a common food item for out-migrating juvenile pink, chum, sockeye and coho salmon in the Anapka and Markelovskaya River estuaries. Stomachs of juvenile salmon contained from 1 to 16 larval herring of 20 mm to 25 mm while in 1982, in addition to these, smaller prolarvae measuring 4,5 mm to 6,0 mm were also found (up to 270 individuals in one stomachs). In July 1982 predation on larval herring was most intensive, their frequency of occurrence in salmon stomachs varied from 19% to 81%. Herring made up from 6,0% to 51,1% of the total weight of food items consumed by juvenile salmon. Larval herring were discovered in salmon stomachs from 1987 to 1989.

Herring prolarvae were found in the stomachs of juvenile salmon which were captured near Karaginskiy Island in July wich uncommon. Spawning of herring at Karaginskiy Island has only been noted during years high herring abundance (1955-1961)(Kachina, 1981). In addition, it seems uncommon to encounter herring prolarvae as late as July. These problems will most likely be resolved only after additional research of the ecology of herring has been completed.

We didn't analize either the extent of salmon predation or its affect on herring abundance. However, the latter has been suggested, particularly in the early developmental stages of these species (Birman, 1985). To attempt an approximate estimate of the impact of predation by juvenile salmon on larval herring, data were cosidered for the period of June through July in the coastal waters northeastern Kamchatka (Figure 2). The influence on herring year-class strength by salmon predation is rather complex. It is known that herring year-class strength is dependent upon the abundance of herring larvae and the amount of plankton available as their food source (Maksimenkov, 1986). Therefore, in years when the abundance of herring larvae is high and their forage base is depressed, predation by salmon tends to lessen intraspecific competition thereby having a positive effect on year-class success (for example in 1983). In comparison with 1983, the 1982 herring larval abundance was lower and the loss to predation greater, which led to a decrease in the strength of the 1982 year-class. In 1987 and 1989 there are a analogous phenomenons. In addition, the extent of herring mortality by predation is not directly related to juvenile salmon abundance (Karpenko, Maksimenkov, 1988).

Latter data confirmed the impact of Pacific salmon on herring year-class success. To estimate the extent of predation, further investigations will be required.

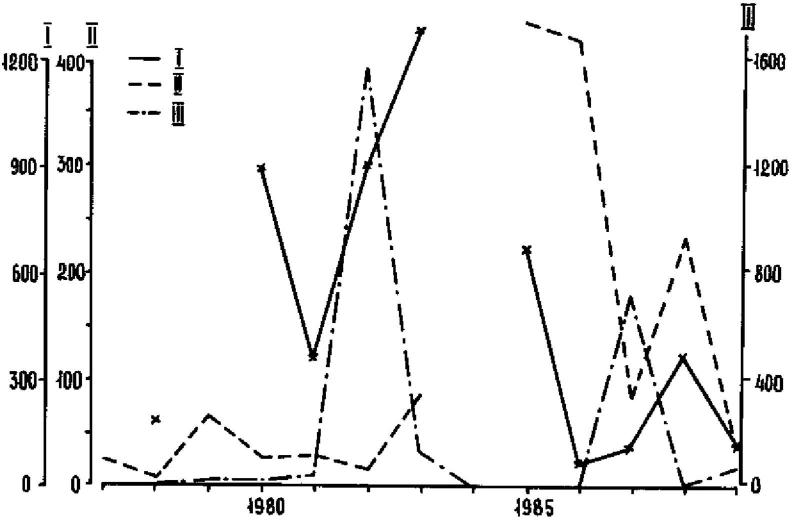

Figure 2. The quantities of larval (I, number per station) and juvenile herring (II, number per trawl) and the relative extent of predation on larval herring by juvenile salmon (III).

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ABSTRACT

This paper presents data on juvenile Pacific salmon preying on larval herring in western Bering sea. Possible predator impact on herring year-class strength is discussed.

Management

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Harvest Policy Implications of Yield per Recruit Models for Pacific Herring in Alaska

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F. Funk
Alaska Department of Fish and Game
Juneau, Alaska

ABSTRACT

A yield per recruit model is used to explore how $F_{0.1}$ and other aspects of growth-mortality tradeoffs relate to existing harvest policies for the Togiak herring stock in the Bering Sea and for the Prince William Sound herring stock in the Gulf of Alaska. Exploitation rates corresponding to $F_{0.1}$ at Togiak (36%) and at Prince William Sound (46%) are considerably higher than the current 20% maximum exploitation rate applied to both stocks. Although $F_{0.1}$ is an arbitrary reference point, growth-mortality tradeoffs indicate that optimal exploitation rates for herring stocks in the Bering Sea are less than those for stocks in the Gulf of Alaska. "Banking" harvest policies, whereby exploitation rates are reduced for one year to increase cohort longevity and sustain egg production over a longer period of time, are shown to cause only minimal reductions in yield from a cohort over its fishable lifespan. Although targeting fishing effort on a newly recruited strong year class can increase the yield from the year class as much as 14%, the disadvantages associated with reduced egg production, reduced roe quality, and uncertainty in first-year biomass assessments likely counteract this benefit.

INTRODUCTION

During the 1970s, sac roe fisheries were developed on a number of previously unexploited Alaskan stocks of Pacific herring (*Clupea harengus pallasi*). Lacking detailed stock assessment information, harvest policies which were considered to be conservative at the time were arbitrarily established. These harvest policies allow a maximum exploitation rate of 20%. Herring harvest policies in Alaska are now being

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Contribution PP-032 of the Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau.

re-examined in light of the stock assessment information collected since the beginning of commercial exploitation. As an initial phase of this examination, a yield per recruit model was used to explore how geographic patterns in the growth and mortality tradeoffs might influence optimal harvest policies for several Alaskan herring stocks.

Typically, yield per recruit models are used to evaluate optimal size at harvest. However, they may be useful for other purposes as well, depending on data availability and recruitment patterns of the stocks considered. Because yield per recruit models have limited data requirements, they can provide guidance on harvest policy for stocks lacking assessment data necessary for application of more sophisticated models, although they do not address stock-recruitment feedbacks and can be overly simplistic representations of complex processes. For fisheries that tend to be sustained by a single successful year class, such as the case with many Alaska herring stocks, yield per recruit models can be particularly useful tools for evaluating optimal exploitation rates and other aspects of alternative harvest strategies. Yield per recruit models are used to calculate $F_{0.1}$, the instantaneous fishing mortality rate that corresponds to a point on the yield per recruit function with a slope of 10% of the slope near the origin (Gulland and Boerema 1973). This biological reference point is usually considered to be a conservative exploitation rate.

With particular application to Alaskan herring stocks, yield per recruit models have two other practical applications. In the Togiak District of Bristol Bay, current fishing regulations allow special fishery openings targeted on new recruits, if the newly recruited cohort is unusually abundant. Newly recruited herring spawn later in the season than older herring, so that fishing effort can be targeted effectively on them. Assuming that a newly recruited strong year class would have to support the fishery over its fishable lifespan, a herring yield per recruit model can be used to evaluate total yield from the cohort under alternative harvest policies that either promote or discourage targeted fishing effort on new recruits.

Another practical application of yield per recruit models to Alaska herring stocks is the evaluation of a temporary harvest rate reduction in a fishery which otherwise has a fixed rate harvest policy. This situation is occasionally encountered in herring fisheries being prosecuted on single strong year classes which have not had significant recruitment for several years. Fishery managers are then pressured to reduce the exploitation rate, in hopes of maintaining greater spawning potential and a smaller, but more stable, fishery over a longer period of time. This harvest policy is commonly termed "banking" fish for the future. In the special case examined here, the exploitation rate is reduced from the maximum 20% for a single year. The exploitation rate is restored to 20% in subsequent years, as managers would likely do if a recruitment event were observed in the year following the "banking" harvest rate reduction. The yield per recruit model is used to evaluate yield over the lifespan of the cohort being fished at the time of the "banking" event, assuming that the new recruits would not become available until the older cohort reached the end of its fishable lifespan. This scenario also can be used to evaluate the yield lost due to a stock assessment error which causes stock biomass to be underestimated for a single year.

METHODS

Yield per recruit models examine how the tradeoffs between growth and mortality over the lifespan of a single cohort affect the yield from that cohort. Under conditions of constant recruitment and mortality over at least one fishable lifespan, the yield from a single cohort over its lifespan is also identical to the yield from all cohorts of a population in a single year. However, because herring fisheries often are prosecuted on single year classes for durations approximating a fishable lifespan, it is useful to consider yield per recruit models as strictly describing the processes affecting a single cohort over its lifespan and to de-emphasize the assumptions required for equilibrium conditions.

Growth was described using a Gompertz model:

$$W(a) = W_\infty e^{-e^{-(g(a-a_0))}} \tag{1}$$

where $W(a)$ is the weight in grams at age a, W_∞ is the maximum weight, g is a parameter controlling the rate of growth and a_0 is an initial condition describing the age at which $W(a) = W_\infty / e$.

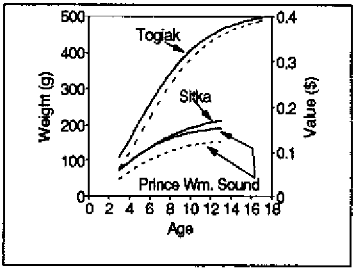

Figure 1. Growth in weight (——) and value (- - -) of an individual herring as a function of age at selected locations in Alaska.

Herring belonging to the stock spawning at Togiak grow substantially faster and attain more than twice the size of herring spawning in Sitka Sound and Prince William Sound (Figure 1). Because growth and mortality in many outer coastal Gulf of Alaska herring stocks are similar, the Prince William Sound herring stock was chosen as a proxy for all other Gulf of Alaska herring stocks for further comparisons. Similarly, growth and mortality for most Bering Sea herring stocks are similar to the Togiak stock which is examined in this analysis.

The yield per recruit model was also extended to estimate ex-vessel value per recruit. Herring sac roe prices depend on the ratio of female ovary weight to total catch weight of both sexes ("roe percent") and ovary weight varies as the 1.208 power of body weight (Ware 1985). Herring sac roe prices are usually quoted as the price given when the roe percent is 10%. Prices typically change by 10% for each one percent change in roe percent above or below 10%. Based on these relationships, the following equation was developed to account for the effect of fish weight, W, on the price received $\Psi(W)$:

$$\Psi(W) = 0.5\,\alpha\,\beta\left(\frac{cW^{\phi}}{W}\right) \tag{2}$$

where 0.5 represents the assumed sex ratio, the coefficient α (=10) reflects the slope of the linear relationship between price and roe percent, β was set at 0.8 to reflect a sac roe fishery achieving 80% of the maximum roe percentage, and c and ϕ were set at 0.098 and 1.208, respectively, based on Ware (1985). Then, the value of an individual herring was determined as $P_{10\%}\cdot\Psi(W)\cdot W$ where $P_{10\%}$, the price for 10% roe content herring, was set at \$0.000551 per gram, equivalent to the common recent price of \$500 per short ton. The value of an individual herring followed a pattern similar to that of growth, but increased slightly faster with age (Figure 1). The value of age three and four herring is probably somewhat overstated because, in catches comprised primarily of very young herring, prices are often less than would be indicated by equation (2). However these price deviations have not been sufficiently frequent or consistent to develop a better model for the prices received for very young herring.

After reviewing the available information on natural mortality for Prince William Sound, Funk and Sandone (1990) concluded that an instantaneous rate of 0.45 best represented the midpoint of a range of estimates. In Prince William Sound, herring older than 12 years of age are very rare, whereas in the Bering Sea herring up to age 16 are sometimes encountered. The oldest age in the fishable lifespan, t_λ, is taken to be 13 in Prince William Sound, and 17 in the Bering Sea. Wespestad (1982) estimated that the natural mortality rate for Bering Sea herring was 0.39, using the method of Alverson and Carney (1975). Because the recorded longevity of Bering Sea herring has increased from the time of Wespestad's study and to account for the differences in longevity at the two locations, a natural mortality rate of 0.35 was used for the Togiak herring stock in the Bering Sea. Herring natural mortality rates may increase with age (Tester 1955). However, because the existing data are insufficient to estimate the age-dependent changes and to separate the confounding effects of changes in maturity and availability with age, a constant mortality rate was used for all ages.

Yield per recruit models describe the accrual of yield from a cohort over its fishable lifespan, from the age of first vulnerability to the fishing gear, $t_{p'}$, to the oldest age, t_λ. Using the notation of Beverton and Holt (1957), the model of survival over this period is:

$$N(t) = R\, e^{-(F+M)(t-t_{p'})} \qquad (3)$$

and the model of yield per recruit is:

$$Y = \int_{t_{p'}}^{t_\lambda} F \cdot N(t) \cdot W(t)\; dt \qquad (4)$$

where Y is the yield over the fishable lifespan, R is the number of recruits (conventionally 1), F and M are the instantaneous rates of fishing and natural mortality, $N(t)$ is a model describing survival from $t_{p'}$ to age t, and $W(t)$ is the growth model given in (1). A similar equation could have been developed to model yield in terms of the weight of roe in the catch. However, modelling yield in this way would cause only very slightly modifications to the shape of the yield per recruit response surfaces. In addition, catch quotas and harvest records from herring sac roe fisheries are expressed in terms total body weight.

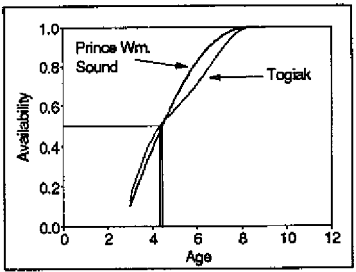

Figure 2. Availability estimates by age showing the age of 50% availability for Togiak and Prince William Sound herring.

Estimates of $t_{p'}$ were derived from the age of 50% availability for each stock, where availability at each age was defined as the proportion of the fish of that age in the harvest, compared to a fully recruited age. In the context of this model, availability is analogous to partial recruitment and includes elements of both sexual maturity and gear selectivity. Immature herring do not partake in the annual spawning migration and are not present on the fishing grounds. For the purse seine fisheries considered in this application, an additional "gear selectivity" component is also applicable because purse seine fishermen actively seek to harvest older, more valuable herring. For the Prince William Sound herring stock, Funk and Sandone (1990) gave separate estimates for partial recruitment and gear selectivity, the product of which was taken to be availability (Figure 2), and $t_{p'}$ was estimated to be 4.45 years. For the Togiak stock the availability schedule given in Rowell and Brannian (1991) was used, and $t_{p'}$ was estimated to be 4.3 years. To provide a better comparison of yield per recruit for the two stocks, R was defined as the number of recruits per tonne of biomass at age $t_{p'}$ for each of the two stocks.

Yield per recruit results are typically presented as a response surface of Y with respect to F and $t_{p'}$. Analogous to the yield per recruit model, a landed value per recruit model was defined as:

$$V = \int_{t_{p'}}^{t_{\lambda}} F \cdot N(t) \cdot W(t) \cdot P_{10\%} \cdot \Psi(W(t)) \, dt \tag{5}$$

A reference point $V_{0.1}$ was defined as the point on the landed value per recruit surface where the slope was 10% of the slope near the origin for a given $t_{p'}$.

Although the concept of $F_{0.1}$ is embedded in the context of the Beverton-Holt yield per recruit model (4), for other applications it is more appropriate to model herring survival with a difference equation, because herring fisheries occur over very short periods of time. The difference equation analogous to the differential equation for survival (equation 3) is:

$$N_{a+1} = e^{-M}(N_a - A_a \mu N_a) \tag{6}$$

where N_a is the number of fish of age a just before the fishery occurs, A_a represents the proportion of the population available to fishing gear at age a and μ is exploitation rate (the proportion of a fully-recruited age class removed by the fishery). The difference equation model tracked ages ranging from age 3 to age t_{λ}. The initial number of fish in the cohort N_3 was defined as the number of fish per tonne of age 3 recruits. Unlike model (3), recruitment is not assumed to be knife-edge at the age of 50% maturity, but occurs over a range of ages from 3 through 8 (Figure 2).

The difference equation form of the yield per recruit model, analogous to the Beverton-Holt model (4) is:

$$Y = \sum_a \mu \cdot A_a \cdot N_a \cdot W_a \tag{7}$$

This difference equation form of the yield per recruit model was used to evaluate the "banking" and recruit fishery scenarios, while the Beverton-Holt differential equation form (4) was integrated to evaluate $F_{0.1}$. The "banking" and recruit fishery scenarios treat herring fisheries as being strictly prosecuted on a single year class from the time of its recruitment to the oldest fishable age.

Exploitation rates for Alaskan herring sac roe fisheries are specified in terms of biomass, while the difference equation models (6 and 7) are expressed in numbers of fish. The biomass-based exploitation rate μ_b is defined as the proportion of the recruited biomass, B_r, taken by the fishery: $\mu_b = Y/B_r$. For the Beverton-Holt model (4), all herring above the age of 50% recruitment are included in B_r. For the difference equation models recruited biomass is defined as:

$$B_r = \sum_a A_a \cdot N_a \cdot W_a \tag{8}$$

Targeted "recruit" fisheries were modelled by increasing the availability of herring at age 4 above the current levels. A range of availabilities at age 4 from the current levels shown in Figure 2 (approximately 0.5) to fully-recruited availability (1.0) was examined.

The change in yield over the lifespan of the cohort resulting from targeting on new recruits was examined. The effect of the recruit fishery on reproductive potential, defined as the total egg production over the lifespan of the cohort, was also examined in Prince William Sound, using the fecundity-age relationship of Funk and Sandone (1990).

RESULTS

For both the Prince William Sound and the Togiak herring stocks, the biomass of an unexploited cohort reaches a maximum before the age of 50% recruitment to the fishery (Figure 3). Because of their larger ultimate size and more rapid growth rates, Togiak herring achieve maximum biomass somewhat later than Prince William Sound herring. Nevertheless, in both stocks, even with no exploitation, the biomass lost to natural mortality exceeds the biomass gain from growth for ages greater than 2 for Prince William Sound and greater than 4 for Togiak. By the time the fishery begins harvesting the year class at approximately age four, the biomass of a cohort is already declining.

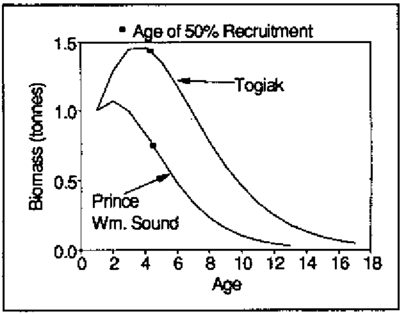

Figure 3. Biomass trajectory of an unexploited cohort consisting of one tonne of age 1 fish for the Prince William Sound and Togiak herring stocks.

For this reason the yield per recruit response surfaces for both the Prince William Sound (Figure 4) and Togiak (Figure 5) herring stocks do not slope downward with respect to age of entry for realistically young ages of entry to the fishery.

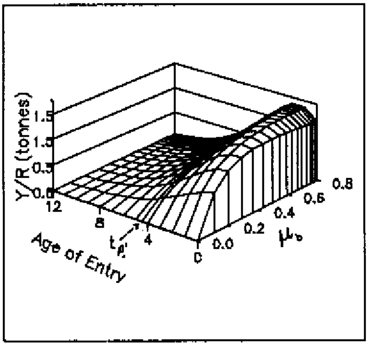

Figure 4. Yield per recruit response surface with respect to age of entry t_p, and biomass-based exploitation rate μ_b for Prince William Sound herring.

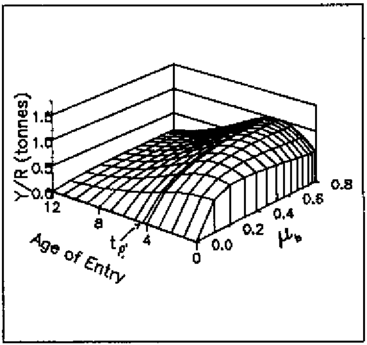

Figure 5. Yield per recruit response surface with respect to age of entry t_p, and biomass-based exploitation rate μ_b for Togiak herring.

As a result, when the age of entry is close to the current value of $t_{p'}$, yield per recruit continuously increases with respect to the exploitation rate μ_b. Value per recruit surfaces (not shown) have a very similar shape to the yield per recruit response surfaces, because the value-age and weight-age relationships have similar shapes (Figure 1).

The biological reference point of F_{max} is conventionally defined as the location along the fishing mortality axis where a maximum yield per recruit occurs, when the age of entry is fixed. F_{max} is generally regarded as a futile harvest policy objective in most applications (Anthony 1982). For both of these herring populations, F_{max} is infinity. Harvest policies which would attempt to achieve exploitation rates approaching F_{max} would almost certainly result in recruitment overfishing in these populations.

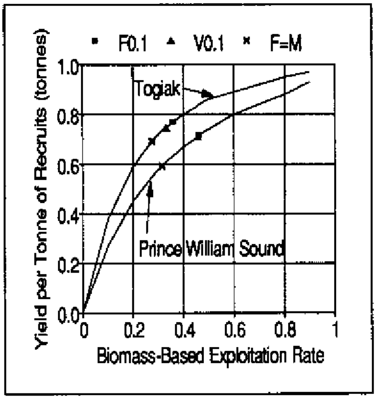

Figure 6. Yield per tonne of age $t_{p'}$ recruits as a function of the exploitation rate μ_b, showing the values estimated for $F_{0.1}$ and $V_{0.1}$.

If the age of entry is considered fixed at the current values of $t_{p'}$ for both herring populations, yield per recruit can be compared in more detail. Because of their more rapid growth and larger ultimate size, yield per recruit for Togiak herring is greater at all exploitation rates than for Prince William Sound herring (Figure 6). The value of $F_{0.1}$ for Togiak herring was 0.48, corresponding to a biomass-based exploitation rate, μ_b, of 36%. For Prince William Sound herring, $F_{0.1}$ was estimated to be 0.77, corresponding to $\mu_b = 46\%$. Yield per recruit for Togiak herring has a steeper initial slope than for Prince William Sound herring and the slope also decreases at a greater rate. As a result the exploitation rate corresponding to $F_{0.1}$ for Togiak herring is only 78% of the corresponding rate for Prince William Sound herring.

Exploitation rates corresponding to $V_{0.1}$ are identical to those for $F_{0.1}$ for Togiak herring (45%), and slightly less for Prince William Sound herring (33%). The ratio of the exploitation rates corresponding to $V_{0.1}$ at Togiak and Prince William Sound in 73%. The similarity in the results for $V_{0.1}$ and $F_{0.1}$ results from the similarity of the value-age and weight-age relationships (Figure 1). The exploitation rates corresponding to both $V_{0.1}$ and $F_{0.1}$ also are higher than the exploitation rates corresponding to F=M for both Togiak herring and Prince William Sound herring.

In evaluating the "banking" harvest policy, a 20% exploitation rate harvest policy was reduced during a single year to 15%, 10%, or 5%. For any given reduction in exploitation rate, the loss in yield over the lifespan of a cohort is greater in the shorter-lived Prince William Sound herring stock than in the longer-lived Togiak herring stock (Figure 7). The largest losses would occur if the exploitation rate were reduced at age 6 in either stock. For herring older than age 8 for which the banking policy would more likely be implemented, the yield loss is always less than 3%. The largest yield loss examined was only 12%, which occurred for age 6 herring in Prince William Sound, when the exploitation rate was reduced to 5%. In general losses in yield from a single year "banking" policy are relatively low. Because the biomass of a cohort is already

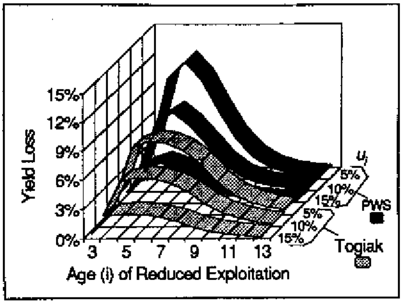

Figure 7. Yield lost as a result of a single year harvest rate reduction as a function of the age at which exploitation is reduced and the magnitude of the reduced exploitation rate for Prince William Sound and Togiak herring.

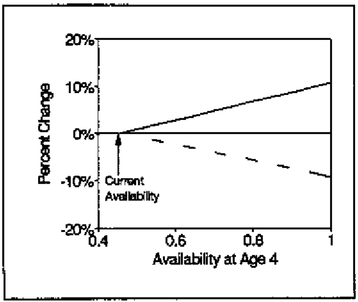

Figure 8. Change in yield (——) and reproductive potential (- - -) over the lifespan of a cohort as a result of altering the availability at age 4 for Prince William Sound herring.

declining at age 4, targeting fishing effort on age 4 herring tends to increase the yield from the cohort. For Prince William Sound, doubling the availability at age 4 from the current 0.39 to 0.78 would increase the yield from the cohort by 14% (Figure 8). However, this would reduce total egg production by the cohort by 6%. The increase in yield from a recruit fishery at Togiak was slightly less. If the availability at age 4 were doubled from the current 0.46 to 0.92, the yield from the cohort would be increased by 9%.

DISCUSSION

The current harvest policy for Alaskan herring stocks specifies a maximum exploitation rate for all stocks of 20%. Based on growth-mortality tradeoffs, this harvest policy appears to be conservative, because it is considerably less than the $F_{0.1}$ biological reference point for the stocks examined. The 20% maximum exploitation rate is also less than exploitation rates corresponding to F=M. Exploitation rates corresponding to F=M have been recommended in data-limited situations (Gulland 1970) for which Deriso (1987) provides some theoretical qualifications. The Alaska Board of Fisheries intended to establish conservative exploitation rates to allow for adequate harvest of herring in subsistence fisheries and to allow for the important ecological niche occupied by herring in both the Gulf of Alaska and Bering Sea food chains.

Regardless of whether the $F_{0.1}$ criteria provides appropriate absolute exploitation rates, the $F_{0.1}$ analysis suggests that the optimal exploitation rates in the Bering Sea should be less (approximately three fourths) of those appropriate for the Gulf of Alaska. For example, if μ_b = 20% was deemed appropriate for Prince William Sound herring, the corresponding μ_b for Togiak should be 15%. The longer periods between successful year classes in the Bering Sea also suggests that exploitation rates should be lower than for the Gulf of Alaska.

When strong year classes are detected, recruit-targeted fisheries will tend to increase the yield from the year class by at most 14% if recruits are intensely exploited. This results from the fact that the biomass of a cohort is already declining by the age of 50% recruitment in both Gulf of Alaska and Bering Sea herring stocks. However, the roe quality of younger fish is often much poorer than for older fish, which tends to offset the increased yield. Because of insufficient data for young fish, the value-age relationship used in this study under-represents this effect. In addition, recruit-targeted fisheries reduce the egg production from a cohort over its lifespan, because fecundity increases with age at a greater rate than growth in weight. Furthermore, biomass estimates of cohort strength during the first recruited year are highly uncertain. Because of this it would be difficult to determine appropriate quotas for recruit fisheries without increasing the risk of overfishing. It is doubtful that the small increases in yield to be accrued from recruit-targeted fisheries would outweigh these potential disadvantages.

When implemented for older herring, the "banking" harvest policy of reduced exploitation causes only slight reductions in yield from a cohort if implemented for a single year. For herring older than age 8 for which the banking policy would more likely be implemented, the yield loss is always less than 3%. The largest yield loss occurred if the banking policy were implemented in a single-year class fishery when the fish were age 6. In general losses in yield from a single year "banking" policy are relatively low. The "banking" harvest policy analysis also addresses the yield lost in situations where stock assessment errors result in less herring being harvested in a single year than the harvest policy would have allowed if the assessment had no error. In general most of the yield "lost" during any single year in such situations would be recovered in subsequent years if the stock assessment errors were corrected.

Although this study did not examine the relationship between spawners and recruits, both "banking" and the prevention of recruit-targeted fisheries would have the benefit of increasing egg production. Furthermore, egg production alone tends to understate the benefit, because spreading the egg production over time increases the probability that larger numbers of young will be produced during oceanographic conditions favorable for survival. Subsequent examinations of herring harvest policies for Alaskan herring stocks should incorporate spawner-recruit relationships and re-examine appropriate exploitation rates and other aspects of harvest policies.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Herring Population Dynamics and Management in Sitka Sound, Alaska

J.S. Collie
University of Alaska Fairbanks
Juneau, Alaska

ABSTRACT

Catch-at-age analysis was applied to Sitka herring data from 1971 to 1989. Among several alternative indices of spawning biomass, aerial and/or egg deposition surveys were most useful as auxiliary information in catch-at-age analysis. Sitka herring biomass was low until 1978 and then increased to a maximum in 1988. The resulting abundance estimates were used to test for density dependent growth and recruitment. Observed variations in mean weight at age are consistent with the hypothesis of density dependent growth. Recruitment was apparently an increasing function of spawning biomass with no evidence of density dependence. In both the growth and recruitment data there was considerable variation (perhaps environmental) that was not explained by stock size. Quotas for the herring fishery are determined by applying a desired harvest rate to an estimated biomass. Examination of the attained harvest rates indicated that the largest source of management error was in projecting the next year's biomass and that recruitment variability is the main uncertainty. Biomass forecasts could be improved with environmental recruitment correlates and/or pre-recruit surveys.

INTRODUCTION

The Pacific herring (*Clupea harengus pallasi*) stock which spawns in Sitka Sound is one of the largest in Southeast Alaska. Sitka Sound is located on the west side of Baranof Island and communicates directly with the Pacific Ocean (See Haldorson and Collie 1991 for map). This paper provides a basic reconstruction of the abundance and dynamics of the Sitka herring population over the past two decades. The motivation for this study was two-fold. First, in the recruitment studies of Sitka herring reported in this volume (Haldorson and Collie 1991, Zebdi 1991) a recruitment index was required against which to test hypotheses about factors affecting recruitment. This catch-at-age analysis provides the first recruitment estimates for Sitka Sound herring.

Second, reliable abundance estimates are required to manage the fishery and to evaluate the effectiveness of harvest strategies. In Sitka Sound the University of Alaska, in cooperation with the Alaska Department of Fish and Game (ADF&G), is conducting a variety of studies on Pacific herring ranging from early life history analyses to management. In this paper I suggest how the more basic recruitment studies might be translated into management policy. Although I focus on a particular herring stock, the results are generalizable to other herring populations.

ABUNDANCE ESTIMATION

Direct estimates of herring abundance come from three sources (Fig. 1). The index extending farthest back in time is miles of spawn from aerial surveys. The unit of measurement is milt-miles converted to corresponding spawning biomass. The second abundance estimate comes from acoustic surveys, and the third from scuba surveys of egg deposition. Biomass was low until the late 1970s at which time the population "flipped" to a higher abundance level, a pattern common to other herring populations. The egg deposition and aerial survey estimates of biomass are not completely independent, so it is not surprising that the two agree. The acoustic survey seemed to miss substantial biomass in some years; spawn deposition is now the primary abundance index. These abundance estimates may suffice for setting annual quotas, but they ignore catch-at-age data that have been collected from the commercial fishery since 1971, and they do not provide annual recruitment estimates.

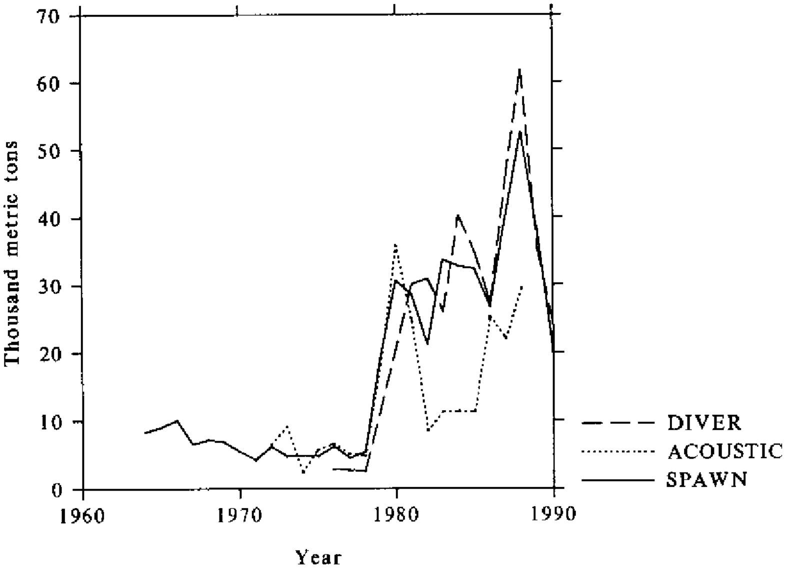


Figure 1. Spawning biomass of Sitka Sound herring measured by three methods: diver egg deposition surveys, acoustic surveys and aerial spawn surveys.

In catch-at-age analysis, the spawn survey data are used to calibrate an age-structured population model. The analysis balances biomass predicted by the model against biomass observed in the survey. A nonlinear optimization program minimizes the squared deviations between observed and expected catch-at-age and between observed and expected spawning biomass. The program I used is called GENCAGE and was written by Fritz Funk of ADF&G specifically for herring; for details of the program see Funk and Sandone (1990). GENCAGE presently accepts only a single series of auxiliary data and it was therefore necessary to select among the three alternative biomass estimates (Fig. 1). In this application I used ADF&G's "best" estimate of spawning biomass which is a hybrid of the three abundance sources, and is most highly correlated with the aerial and egg deposition surveys. GENCAGE strives to minimize the difference between predicted and observed biomass, subject to errors in measuring biomass and catch-at-age (Fig. 2). There was fairly good agreement between observed and estimated biomass except in 1980-1982. The abundance peaks reflect the recruitment of strong year-classes to the spawning biomass. The catch-at-age model picks up these cohorts as three-year-old recruits; the survey picks them up as four-year-old spawners. The predicted biomass is probably the most reliable because it incorporates all the data sources. The output of GENCAGE includes abundance at age, and the corresponding exploitation rates. For a full description of the catch-at-age analysis see Collie (1990).

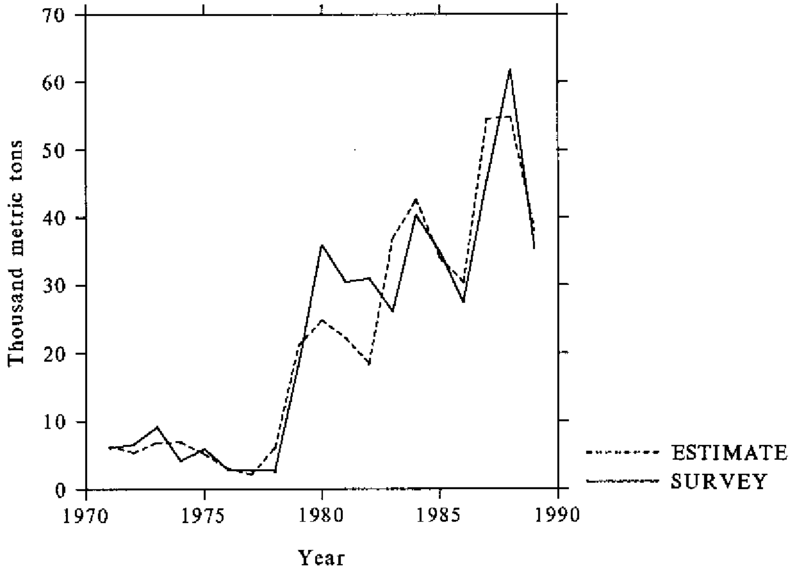


Figure 2. Spawning biomass of Sitka Sound herring: solid line - best estimate from ADF&G spawn surveys: broken line - estimate from catch-at-age model.

Recruitment at age three, as estimated by GENCAGE, was low until the 1976 year class and has described a four-year cycle since then (Fig. 3). This is the same recruitment series that Zebdi (1991) correlated to various environmental indices. The only environmental variable that exhibits a four-year period is sea-surface salinity. Recruitment of Prince William Sound herring, as estimated by Funk and Sandone (1990) has a pattern very similar to Sitka. The two spawning areas are separated by about 1000 km and are thought to support discrete stocks. The most likely explanation of this correlation in recruitment is that the two stocks are influenced by a common large-scale environmental factor.

From 1985 to 1989 mean weight at age of Sitka herring decreased substantially, and in 1989 per capita fecundity was below the industry standard. I compared the recent decline in weight at age to the variability observed during the past two decades. When the data are plotted as growth increments (Fig. 4), it is apparent that some of the variability is biologically unfeasible. During 1978 for example, all ages apparently lost weight! At least part of the variability in weight at age is due to spatial and temporal sampling variability and perhaps aging error. One problem in particular

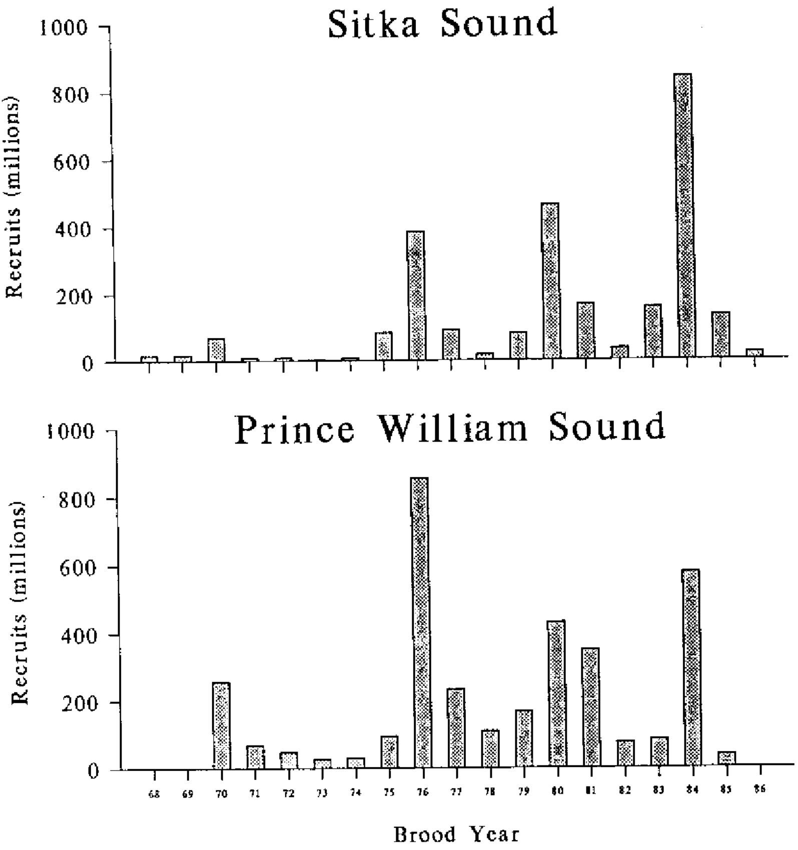


Figure 3. Numbers of age-three herring in Sitka Sound and Prince William Sound as estimated with catch-at-age analysis. Prince William Sound data are from Funk and Sandone (1990).

is that the samples are collected during the spawning season and apparent weight loss may be due to the extrusion of gametes (Robert Larson, ADF&G, Petersburg, pers. comm.). If the 1979 samples were collected post spawning, it would explain why all ages apparently lost weight during 1978.

Arbitrarily ignoring the data from 1978 with the negative growth increments, I plotted the rest of the data against spawning biomass (Fig. 5). Ignoring the anomalous year

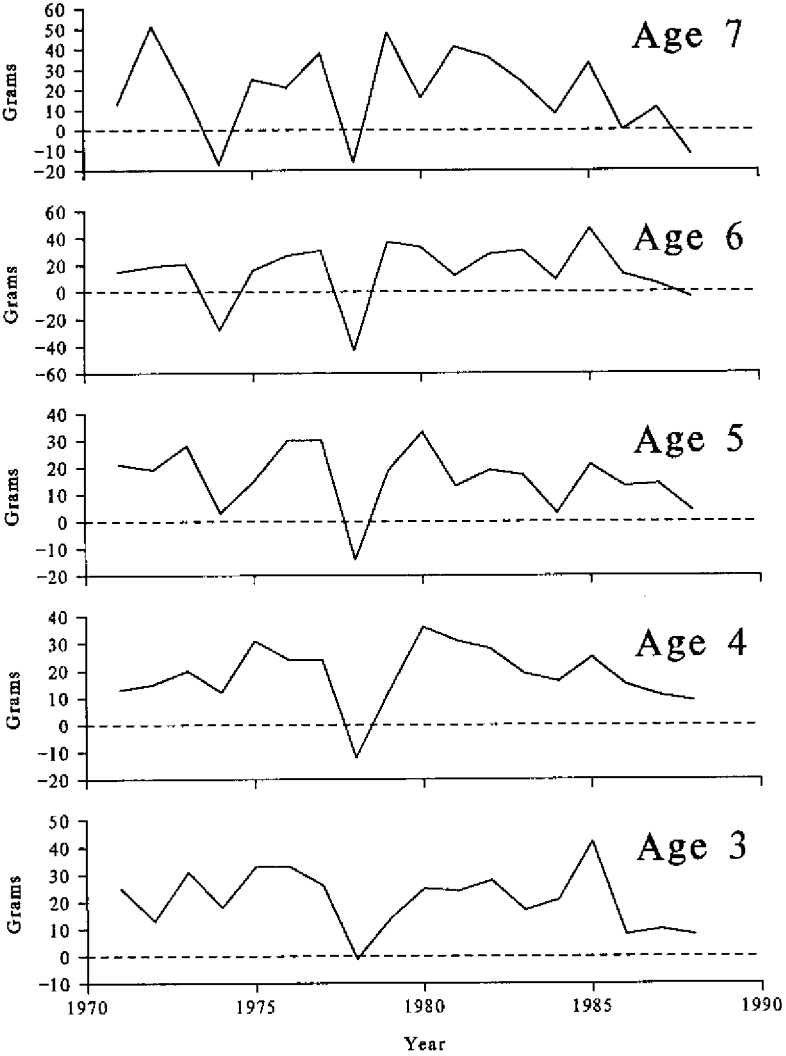


Figure 4. Growth of Pacific herring in Sitka Sound. The weight increment is plotted for each age during each year. The biological year for herring starts with spawning, approximately at the beginning of April.

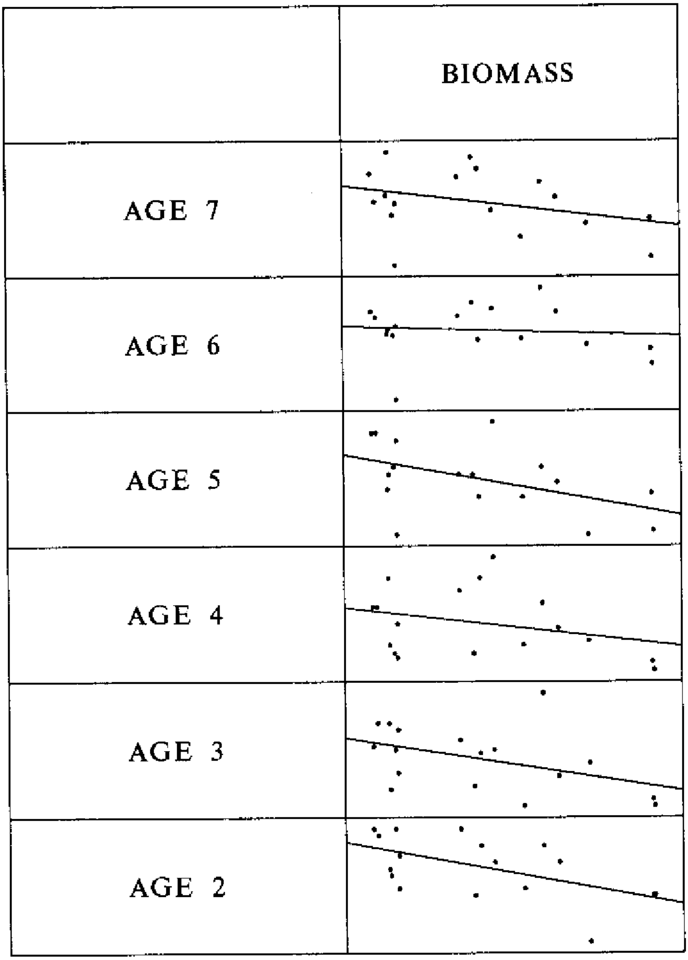


Figure 5. Growth increments of Sitka herring (from Fig. 4) plotted against spawning biomass during the same year. Data for "AGE 2" are the actual weights at age three plotted against biomass the previous year. The linear regression line in each sub-plot indicates a negative trend for all ages.

there is a negative trend between growth and biomass for all ages, which is consistent with the hypothesis of density-dependent growth. Also included in Fig. 5 is the relationship between weight at age three and spawning biomass the previous year. This tests whether cumulative growth up to age three depends on spawning biomass when the fish were age two, and is thus labelled AGE 2 in Fig. 5. The relationship between age-three weight and biomass the previous year is negative even including the 1978 datum. In summary there is weak evidence of density-dependent growth in

Sitka herring but statistical testing of this hypothesis is hampered by sampling variability. There was no apparent relationship between sea surface temperature and growth or growth increments. If temperature has any effect on growth it is via the indirect effect of temperature on biomass.

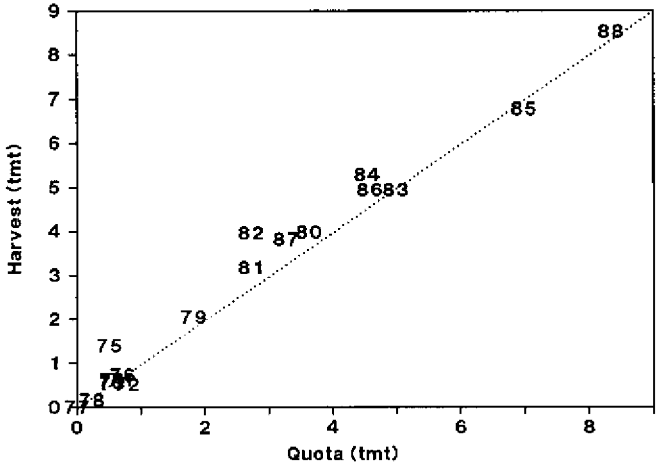


Figure 6. Target quota and realized harvest of Sitka Sound herring. Units are thousand metric tons.

FISHERY MANAGEMENT

The biomass estimates also allow one to calculate the exploitation rates, defined as yield divided by total biomass. With these harvest rates one can then evaluate herring harvest policy and the components of management. The steps are to determine an optimal harvest rate (u), forecast biomass the next year (B) and finally calculate the next year's quota as a function of u and B.

The Sitka herring fishery is a sac roe fishery. The spawning population is harvested with purse seines and the duration of the fishery is a matter of hours. Interestingly, most participants prefer the derby-style fishery. Despite the short duration, the fishery is manageable which is a credit to the managers who must make snap decisions, often with limited information. Management precision is illustrated by plotting the realized harvest against the target quota (Fig. 6). Realized harvest tends to exceed the quota but not by much. This is important because there is no point trying to optimize the harvest without the ability to regulate the harvest.

The target harvest rate is determined on a sliding scale as a function of biomass remaining after the previous year's catch (Fig. 7). There is a threshold biomass below which the fishery is closed. Above the threshold, the harvest rate increases from 10% to a maximum of 20%. This is a conservative policy because the harvest

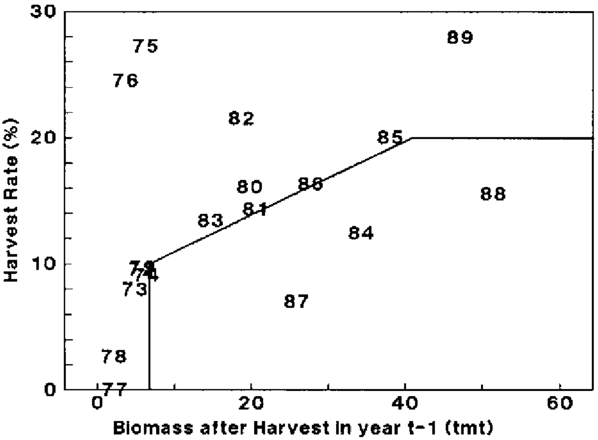


Figure 7. Harvest policy for Sitka Sound herring. The solid line indicates the target harvest rate in relation to biomass after harvest the previous year. The dates indicate realized harvest rates in relation to biomass as estimated with catch-at-age analysis.

rate is reduced at low abundance. The years denoting the realized harvest rates (Fig. 7), do not fall very close to the target rates. The problem is not in meeting the quota; Fig. 7 demonstrated that there is high management precision. The difficulty is in forecasting the biomass from which next year's quota will be taken. In Sitka there is no attempt to forecast, and next year's quota is based on this year's biomass. This calculation ignores losses and additions to the spawning biomass during the year, namely natural mortality and recruitment. To some extent, recruitment and natural mortality balance each other, but recruitment in particular is highly variable. For a sliding-scale harvest policy to be useful, the biomass forecasts need to be more precise, and recruitment is the wild card.

A broken line joining the realized data points in Fig. 7 would describe three counter-clockwise loops with each loop corresponding to a cyclic change in biomass (Fig.2). The herring harvest policy is a delayed feedback control policy with the managers lagging one year behind changes in biomass. Such a delayed feedback mechanism tends to overcompensate for changes in biomass and can actually amplify the biomass cycles and increase the probability of stock collapse. In any fishery that is managed with an annual quota set in advance of the fishing season, the manager must always react to, rather than anticipate changes in abundance.

There are three ways to predict recruitment, the first of which is with stock-recruitment relationships. Although herring recruitment is notoriously variable, usable stock-recruitment relationships have been obtained for some stocks (Rothschild 1986) especially when environmental correlates have been included

(Winters and Wheeler 1987, Stocker et al. 1985). For Sitka herring only a small proportion of recruitment variability is explained by egg production (Fig. 8). In view of the recruitment time series (Fig. 3) it is surprising that there is any relationship at all. On the average, recruitment has been lower at low spawning biomass, but the third highest recruitment was produced by the second lowest biomass. Presently there is no evidence of a compensatory decrease in per capita recruitment at high stock size. Recruitment of the 1987-1990 progeny of large spawning biomasses (Fig. 2) will help to delineate the relationship.

The second approach to predicting recruitment is to use environmental correlates of recruitment. In herring there appears to be a strong environmental component to recruitment variability, and in Sitka recruitment appears to be correlated with temperature (Zebdi 1991). Environmental correlates and the stock-recruitment relationship can be combined into a single model to forecast recruitment (Stocker and Noakes 1988).

A third approach to predicting recruitment is preseason surveys. Preseason acoustic surveys were conducted in Sitka Sound for at least 16 years, and herring were caught to validate the echograms. The acoustic estimates have proven not to be very reliable, but the age composition data alone may be sufficient to predict recruitment. Suppose we wish to predict the number of age-three recruits entering the fishery in year y with preseason age composition data. The ratio of age-three fish to other ages (4+) is

$$\frac{N_{3,y}}{N_{4+,y}} = \frac{p_{3,y}}{1-p_{3,y}} \times \frac{v_{4+}}{v_3} \qquad (1)$$

Where $N_{a,y}$ is the number of age a fish in year y, $p_{a,y}$ is the proportion of age a fish in the pre-fishery survey in year y and v_a is the vulnerability of age a to the sampling gear. The number of post-recruit fish in year y can be estimated from the survivors of the previous year as estimated with catch-at-age analysis.

$$N_{4+,y} = \sum_a (N_{a,y-1} - C_{a,y-1})S_a \qquad (2)$$

Where S_a is natural survival and $C_{a,y}$ is catch at age. Substituting (2), equation (1) can be solved for the preseason estimate of age-three recruitment

$$N_{3,y} = \frac{p_{3,y}}{1-p_{3,y}} \times \frac{N_{4+,y}}{v_3}$$

Where v_3 is expressed relative to $v_{4+} = 1$.

The reliability of the recruitment forecast depends on the preseason age-composition sample and the projected abundance of the other ages. So far only four years of preseason age-composition data are available. In two years the preseason samples underestimated the proportion of age 3 (p_3) herring in the fishery (Fig. 9a). The first large year-class entered the fishery in 1979 and the preseason proportion is low because the acoustic survey deliberately avoided schools of young herring. In 1978, the year before the large 1979 cohort, p_3 was reduced by the high p_2 which were immature herring and didn't contribute to the fishery. The underestimates in p_3 translate to underestimates in recruitment (Fig. 9b). Had the proportion of age-three fish been correct, the recruitment forecasts would have been very close to the 1:1 line. These relationships suggest that it would be worth collecting additional years of data, and if the relationships persist, it may be worth conducting preseason surveys for the sole purpose of determining age composition.

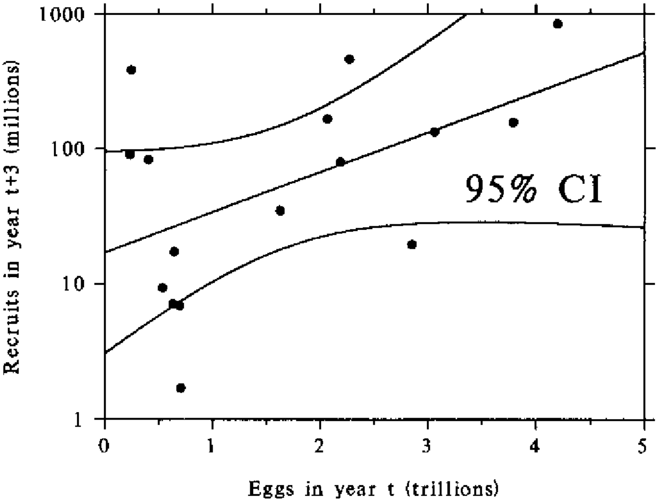
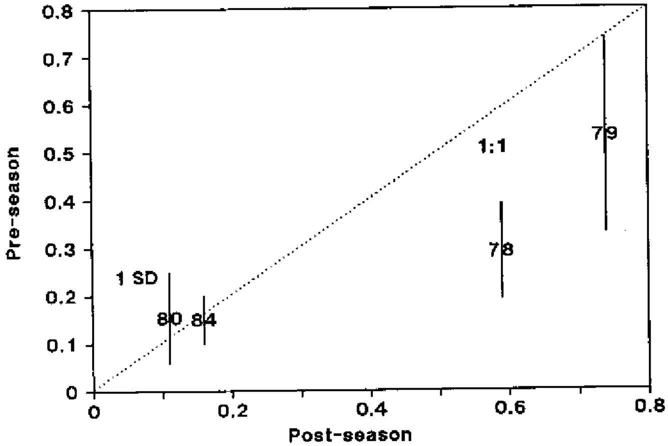


Figure 8. Stock-recruitment data for Sitka Sound herring. The data are for brood years 1971 to 1986. The linear regression line and corresponding confidence intervals illustrate the generally increasing trend in log recruitment with the number of eggs spawned.

The various approaches to predicting recruitment are summarized by plotting the reduction in variance associated with each type of information (Fig. 10). The hypothetical variance (or coefficient of variation) is plotted against the age of the cohort. Prior to spawning the variance is just the variance of mean recruitment. At spawning, the variance is reduced slightly by the spawner-recruit relationship. Environmental factors are thought to be most important during the first year of life, but could influence recruitment during a longer interval. Pre-recruitment surveys are useful during the year prior to recruitment to the fishery. Once the cohort enters the fishery the variance of the recruitment estimate drops because recruitment can then be estimated by catch-at-age analysis. Variance continues to decline as the cohort is observed in the fishery year-after year. The variance becomes constant once the cohort disappears from the fishery. The challenge to fishery scientists is to forecast recruitment soon enough and with enough precision to use the information in setting quotas.

a. Proportion of Age Three Herring



b. Recruitment Estimates (millions)

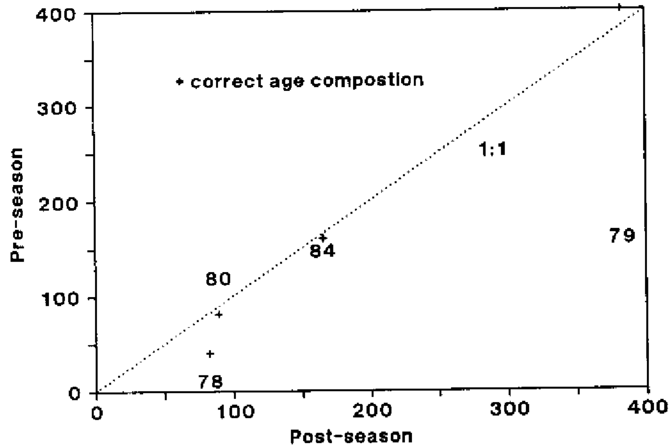


Figure 9. Pre- and post-season estimates of age-three herring abundance. a.) Proportion of age-three herring in pre-season surveys compared with the proportions in samples collected during the fishery. The years denote mean proportions and the lines plus and minus one standard deviation. b.) Recruitment predicted from preseason surveys compared with post-season catch-at-age estimates. The years denote the predictions; plus signs are predictions with the correct age composition.

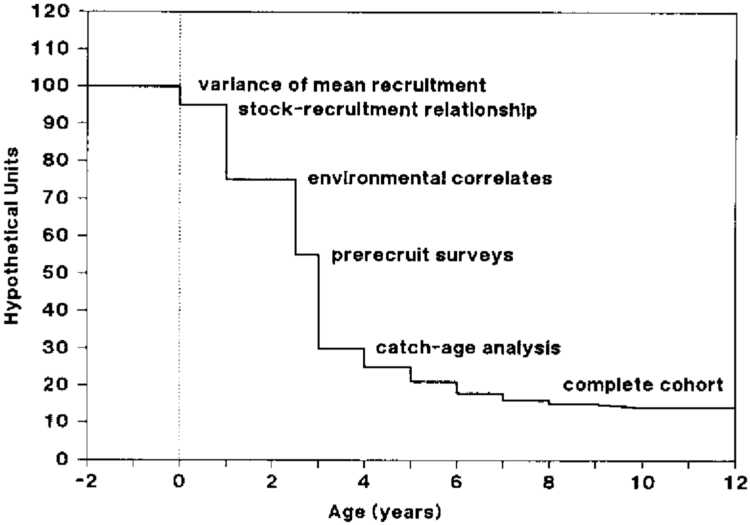


Figure 10. Hypothetical variance of recruitment estimates in relation to the age of the cohort.

DISCUSSION

Catch-at-age analysis was used to reconstruct the abundance of Sitka Sound herring from 1971 to 1989. Of the alternative spawning biomass estimates available, the aerial and spawn-deposition surveys were most consistent with the catch-at-age data. The pattern in biomass from 1971 to 1989 (Fig. 2) is only one half of a full abundance cycle. Aerial survey data indicate that abundance was as high in the late 1950s as in the late 1980s suggesting a full abundance cycle on the order of 30-40 years. Age composition data were not collected until 1971 and thus do not permit an age-structured stock reconstruction before that date. Abrupt declines and increases in abundance have occurred in practically every herring population that has been studied and are to be expected even if the cause of these abundance flips remains unexplained.

Observed variation in mean weight at age is consistent with the hypothesis of density-dependent growth. Thus the high abundance during the late 1980s could explain the decline in weight at age during that period. There remains, however, considerable variation in weight at age not explained by abundance. Evidence of density-dependent growth has also been found in Gulf of Maine (Anthony and Waring 1980) and Newfoundland herring (Winters et al. 1986).

Recruitment at age three appeared to have a weak relationship with spawning biomass (Fig. 8) with no evidence of compensation at high abundance. The tests of density-dependent growth and recruitment have low statistical power because there has been only one period of low and high abundance and there may be other explanations for the variation in growth and recruitment. More powerful tests of density dependence will be possible if and when Sitka herring abundance declines.

The Sitka herring fishery is sufficiently regulated to meet the quotas (Fig. 6). This management precision makes it possible to adjust the quota to optimize the harvest. Both components of the quota -- the optimal harvest rate and projected biomass – are uncertain. The current sliding scale harvest policy (Fig. 7) is deliberately conservative because the herring is a forage fish for other predators. Using a yield-per-recruit approach, Funk (1991) calculated a harvest rate, equivalent to $F_{0.1}$, which is substantially higher than the maximum of 20% used in Sitka. Simulation studies likewise indicated that harvest rates of about 30% would maximize the catch of herring in the Strait of Georgia, British Columbia (Hall et al. 1988).

Regardless of how the target harvest rate is determined, achieving that rate is difficult because the biomass is the sum of the survivors of the previous year's exploitable biomass plus new recruitment. Of the two components recruitment is the more variable and unpredictable. Recruitment could be forecasted from preseason surveys of the proportion of age three fish, or perhaps even from two-year-old abundance the previous year.

Continuing investigations in Sitka Sound (Haldorson and Collie 1991, Zebdi 1991) will identify the best predictive models of recruitment; these models are likely to include spawning abundance and one or more environmental indices. Even the best recruitment models have relatively high forecast error (Stocker and Noakes 1988) and therefore herring managers will continue to respond to abundance changes and not anticipate them. Recruitment models are useful for interpreting past abundance changes and for determining optimal harvest rates.

Existing management policies deal fairly well with minor year-to-year abundance changes. It is more important to understand the major abrupt flips in abundance such as occurred in Sitka in the late 1970s (Fig. 1). Are such flips purely the result of environmental variation or is fishing implicated as well? The history of other herring stocks indicate that flips in abundance are unavoidable although the declines may be hastened by fishing pressure. In Sitka, the lack of strong recruitment in recent years suggests that biomass will decline as the 1984 year-class dies off. The value of maintaining a large spawning population to enhance recruitment appears quite limited (Fig. 8). Nor is there a clear indication of depensation at low abundance. Thus there is no compelling biological reason for closing the fishery below a threshold biomass. However there may be a biomass threshold below which it is uneconomical to conduct a fishery at all. Rather than concentrating on a single biomass number, it may be more important for managers to conserve the different geographic components of the spawning population as total biomass declines.

ACKNOWLEDGEMENTS

Many of the basic data used in this study were collected by Dennis Blankenbeckler, recently retired from the Alaska Department of Fish and Game. Data were also furnished by Fritz Funk, Robert Larson and Tim Minicucci of ADF&G. Funding was provided by the Commercial Fisheries Division of ADF&G.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Management of North Sea Herring in the 1980s

A. Corten
State Fisheries Research Institute
Ymuiden, The Netherlands

Abstract

After a period of closed fishing from 1977-1983, the North Sea herring fishery rapidly increased to a catch level of more than 500,000 t after 1985. The fishery was regulated by a system of TACs and national quotas. Despite the occurrence of a series of strong year classes, the management objective of 1.5 - 2.2 million tonnes spawning stock size was not achieved within the period under review. Factors contributing to the slow recovery of the stock were the continuation of an illegal fishery for juvenile herring, over-estimates of stock size and too high TACs, and overshooting of national catch quotas. The problem of inadequate enforcement of catch quotas in certain areas had not been solved by the end of the decade. Stock estimates were based on acoustic surveys, larvae surveys, and recruit surveys. Estimates from acoustic surveys and larvae surveys were subject to large variations, and a combination of both methods was considered the best strategy for stock assessment.

1. Introduction

This paper reviews the developments in North Sea herring that took place after the previous international herring symposium in Nanaimo, Canada, in 1983. As such, the paper is a follow-up of the review presented by Jakobsson at that symposium (Jakobsson 1985).

At the beginning of the 1980s, all North Sea herring fisheries were closed, following the introduction of a ban in 1977. This fishing ban was a last resort, taken by managers after all other conservation measures in the 1970s had failed. Detailed descriptions of research and management in the period leading up to the closure have been given in the above review by Jakobsson, and also by Saville and Bailey (1980), and Burd (this symposium).

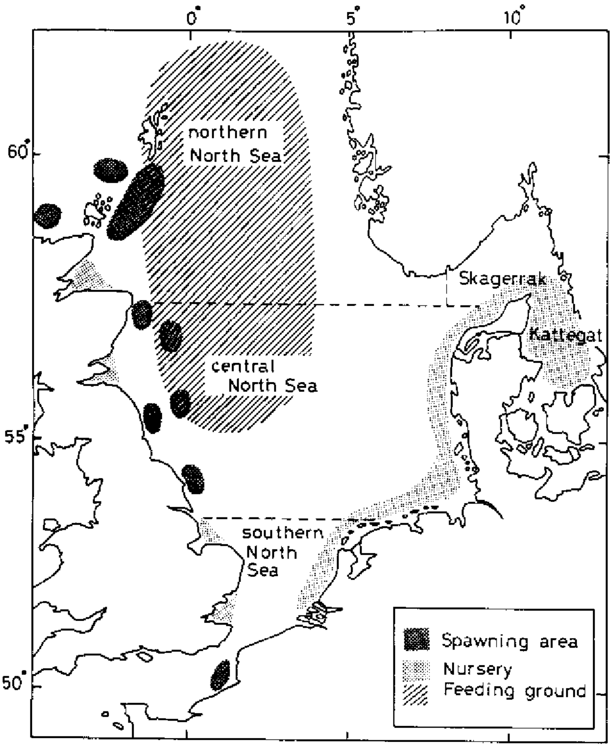

Figure 1. Distribution area of North Sea herring

After the closure of the North Sea herring fishery, biologists advised that the spawning stock should first be rebuilt to 800,000 t before a re-opening of the fishery could be considered (Anon 1978). The 800,000 t was assumed to be the minimum spawning stock that could produce average recruitment. The main task of biologists was then to monitor the growth of the stock, and to indicate when the minimum level of 800,000 t would have been reached.

After the re-opening of the fishery (1981-1983), catches were controlled by a system of total allowable catches (TACs) and national quotas. Biologists had to produce the necessary stock estimates on which the TACs were based. They also advised on optimum levels of fishing mortality, and on additional conservation measures. This paper will briefly describe the main assessment techniques used, and the biological advice presented to the managers.

The re-opening of the herring fishery occurred at a time when fishery management in the North Sea was in a state of turmoil. After the extension of economic zones in the North Sea in 1977, fish stocks had to be re-allocated among the coastal states, and this took many years of political negotiations. The problems with international management in the early 1980s also reflected on the biological research. Without clearly defined questions and feedback from managers, it was difficult for biologists to improve the quality of their advice.

Before stock assessment and management are discussed, some background information on the development of the North Sea herring stock and herring fishery in the 1980s is presented. Data have been taken from the annual reports of the ICES Herring Assessment Working Group, e.g. Anon 1990a.

2. Development of stock size and catches in the years 1980 - 1989

After a period of extremely low recruitment in the 1970s, year-class strength steadily increased in the early 1980s, and stayed at a high level for a number of years (Figure 2).

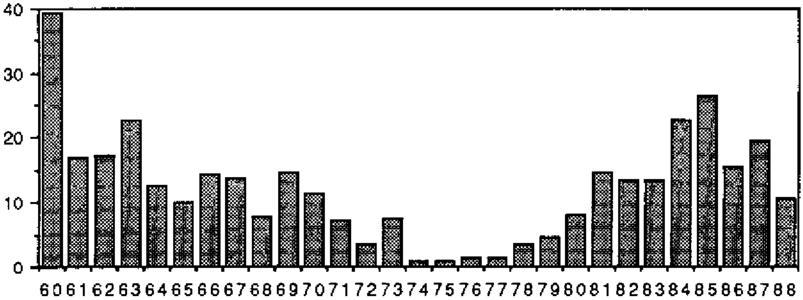

Figure 2. Year class strength of North Sea herring in billions at age 2.

The recruitment failure in the 1970s was initially attributed to a shortage of adult spawning fish. Therefore, the biological advice after the closure of the fishery was to rebuild the spawning stock to a minimum level of 800,000 t, supposedly necessary for the production of average recruitment.

In later years, doubts arose about the postulated stock/recruitment relationship. Corten (1986) noted that the stock that produced strong year-classes in the early 1980s was no bigger than the stock at the start of the recruitment failure in the early 1970s. He suggested that the recruitment failure in the 1970s was not merely the result of a stock/recruitment relationship, but that recruitment in the 1970s was also adversely affected by long-term hydrographic changes. In this respect it is interesting to note that recruitment to the adjacent herring stock west of Scotland collapsed nearly simultaneously with the North Sea recruitment, despite the fact that this stock had not been over-exploited to the same extent as the North Sea herring (Jakobsson, 1985).

Whereas the 1970s were a decade of exceptionnaly low recruitment, the 1980s were characterised by an unusual series of of good year-classes, culminating with the two strong year-classes 1984 and 1985. An interesting aspect of the recruitment series is the apparent trend that exists over the years, suggesting the influence of a long-term hydrografic effect. Although theories about a possible environmental effect on herring (and other pelagic species) have been put forward (Corten 1990), there is no clear evidence yet of hydrographic changes over the period concerned.

Spawning stock size (Figure 3) size increased gradually from about 100,000 t in 1980 to an estimated 1.2 million t in 1989. Impressive as this increase may seem, it fell short of the objective set by scientists and managers to create a stock between 1.5 and 2.2 million t. The main cause of the relatively slow recovery of the stock were the high catches taken in the latter half of the 1980s.

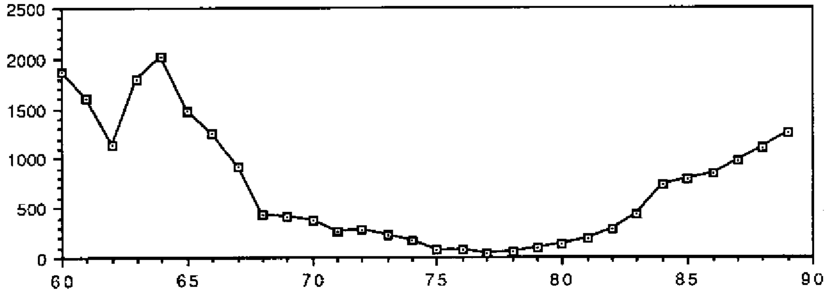

Figure 3. Spawning stock North Sea herring in '000 tonnes

Catches started at a modest level in the first years after the re-opening (Figure 4). The first permission for a re-opening of the fishery was given in the southern North Sea in the autumn of 1981. In the central and northern North Sea the fishery was not opened until 1983. Catches presented in figure 4 include both catches of adult herring in the directed fishery for human consumption, and catches of juvenile herring, taken in the industrial sprat fishery.

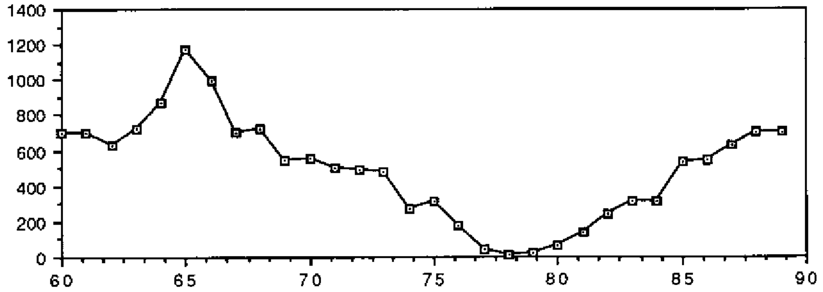

Figure 4. Catches of North Sea herring in '000 tonnes

Catches increased rapidly in the mid-1980s, despite a restrictive TAC regime. In 1985 the total North Sea catch surpassed the 500,000 t mark, which had been the average catch level in the early 1970s. A further increase in catches occurred in 1987, after the TAC for the total North Sea was drastically increased. By the end of the 1980s, total North Sea catches had levelled off at about 700,000 t, which is considered to be at least 100,000 t above the long-term sustainable yield (Anon, 1987). A large proportion of the catch (15 % in weight) consisted of juvenile herring that were taken as "by-catch" in the industrial fishery for sprat (see below).

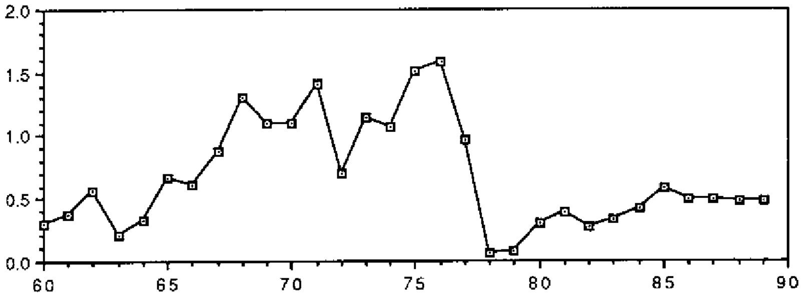

Figure 5. Fishing mortality on North Sea herring, ages 3-6.

Fishing mortality on adult herring (Figure 5), which had been close to zero during the early years of the closure, started to rise already in 1980 as a consequency of illegal catches, taken predominantly in the southern North Sea. In the first 3 years after the re-opening of the fishery in the whole of the North Sea, fishing mortality increased from 0.20 to 0.60. This was due to the sharp increase of catches, at a time when total stock size was still fairly low. When stock_size increased in the latter half of the 1980s due to strong recruitment, fishing mortality stabilised around 0.50.

3. Assessment Methods

Fisheries management through TACs is very dependent upon accurate estimates of stock size. In the case of the North Sea herring, three methods of direct stock estimation were used during the 1980s: larvae surveys, echo surveys, and tagging. Recruitment forecasts were based on a bottom trawl survey. Each of the assessment methods will be briefly described below.

Herring larvae surveys. Prior to 1980 surveys of herring larvae had already been conducted for many years in order to monitor changes in the various spawning populations of North Sea herring. Biologists had adopted this method because of its relatively simple technique (important in international programmes), and because it could detect differences in evolution between adjacent spawning stocks.

Until the early 1980s, results from larvae surveys were analysed separately for each part of the North Sea (northern, central and southern area). Within each of these areas, historic series of larvae data were regressed against stock estimates from VPA for that same area. These area-VPAs were based on the (unrealistic) assumption that all herring taken in the area throughout the year would have spawned there, and that no indigenous spawners were taken in other areas. The results of the regressions of larvae on VPA stock size were not very impressive; either the correlation between larvae and VPA stock size was not significant, or the regression had a large intercept. In both cases, results from larvae surveys could not be used to estimate stock size accurately from a predictive regression (Anon, 1985).

A new methods was introduced in 1985, which combined larvae data from all spawning grounds in the North Sea, and compared these with a VPA for the total North Sea. This approach turned out to be more successful. After corrections for sampling coverage (some areas were covered only during peak hatching, whereas others were sampled throughout the hatching period), the numbers of larvae <10mm were combined for all areas into a "larval abundance index" (LAI) for the total North Sea. This LAI was reasonably well correlated with VPA estimates of the total North Sea stock size (r = 0.844)

A further refinement was introduced in 1986, when a method was devised to utilise all length groups of larvae for the calculation of an index (Anon 1986a). The method back-calculated the number of larvae at the time of hatching by assuming certain constant values for daily growth and mortality. In this way, each size group of larvae sampled during the survey was projected backwards to the moment of hatching, and a "larval production estimate" (LPE) was calculated for the total North Sea. This index showed a higher correlation with VPA stock size than the LAI (r = 0.881, see Anon 1990b).

Despite these refined methods of analysis, larvae surveys were still unable to provide very precise estimates of stock size in the latest year. This is probably due to the fact that larval abundance is only an indirect function of stock size. Mortality in the egg- and early larval stage fluctuates from year to year, which introduces an error in the calculated stock size. This error apparently is quite large, and so the results from larvae surveys in a particular year cannot be used to provide an accurate point estimate of stock size (see below).

Acoustic surveys. Large scale acoustic surveys for herring in the North Sea were initiated in 1980, shortly after the closure of the directed herring fisheries. The objective of these surveys was to monitor the growth in stock size, and to indicate the moment when the stock would have reached a level at which the fishery could be re-opened. Obtaining reliable estimates from acoustic surveys, however, turned out to be more difficult than envisaged. Much effort was spent during the first years in finding the most suitable season for an acoustic survey. By the time the surveys started to produce accurate results, the herring fishery had already been opened on the basis of other information. However, because of the great demand for fishery independent stock estimates under the TAC management regime, acoustic surveys were continued also after the re-opening of the fishery in 1983.

After initial trials, the period July/August was selected as the best time for an international survey. In most of the distribution area, the herring at that time start aggregating in bottom or midwater schools that are easily recognised on the echo sounder. The area that has to be covered by the survey is very large: approximately 100,000 square miles. Four countries (Scotland, Norway, Denmark, and Sweden) have participated in the programme in recent years, each putting in about 3 weeks of research vessel time.

Acoustic instrumentation used by the various countries is to some degree standardised (SIMRAD EK-400 scientific sounders, different integrators), and the same T/S relationship is used by all participants.

Tagging. During the period of closed fishing, also a tagging programme was initiated to provide direct stock estimates using the Peterson method. The type of tag selected was the magnetic microwire tag manufactured by Northwest Marine Technology, Inc., Shaw Island, Washington, USA. The technique had been developed for salmon fingerlings, and the tag size had to be increased for herring, which caused some initial technical problems. After initial field experiments with the detection method and a pilot tagging and monitoring experiment in the Firth of Clyde (Morrison, 1982), a full scale experiment was started in the Shetland area in 1983.

A total of 48,000 tags was released in 1983, and another 10,000 in 1984. Tagging mortality and tag shedding were estimated to be very low (together not more than 10%). Recovery of the microwire tags presented some problems because of the minute size of the tag. Very sensitive equipment, needing constant supervision, had to be used for detection. It was not possible, therefore, to screen large commercial catches on a routine basis. Instead, only catches taken by research vessels, or by specially chartered commercial trawlers would be monitored for tags. The total amount of catch screened was rather small: 1,580 t in 1984 and 1,259 t in 1985. This yielded a total of 48 recoveries in both years combined .

Although the experiment demonstrated the feasibility of the microwire tagging method for herring, the results obtained did not permit very accurate stock estimates to be made. The reason was that fish tagged in the Shetland area consisted mainly of the older stock component (year-classes 1979 and older). At the time of the recovery operations in 1984 and 1985, the stock had been rejuvenated by the recruitment of strong year-classes 1980, 1981, and 1982. Although the tag recoveries permitted a fairly precise estimate of the older stock component, total stock size (including the younger year-classes) could not be estimated within a reasonable margin of precision (Morrison, 1986).

Early 1986 it was estimated that a continuation of the tagging experiment would require the annual release of some100,000 tagged fish, and annual monitoring levels of several thousand tonnes. At this point it was decided to terminate the tagging programme, and to concentrate resources on the other existing assesment programmes.

The combination of various indices of stock size into one estimate.
In recent years, indices of adult stock size have been derived both from herring larvae surveys and from acoustic surveys. Table 1 compares the results of these programmes with results from the converged VPA.

Year	larvae surveys	echo surveys	VPA
1972	146	-	290
1973	116	-	236
1974	77	-	164
1975	61	-	88
1976	20	-	85
1977	-	-	58
1978	108	-	79
1979	224	-	123
1980	365	-	148
1981	636	305	214
1982	480	402	293
1983	635	440	451
1984	871	807	742
1985	1022	697	799
1986	1244	942	892
1987	699	667	
1988	1249	801	
1989	1287	1490	

Table 1. Estimates of spawning stock size (thousand tonnes)

It is seen that both acoustic and larvae estimates are quite variable, and this implies that neither of these estimates can be used directly to predict adult stock size. The best way to use information from these surveys is to look at trends over the last years, and to match these with trends from VPA.

The ICES herring working group has used a standard computer programme (RCRTINX-2) to regress each time series of indices individually with the converged part of the VPA. For the 3 most recent years, predictions based on these regressions were weighted inversely to their variance to give average weighted predictions of stock size in each year. These predicted stock sizes are then compared with a series of VPA-runs, based on different input-Fs. The VPA that best matches predicted stock sizes over the last 4 years (least sum of squared residuals) is chosen as the starting point for stock prediction and management advice.

Recruitment forecasts. After the re-opening of the herring fishery in 1983, the stock of older herring in the North Sea was still relatively small and the incoming year classes made up a large proportion of the catch. The advice for TACs, therefore, depended heavily on estimates of incoming recruitment.

Fortunately, a programme of annual recruit surveys existed already since the mid 1960s: the "International Young Fish Surveys". This was an annual exercise in which at least 7 countries participated. Initially intended as a survey of juvenile herring, the programme was expanded in the 1970s to include juvenile gadoids and other species of commercial interest. While there was some diversity in fishing gear during the earlier years, a high degree of standardization was achieved after 1978 when the French GOV-trawl ("chalut à Grande Ouverture Verticale") was adopted as standard gear for the survey. For a description of survey methodology, the reader is referred to the survey manual (Anon, 1981)

Sampling of juvenile herring during the IYFS in February is aimed at 1.5-year-old herring. Results from the GOV-trawl sampling are strongly correlated with VPA-estimates of year class strength at the corresponding age ($r = 0.95$).

At the time of the IYFS (February), the next younger year class (6 month old) is also present in the North Sea. This age group is still in the larval stage, with individuals measuring 20 - 40 mm, and it is not caught in the GOV-trawl. In order to obtain information on this age group, a sampling scheme with Isaacs-Kidd midwater trawls (IKMT) was initiated in 1978, in conjunction with the IYFS.

Results from the IKMT also show a correlation with VPA-estimates of the year class at the corresponding age. This correlation is not as strong as the one for 1.5 year-old herring, and until the late 1980s the IKMT-index was only used as a qualitative indication of year-class strength.

4. Biological Advice

Biological advice on North Sea herring is provided annually by the International Council for the Exploration of the Sea (ICES) through its specialised herring assessment working group, and its Advisory Committee on Fisheries Management (ACFM).

Table 2 gives a summary of the TACs advised by ACFM in the period 1980-89. Also shown in this table are the official TACs agreed by managment bodies, and the actual catches taken by the fishery.

year	central + northern North Sea			southern North Sea		
	advice	TAC	catch	advice	TAC	catch
1980	0	0	18	0	0	43
1981	0	0	99	20	20	42
1982	0	0	167	60	72	69
1983	62	72	244	36	73	64
1984	95	-	272	49	-	46
1985	166	-	467	62	90	70
1986	235	500	493	42	70	51
1987	600	560	548	10	40	42
1988	500	500	646	15	30	52
1989	484	484	620	30	30	79

Table 2. TAC advice and agreed regulations for North Sea herring, compared with actual catches (in '000 tonnes)

It is seen that the first catches of North Sea herring were allowed in the southern sector, starting from 1981. The advice to re-open the fishery in this sector was based upon high catches of herring larvae in the winter of 1980/81, and on reports of large concentrations of fish on the spawning grounds. As there were no signs of a substantial recovery in the central and northern North Sea, ACFM at that time concluded that the southern North Sea stock could be considered as a separate mangement unit, and that fishing in this area could be resumed while the rest of the North Sea still remained closed.

Once the southern North Sea had been designated a separate management unit, ACFM each year had to advise a separate TAC for this area; also when the remainder of the North Sea was opened up for the fishery in later years. The provision of separate advice for the southern stock turned out to be rather difficult. An analytical assessment of the southern North Sea stock, based on VPA, was not feasible since a large proportion of the catch was taken in the central and northern North Sea. Another problem in making an analytical assessment for the southern North Sea was the prediction of recruitment. The International Young Fish Survey only yielded estimates of total recruitment to all North Sea stocks combined. No reliable method of racial separation could be developed to separate the southern North Sea recruits from the other North Sea juveniles.

The problems in making accurate assessments for the southern North Sea stock are reflected in the highly fluctuating TACs that were advised for this area. After a period of relatively high TACs in 1982-85, scientists abruptly changed ideas about the state of the stock, and advised very low TACs in the following seasons. In 1988 ACFM accepted the fact that an analytical assessment for the southern North Sea stock was impossible, and they recommended an empirical approach for this area. The TAC should be set at an arbitrary level, well below that in the early 1980s, and be kept at that level for a number of years, in order to see how age composition and mortality estimates would react. Since 1989 the TAC has been set at 30,000 tonnes, but actual catches have been much higher due the fact that fishermen reported their excess catches as coming from the central North Sea.

In the central and northern North Sea the fishery was not re-opened until 1983. The advice to open the fishery was based mainly on the prediction (based on results from the IYFS) that the recruiting year class 1980 would be strong. The first years after the re-opening of the fishery, ACFM advised rather low TACs, corresponding with the $F_{0.1}$ value of 0.13 (for a definition of biological reference points used by ICES see Anon 1989). In 1986 ACFM changed its policy on and advised a TAC based on the F_{max} value of 0.33. This resulted in an increase in recommended TAC for the central and northern area from 235,000 t in 1986 to 600,000 t in 1987. Even management bodies thought this increase was too steep, and they settled on a TAC of 560,000 t. New assessments in subsequent years indicated that the advice given in 1986 had been too optimistic, and ACFM had to reduce the TAC-advice for the next years again.

5. Management

The TAC and quota system.

In the mid-1970s fishery managers in the North Sea had chosen the TAC-system to manage fish stocks in international waters. In the case of pelagic fisheries, this was probably a sensible choice. Fishing mortalities in these stocks can be better controlled by restricting catches than by restricting effort. A TAC system has the extra advantage that it allows the allocation of fixed proportions of the catch to various countries; something that is very attractive from an administrative point of view.

The only problem with a TAC system was to get agreement on the proportions of the TAC that each country was entitled to. Within the EC, countries were negotiating from 1976 until 1983 before agreement was reached on this issue. Of all fish species in community waters, the North Sea herring presented the biggest problems. After the EC-countries had reached an agreement, negotiations were started with Norway, which country also had an interest in North Sea herring. To discuss the "zonal attachement" of North Sea herring (and other species), a special EC/Norwegian study group met in Hamburg in 1984. On the basis of information then available, they concluded that only 4% of the total North Sea herring stock was present in Norwegian waters, and the rest in the EC zone. Norwegian fisherman did not agree with this assessment, and to prove their point, they caught 80,000 t of herring in the Norwegian zone in the following season (out of a total North Sea adult catch of 450,000 t). A new meeting of the Norwegian-EEC joint scientific group was convened in 1986, and this time it was concluded that the distribution of North Sea herring had changed since the early 1970s, and that the proportion of North Sea herring in the Norwegian zone varied between 22% - 30%, depending on the total size of the stock. This put the Norwegian government into a stronger bargaining position, and in 1986 an agreement was reached between EC and Norway in which 27% of the North Sea herring TAC was allocated to Norway (at stock sizes below 2.2 million ton).

The administration of national quotas was different in each country. Sometimes national governments directly administered the quotas, and sometimes this task was delegated to producers organisations. National quotas were sometimes divided into ship- of company-quotas, or they were applied to the entire fleet.

Enforcement of national quotas

Enforcement of the national quotas was rather slack in some countries after the re-opening of the fishery. Independent estimates of catches made by fisheries scientists indicated an overshooting of national quotas by a factor 3 in some areas. This resulted in total catches that were considerably greater than the agreed North Sea TAC (table 2). National inspection services were not always equipped to monitor individual landings, and governments were not really trying to improve things. It was only after the EC set up an international inspection team that deficiencies in enforcement in the various countries were exposed, and national governments were forced to step up enforcement activities. By the late 1980s, inspection of landings in the EC-countries was gradually improving, although misreporting in some areas still occurred. The main cause of TAC overshooting in later years was the by-catch of juvenile herring in the sprat fishery (see below).

Discards not included in TAC and quotas

Managers in the EC interpret TACs as total allowable landings rather than as catches. This means that discards of herring at sea are not counted against national quotas. Only Norway has legislation to prevent fish above legal size being discarded at sea. Within the EC-zone, deliberate discarding of legal sized fish may occur in various situations. In some countries, boats have individual quotas per trip or per week. Accidental catches in excess of the boat's quota have to be passed to other vessels, or else dumped. Most freezer trawlers are equipped with sorting machines that allow grading of catches. In times of low prices for small herring, boats dump the smallest size groups in order to fill their quota only with herring of the highest value. A similar situation occurs in the roe fisheries, where the boats are fishing only for herring in a particular maturity stage.

All these practices are legal within EC regulations, and neither administrators nor scientists have a clear idea as to how this situation can be improved. A ban on discards, as has been introduced in Norwegian waters, is not considered feasible by the EC in view of the likely enforcement problems.

Catches of juvenile herring in the sprat fishery

Another management problem exists in the by-catch of juvenile herring in the sprat fisheries. Sprat is fished mainly for reduction purposes, and throughout most of its distribution area the species occurs mixed with juvenile herring of the same size. In order to prevent fishermen from fishing deliberately for juvenile herring, a by-catch regulation was introduced in 1976. This regulation, stated that no industrial catch of sprat should contain more than 10% of juvenile herring.

During the closure of the North Sea herring fisheries, the sprat fishery was allowed to continue, despite the fact that small quantities of juvenile herring were taken as by-catch in this fishery. Sprats were very abundant in the North Sea in the 1970s, whereas juvenile herring were scarce. The percentage of juvenile herring in sprat catches was nearly always less than 10%, even without fishermen actively trying to avoid the young herring.

The situation changed drastically in the early 1980s, when the sprat stock suddenly declined and herring recruitment increased. The ratio of juvenile herring to sprat increased sharply, and the former sprat fishery turned into a fishery for juvenile herring. Since sampling of industrial catches was very limited (unco-operative fishermen) it took biologists and fishery inspectors over a year to dicover what was really happening. By that time, an estimated 80,000 t of 1-year-old herring had already been caught in the North Sea in 1981 (figure 6).

The news that massive catches of juvenile herring had been taken by the industrial fishery, at the time when consumption fishermen were still waiting for the official re-opening of the herring fishery, caused sharp protests from scientists and fishermen. As the biggest catches seemed to occur in coastal waters of the eastern North Sea (the traditional nursery area for herring), ACFM in 1982 recommended the introduction of a "sprat box" in this area, where fishing with small meshed gear for small clupeoids was banned. This sprat box along the Danish coast was came into force in 1983. Smaller sprat boxes were also defined in herring nurseries along the along the UK coast.

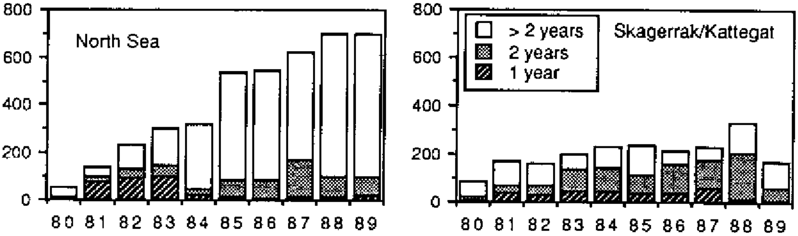

Figure 6. Catches of juvenile herring (1- and 2-years-old) in North Sea and Skagerrak/Kattegat. Weights in '000 tonnes.

The sprat box along the Danish coast has been very useful in protecting the 1-year-old herring of 8-10 cm; after the introduction of the box, catches of this age group declined considerably (figure 6). However, the sprat box covers only the shallow coastal area, up till 40 miles affshore, and once the herring grow to a size of about 15 cm, they migrate out of the sprat box into deeper water. Here they may again become a target for the "sprat" fishery.

Catch statistics for the late 1980s show that despite the existence of the sprat box, a total of about 100,000 t of juvenile herring was taken each year by the industrial fishery. Obviously, the 10% by-catch rule was not observed by the fishermen, nor enforced by the inspectors. This is not surprising as the distinction between sprat and juvenile herring is difficult, even for a trained technician. Sprat fishermen can not be expected to scrutinise each kilogramme of catch for the possible presence of herring. Also, in areas where both sprat and juvenile herring occur, it is unpredictable which species will dominate in the next haul. Probably he best way to restrict by-catches of juvenile herring in the sprat fishery is to restrict the sprat fishery itself. This was the approach taken in another nursery area of North Sea herring: the Skagerrak and Kattegat.

Also in this area a shift of industrial catches from sprat to juvenile herring occurred in the early 1980s. Catches of juvenile herring (mainly North Sea recruits) soared to 170,000 t in 1983. Administrators were not able to enforce the existing 10% by-catch rule for herring in the sprat fishery; the strict application of this rule would effectively have stopped all sprat fisheries. In an attempt to protect juvenile herring, but at the same time allowing some industrial sprat fishery, scientists advised the use of a TAC for "mixed clupeoids" (Anon 1986b). This TAC should be set at a sufficiently low level to reduce the total volume of industrial catches. In this way, catches of juvenile herring would be automatically reduced. The mixed clupeoid TAC was initially set at a level of 80,000 t (in 1986), which still resulted in a rather high mortality among juvenile herring. In 1989, following protests from the North Sea herring industry, the TAC for mixed small clupeiods in Skagerrak/Kattegat was reduced to 65,000 t.

Enforcement of the mixed clupeiod TAC was slack in 1986-88, but it seemed to have improved in 1989.

A major question in the discussion about catches of juvenile herring was the loss to the consumption fisheries. For many years, countries with industrial fisheries argued that natural mortality in juvenile herring was very high, and that catching a certain amount of juveniles would not affect the fishery for adult herring. The ICES herring working group tackled this question on several occasions, each time using new estimates of natural mortality that came out of a multispecies VPA carried out by the ICES ad hoc multispecies working group. The latest estimates (Anon 1988) were that a catch of 1 kg juvenile herring would cause a loss of 1.75 kg to the catch of adult herring. This estimate still was very dependent on the value used for natural mortality, and on the season and area where the juvenile herring was caught.

The main political problem in restricting the catches of juvenile herring was that by far the largest sacrifices in the industrial fisheries would have to be made by one country, Denmark, whereas the benefits would go to all countries around the North Sea. The European Community would have been the ideal organisation to share losses and gains from restricting the industrial fishery among all countries involved. However, when EC in 1989 looked into this problem in relation to the sprat fishery in Skagerrak/Kattegat, they concluded that given the low market price for adult herring, the economic gain of reducing catches of juvenile herring would be very small. They were not prepared, therefore, to susidize a reduction of the sprat fisheries in this area.

6. Conclusions

Despite the shortcomings listed in the previous section, we can conclude that management of North Sea herring in the 1980 has been moderately successful. Spawning stock size at the end of the decade was an order of magnitude larger than at the beginning, and although TACs may temporarily go down in future, there is no imminent danger of stock collapse or fishing bans.

The main problems that remain are the catches of juvenile herring in the industrial sprat fishery, and the discards of low quality adult herring in the consumption fisheries. Present by-catch regulations for the sprat fishery are not practicable, and should be replaced by overall restrictions on the fishery for small clupeoids. Discards at sea are difficult to prevent, unless a fishery inspector is placed on board every fishing vessel. This will lead to extravagant inspection costs.

Because the herring market in Europe has been saturated in recent years, fishery managers no longer give a high priority to conservation measures in the herring fishery. One example is the unwillingness of the EC to reduce sprat catches in order to protect the juvenile herring. Maybe this attitude will change if recruitment to the North Sea stock would drop again in future, and TACs for adult herring would have to be reduced.

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Oct. 1990, Anchorage, Alaska

Pacific Herring Management in the Bering and Chukchi Seas: A Federal Perspective

H.J. Weeks
North Pacific Fishery Management Council
Anchorage, Alaska

ABSTRACT

Extension of U.S. fisheries jurisdiction to 200 nautical miles under the Magnuson Fishery Conservation and Management Act displaced substantial offshore herring harvests by Japan and the Soviet Union averaging some 48,000 metric tons annually. The North Pacific Fishery Management Council prepared several iterations of a fishery management plan for Pacific herring in the Bering/Chukchi Seas which attempted to provide opportunities for U.S. fishermen to take herring in directed offshore fisheries, while protecting traditional inshore subsistence and commercial fisheries. The final iteration of this plan was adopted by the Council in September 1983, and submitted for review and approval by the Secretary of Commerce, but was withdrawn by the Council in March 1984. The plan has remained dormant pending the collection of further information on stock distribution and composition, migration patterns, and biomass estimates.

In 1990, the Council responded to the decline in Bering Sea herring stocks due to repeated recruitment failure with measures to limit the bycatch of herring in groundfish trawl fisheries. A central issue in deliberations of both a herring fishery management plan and bycatch management is the impact of offshore mixed stock harvests (direct or bycatch) on traditional inshore subsistence and commercial fisheries.

INTRODUCTION

Pacific herring (Clupea harengus pallasi) have been harvested commercially along the Bering Sea coast of Alaska since the early 1900s, and have been harvested for subsistence in western Alaska since at least 500 B.C. (Skrade, 1980). Traditionally, this species has been harvested in subsistence and inshore commercial fisheries managed by the State of Alaska on a single stock basis. This management philosophy entails limiting harvests to near-shore areas where they become segregated; inadvertent overexploitation of individual stocks while in mixed offshore aggregations is thereby avoided (Skrade, 1980).

In most areas off Alaska, herring remain in coastal waters for most or all of the year. In the Bering Sea, however, many herring stocks undertake substantial migrations from offshore wintering areas northwest of the Pribilof Islands to spawning and feeding areas in near-shore coastal waters (Wespestad, 1978; Wespestad & Fried, 1983; Funk, 1990) (Fig. 1). The availability of commercially valuable concentrations of herring in offshore waters was unknown until the Soviet fisheries investigations which began in the late 1950s (Favorite, Laevastu & Straty, 1977). Prior to the extension of U.S. jurisdiction to 200 miles, substantial fishing operations for herring were conducted by the Soviet Union and Japan in the Bering Sea beginning in 1959. These combined harvests averaged over 48,000 metric tons during the period 1962-1976 and peaked at some 145,000 metric tons in 1970 (Wespestad, 1978; Skrade, 1980; NPFMC, 1983).

Pursuant to the Magnuson Fishery Conservation and Management Act of 1976 (MFCMA); the North Pacific Fishery Management Council (NPFMC) is responsible for the management of fisheries in the U.S. Exclusive Economic Zone (EEZ), extending from 3 to 200 miles, off of Alaska[1]. Extension of federal jurisdiction created a potential management conflict over a resource found in both state and federal areas of jurisdiction. On the one hand, the state considered the herring resource to be fully utilized in its inshore subsistence and commercial fisheries. On the other hand, the MFCMA encourages the development of underutilized fishery resources and charges the Council to achieve and maintain optimum yield to the nation from each fishery. U.S. joint venture and domestic fishing concerns rapidly developed and expressed interest in opportunities to replace foreign offshore herring harvests with their own, on the assumption that the resource could support both inshore and offshore harvests.

A preliminary groundfish management plan (PMP) for the Bering Sea was prepared by the National Marine Fisheries Service and implemented on March 1, 1977. This plan provided for an allowable catch of 20,400 metric tons of herring, a substantial reduction from the catch levels of the previous decade. However, in February 1980, the provisions of the PMP which allowed for foreign or joint venture harvests of herring were invalidated by a U.S. District Court decision. Consequently, at the time of the 1980 Alaska Herring Symposium, the Council was in the process of developing separate groundfish and herring fisheries management plans for the Bering Sea There was no offshore fishing for herring at that time: foreign and joint venture efforts had been prohibited by the above-mentioned court decision, Alaska state law prohibited offshore herring fishing under its jurisdiction, and domestic offshore fishing in areas under federal jurisdiction had not yet developed. However, the PMP did not regulate potential domestic operations and a strong need was perceived to provide the

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[1] The EEZ was formerly known as the Fishery Conservation Zone, or FCZ, until 1983.

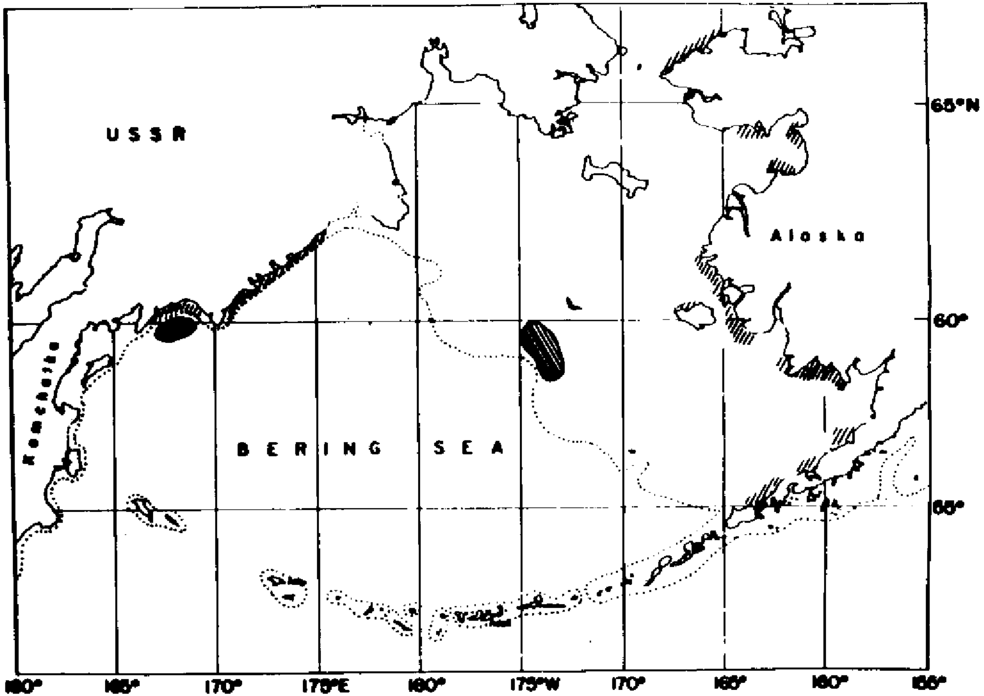

Figure 1 --Location of major herring spawning and wintering areas in the Bering Sea.
From Wespestad 1978

opportunity for such a potential fishery in response to industry interest while coordinating federal and state management activities (Duff et al., 1983; Glock et al., 1983).

During the following three years, the Council developed several iterations of a Bering-Chukchi Sea herring fishery management plan (FMP). The final version was adopted by the Council in September 1983. It was submitted for review and approval by the Secretary of Commerce, and then withdrawn in March 1984. This action was based (1) on the opinion of NOAA General Counsel that the FMP could not be approved because it could not provide a basis for the prevention of overfishing because it had no jurisdiction over the state managed fishery and, (2) the need to collect and assess more information on herring stocks, stock separation, and migration. This additional information was necessary to resolve questions concerning whether an offshore herring fishery in Federal waters could be permitted given that priority in the FMP was addressed to subsistence and inshore commercial fisheries managed by the state.

Since the demise of the NPFMC Herring FMP, little federal activity took place to manage herring. Herring was a prohibited species under the terms of the Bering Sea/Aleutian Islands Groundfish fishery management plan implemented on January 1, 1982; herring taken in foreign and domestic groundfish fisheries had to be returned to the sea as quickly as possible. However, groups dependent on herring in western Alaska became increasingly concerned that the incidental catch of herring in offshore groundfish trawl fisheries had an impact on the subsistence and commercial inshore herring fisheries. These interests have worked actively since 1985 to persuade the Council to impose limits on the incidental catch of herring in groundfish fisheries (H. Sparck, pers. comm.). In 1990, it became apparent that the declining stock size of eastern Bering Sea herring threatened the inshore subsistence and commercial fisheries of Nelson Island and Nunivak Islands. While the decline in the EBS herring stocks is principally due to repeated recruitment failure, increasing concerns were expressed over the magnitude of herring interceptions in groundfish trawl fisheries.

The balance of this paper describes the provisions of the Council's herring management plan, and its more recent efforts to address herring bycatch in the groundfish fisheries.

The NPFMC Bering-Chukchi Sea Herring Fishery Management Plan

Development of the NPFMC Herring Fishery Management Plan represented efforts to balance traditional inshore subsistence and commercial fisheries, managed as discrete stocks by the State of Alaska, with opportunities for full utilization of the resource by commercial offshore fisheries.

When development of the herring FMP was initiated, the total herring harvests were low relative to the yield believed to be available from the resource--subsistence needs and harvests were low, the inshore commercial fishery was undeveloped and little or no offshore fishing was taking place, while the maximum sustainable yield from the resource was estimated to be on the order of 48,000 mt on the basis of historic catch from 1962-1976 (Wespestad, 1978; Duff et al., 1983; NPFMC, 1983; Pete, 1989).

During the development of the FMP, domestic inshore harvesting capacity and demand increased substantially, and by 1980 it exceeded the total harvest which would be allowed by FMP provisions. However, domestic offshore operations, while still undeveloped, were also unregulated and the potential existed for overfishing herring if inshore and offshore harvests were not managed in a coordinated fashion (Duff et al., 1983).

The Plan, as finally adopted by the Council and submitted to the Secretary of Commerce in 1983, was limited to the management of herring fisheries in the EEZ of the Bering and Chukchi Seas. Subsistence and inshore commercial fisheries were beyond the scope of the plan and were left to the management authority of the State of Alaska. The plan's principal impact would have been to ensure coordination and cooperation among management agencies.

The Plan specified priorities for the fisheries which utilize herring stocks:

1. Subsistence fisheries
2. Inshore commercial fisheries
3. Offshore domestic fisheries

Based upon these priorities, the Plan was developed to address the following specific objectives:

1. To conduct any harvest of herring in the EEZ in such a manner to insure:

    a. Maintenance of the herring resource at a spawning level that will provide the maximum production of recruits.
    b. Maintenance of the subsistence herring stocks and the subsistence fishery.
    c. Maintenance of the herring resource at a level that will sustain populations of predatory fish, birds and mammals.
    d. Development and maintenance of the inshore commercial fisheries.

2. Consistent with objective 1, promote full utilization of the herring resources by domestic offshore fisheries.
3. Provide to the extent possible a unified management regime between federal and state jurisdictions.

Within these objectives, the Plan was structured to calculate an **Acceptable Biological Catch (ABC)** by applying an exploitation rate to the current spawning biomass of herring. After making allowances for subsistence and inshore commercial fisheries, an **Optimum Yield (OY)** would be made available for offshore harvest.

Spawning biomass (B) estimates were to be derived annually from ADF&G aerial surveys of discrete stocks during the spring spawning period, and supplemented by virtual population analysis applying data from the previous years catch surveys and commercial catch data. The spawning biomass estimates would deliberately exclude

Nelson Island stocks to provide a modest additional degree of protection for the subsistence fishery.

The **Annual Exploitation Rate** (E) was to be determined based upon a ratio of current spawning biomass (B) to MSY biomass. Because of the uncertainties involved in determining MSY, a maximum exploitation rate was set at 20%. MSY was estimated to equal 48,712 mt based upon the average annual catches from 1962 through 1976, excluding 1967 due to lack of data. The logic underlying the calculations was circular, as an exploitation rate of 20% during these years was assumed. Consequently, MSY spawning biomass (B_{msy}) was estimated as 243,560 mt.

Acceptable Biological Catch would annually be calculated as the appropriate exploitation rate applied to the current spawning biomass.

$$E = 0.20 \times B/B_{msy}$$

$$ABC = E \times B = [B/B_{msy} \times 0.20] \times B$$

Acceptable Biological Catch would apply to all harvests taken from eastern Bering Sea herring stocks; the State of Alaska would maintain management authority over subsistence and inshore commercial fisheries. Any remaining quantity of fish (the difference between ABC and State-managed inshore harvests) would be available as Optimum Yield (OY) which could be taken in the EEZ. This OY was divided into three components in order of priority:

1. Allowable Incidental Catch
2. Summer Apportionment
3. Winter Apportionment

Allowable Incidental Catch (AIC) in groundfish fisheries calculated as 0.1% of groundfish allocations. Domestic vessels could retain their AIC of herring, until that time that the AIC quota was reached. Upon attainment of an AIC quota, the Regional Director would close all or part of the Herring Winter Savings Area (Fig. 2) would be closed to trawl vessels from October 1 through April 1 of the following calendar year. Once the AIC was reached, domestic vessels would no longer be allowed to retain herring taken as bycatch in groundfish fishing operations anywhere in the Bering Sea.

Similarly, a **Foreign Prohibited Species Catch** (PSC) limit equal to 0.1% of a nation's groundfish allocation would be designated annually for each nation with a groundfish allocation in the Bering Sea/Aleutian Islands management area. It would be allocated for the period April 1 through March 31, and would be inseparable from the groundfish allocations. Foreign flag vessels would be prohibited from retaining incidentally caught herring. Once a nation's PSC limit had been attained, the winter savings area (Fig. 2) would be closed to trawl vessels of that nation through March 31 of the following calendar year.

The Herring Winter Savings Area was selected to provide protection to herring in those areas northwest of the Pribilof Islands where they are known to aggregate during the winter months (Fig. 1).

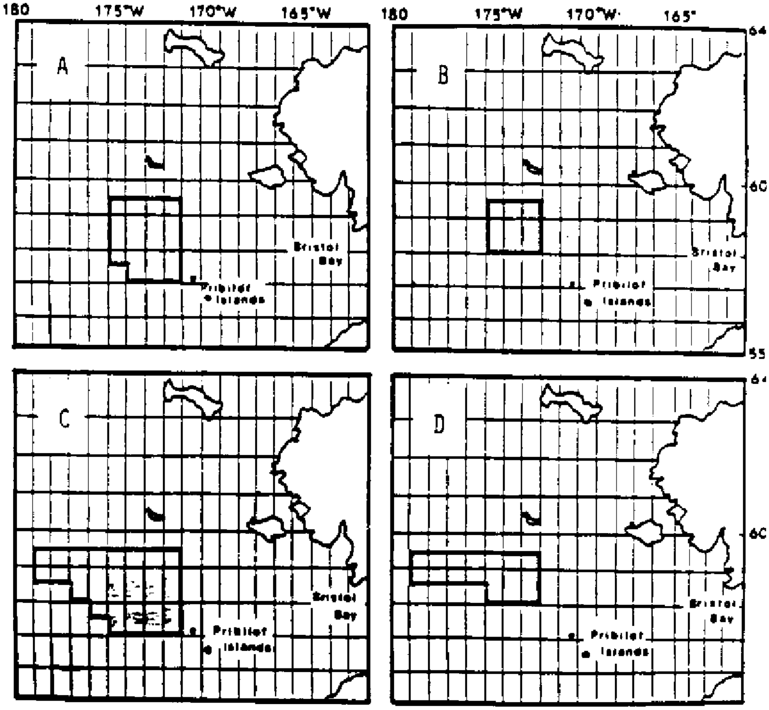

Figure 2 Options considered for the Herring Savings Area. Area C provides the maximum protection to the wintering herring populations.
From NPFMC 1983.

Summer Apportionment of the OY would be 2,000 mt and made available for harvest south of 55° 47' N. from July 1 through September 30. The fishery would close when the summer apportionment was reached, and the summer OY could be reduced based upon any of the following factors:

1. Extent to which the subsistence and inshore commercial fisheries harvested or overharvested the ABC.
2. Condition of the spawning stocks of herring with special focus on the subsistence stocks.
3. Abundance of spawning herring and their spawning success.
4. Age composition of the spawning herring.
5. Recruitment to spawning stocks of herring.
6. Variation in exploitation rates between the spawning stocks.
7. Changes in the State's management of the inshore commercial fishery.

The **Winter Apportionment of OY** for directed domestic offshore fishing would be available for harvest throughout the management area from October 1 to March 31. It would be determined conservatively based on a fraction of the ABC remaining after other priorities were met:

1. Subsistence Adjustment (500 mt)
2. Inshore Commercial Harvest
3. Allowable Incidental Catch (domestic trawl vessels)
4. Prohibited Species Catch (foreign trawl vessels)

Winter Apportionment of OY = 50% x (ABC - Inshore Commercial Harvest[2] - Subsistence Adjustment - AIC - PSC).

The 50% reduction was intended to insure that the winter apportionment remained conservative to protect priority subsistence and inshore commercial fisheries under state jurisdiction and management. The winter apportionment of OY was further limited by having an upper cap of 10,000 mt, and it would be set at 0 if the formula calculated it as less than 2,000 mt, or if the current herring spawning biomass is less than 50% of MSY biomass.

The winter OY could be further reduced by the Council or the Regional Director, in consultation with the State, if either finds a serious problem due to the same six factors listed above for the summer apportionment of OY.

HISTORY

The Plan was approved by the Council on September 28, 1983 and submitted to the Secretary of Commerce for review and approval. In March 1984, the Council voted to withdraw the plan based on advice from NOAA General Counsel that it was unlikely to be approved. Specifically, NOAA GC indicated that over the preceding several years, the State of Alaska had managed the inshore fisheries in a way that the ABC as calculated in the FMP for the combined inshore and offshore fisheries had

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2. The Inshore Commercial Harvest includes both the commercial harvests managed by the State of Alaska and the Summer Apportionment of the OY.

been exceeded. Because the plan could not impact upon these results, the FMP could be challenged as (1) unnecessary under the MFCMA and not cost-effective, (2) in violation of the MFCMA National Standard 1 requirement that FMP measures prevent overfishing, (3) in violation of the National Standard 3 requirement that a stock be managed as a unit throughout its range, and (4) in violation of the National Standard 4 requirement that allocation of fishing privileges be fair and equitable to all fishermen (due to the FMP's deference to inshore subsistence and commercial fisheries) (Travers, 1984).

In May 1984, the Council voted to take no further action on the plan pending the availability of more scientific data on biomass, stock distribution and composition in offshore waters, and migration patterns.

This additional information was deemed necessary to resolve questions concerning whether a Federally managed offshore herring fishery could be permitted given the conservation and allocation issues raised.

The Council issued requests for proposals for U.S. trawlers to collect this data in experimental fisheries commencing in January 1985. Due to conflicts with other fisheries at the same time, the opportunity to participate in this experimental fishery generated little interest from U.S. commercial fishermen; consequently, the Council requested the Secretary of Commerce to generate the necessary data in October 1984.

Herring Bycatch Management in Groundfish Trawl Fisheries

Concurrently with the development of a debate over the herring FMP, the Bering Sea Aleutian Islands groundfish fishery management plan was adopted, approved and implemented on January 1, 1982. Under this management plan, herring are considered a prohibited species in the groundfish fisheries, and may not be retained in these fisheries.

During this period, Bering Sea stocks have undergone a marked decline due to repeated recruitment failure (Fig. 3). Simultaneously, herring bycatch exploitation rates (the proportion of the herring biomass taken incidentally in trawl operations) have risen from less than 2% to an estimated 4%-7% (Funk et al., 1990). Consequently, the issue of management of herring bycatch has steadily risen in prominence on the Council's agenda over the past several years. Proposals have been submitted to the Council to limit herring bycatch in groundfish trawl fisheries annually since 1985 (H. Sparck, pers. comm.).

In January 1990, the Council, with State of Alaska support, agreed to develop an analysis of a groundfish plan amendment to limit herring bycatch in Bering Sea trawl fisheries. At that time, the Council heard from the Alaska Department of Fish and Game (ADF&G), that subsistence fisheries for herring may be threatened due to increasing herring bycatch in Bering Sea trawl fisheries concurrent with herring stock declines.

At its April 1990 meeting, the Council remanded the draft herring bycatch chapter of the plan amendment package to the plan team for redrafting and reconsideration at its June 1990 meeting. During this meeting, ADF&G reported again that several

Fig. 3: Spawning biomass of eastern Bering Sea herring stocks from 1983 through 1989, and the projected 1990 spawning biomass. (From Funk et al. 1990)

Bering Sea herring stocks are depressed due to repeated poor recruitment and presented information suggesting that the bycatch of herring in trawl fisheries has grown in recent years. ADF&G indicated that emergency action was needed to control herring bycatch for 1990 and urged that bycatch caps be established at rates below 2% of the Bering Sea herring biomass.

After consideration of its Advisory Panel recommendations, the Council requested the Secretary of Commerce to take emergency action to limit the bycatch of herring in Bering Sea trawl fisheries. The measures requested would:

1. Establish a bycatch cap for herring of 2.5% of the biomass (approximately 1,875 mt);
2. Temporarily close two areas north of the Alaska Peninsula (Fig. 4) if this cap is attained (herring bycatch to be accounted starting January 1, 1990):

    a. Between 162° and 164° W. and south of 56° 30' N. from June 15 through July 1; and
    b. Between 164° and 166° 30' W. and south of 55° 30' N. from July 1 to August 15;

3. Allocate the bycatch cap equally between shorebased trawlers and trawl catcher-processors; and
4. Require 100% observer coverage on trawlers fishing in these zones during the specified times if they had not been closed.

The action was intended to protect herring during their summer migration along the Alaska Peninsula. The Council also indicated that it would consider making a request for further emergency measures based upon a 1990 assessment of spawning stocks by ADF&G. These additional measures could include a winter closed area to protect herring in their wintering area northwest of the Pribilof Islands and a migration corridor along the continental shelf break between the Alaska Peninsula and the winter areas (NPFMC, 1990a).

At its June 1990 meeting, the Council heard that ADF&G determined that Nelson Island stocks, those most critically depressed, were above threshold and that a commercial fishery could be held. NMFS suspended further work on the emergency rule because all stocks except Nunivak Island were above threshold for commercial exploitation. At that meeting, the Council made a request to the Secretary of Commerce for emergency action to protect herring in their wintering area Northwest of the Pribilof Islands. The request would close a small area (Area A, Fig. 2) when 600 mt of herring had been taken in a larger area (Area C, Fig. 2). The closure would begin September 1, even if the cap had been attained earlier in the year, and would remain in effect for the remainder of 1990.

The Council recessed and continued its June meeting in Juneau in August. At that meeting, the Council approved the herring bycatch management analyses for public review and comment prior to final action at its September meeting. In addition, the Council heard from NMFS that the emergency action requested in June had not been forwarded to the Secretary of Commerce because it could not be determined that an

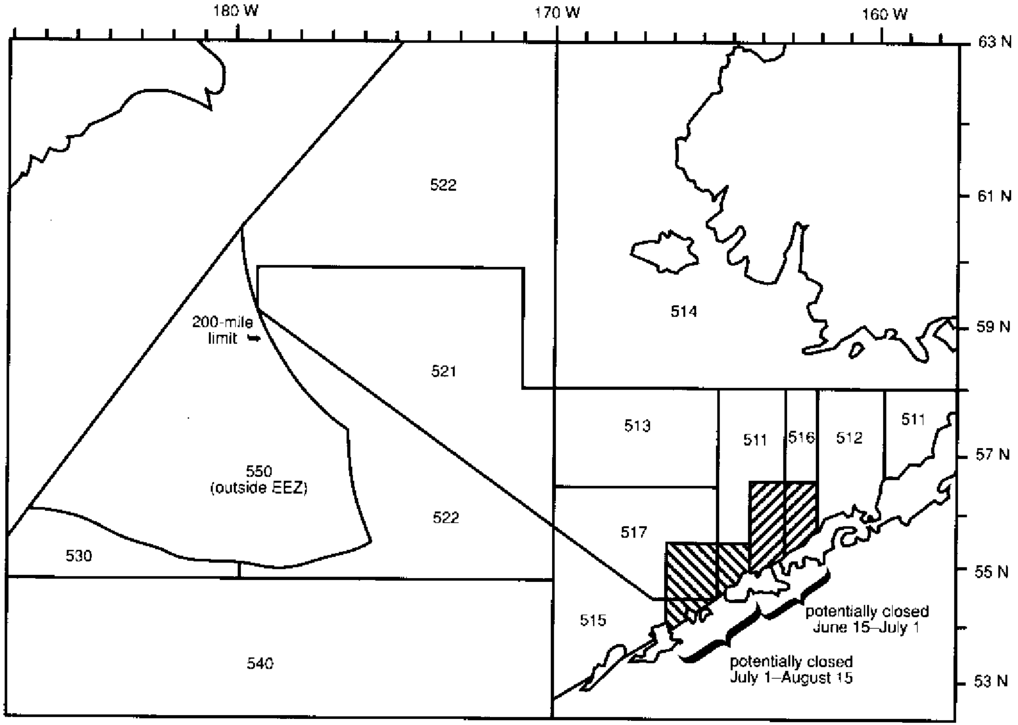

Fig. 4: Herring Savings Areas in Council's Emergency Action Request of April 1990.

emergency existed: every herring fishery save one had been permitted to open, overall stock conditions were higher than expected, and the stock of concern is a small portion of the total and apparently randomly mixed with other stocks in wintering areas, making it difficult to protect. Further, bottom trawling would be closed in the winter months in the intended winter savings area due to halibut bycatch.

In September 1990, the Council approved Amendment 16a which addresses herring bycatch management in Bering Sea trawl fisheries. The Amendment establishes a framework to set the herring bycatch cap at 1% of the eastern Bering Sea herring biomass, and two Summer Herring Savings Areas along the Alaska Peninsula and a Winter Herring Savings Area northwest of the Pribilof Islands (NPFMC, 1990b; Fig. 5).

The cap would be apportioned among those trawl fisheries expected to take herring as bycatch. Any fishery taking its apportionment of the herring PSC cap would face temporary time/area closures in the three herring savings area for the balance of that fishing year. At the current time, the implementing regulations envision that these fisheries will be domestic and joint venture flatfish fisheries, the domestic midwater pollock fishery, and the domestic "other bottom trawl" fishery, which is principally bottom trawling for cod and pollock. The cap for a fishing year would be based upon the ADF&G herring stock status analyses prepared the previous fall.

CONCLUSION

Bycatch management of herring, as well as of other prohibited species, in the groundfish fisheries of the Bering Sea will continue to be a dynamic and contentious focus of Council activity for the foreseeable future. The bycatch of herring taken in groundfish fisheries impacts upon the traditional subsistence fisheries. Herring taken in directed inshore fisheries is valued very differently than herring taken as bycatch in offshore trawl fisheries. These differing values are not directly commensurable due to the cultural and economic importance of herring in subsistence-based economies.

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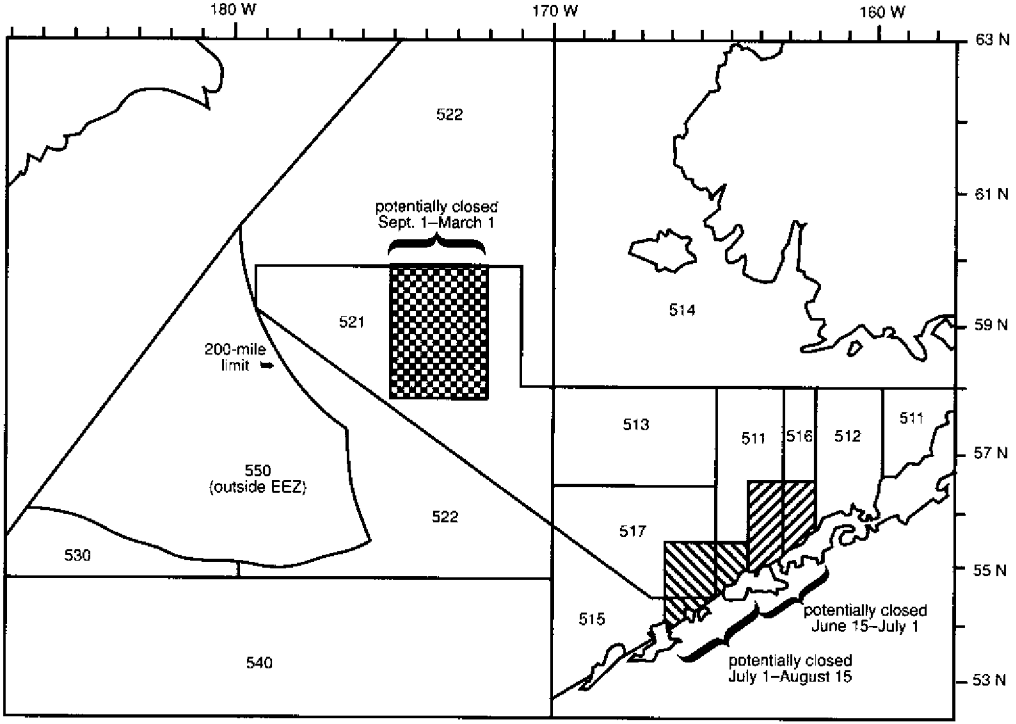

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Biological and Sampling Considerations When Maximizing Roe Recovery for Alaska's Herring Fisheries

L.K. Brannian and K.A. Rowell
Alaska Department of Fish and Game
Anchorage, Alaska

Contribution PP-028 of the Alaska Department of Fish and Game,
Division of Commercial Fisheries, Juneau

ABSTRACT

Most herring sac roe fisheries in Alaska are timed to maximize the weight and quality of roe recovered from the allowable harvest. Percent mature roe is judged by the seafood industry using a standard 10-kg sample of herring. The result is that the average number of herring in a sample can vary from 98 fish in Prince William Sound (1988) to 29 herring in Togiak District. Precision was estimated by the half width of a 95% confidence interval for the average roe percentage from 1,000 bootstrap replications. The precision of the 10-kg sample ranged from ±2.3% for 98 fish from Prince William Sound to ±4.4% for 29 fish from Togiak District. Precision increased with increasing sample size; this relationship was similar when sampling from Prince William Sound or Togiak District data sets with various age compositions, sex ratios, and roe maturities. A sample size of 125 fish for Prince William Sound and 150 fish for Togiak District was recommended. When female gonad size is expressed as a percentage of total body weight, or as the gonosomatic index, Prince William Sound herring showed higher average values at young ages, equaling those of Togiak herring by age 8. Average gonosomatic index for both stocks was lower at young ages. Harvest strategies to maximize roe recovery include harvesting when females are 100% mature, percentage female is maximum, and targeting the harvest on older fish.

INTRODUCTION

Pacific herring fisheries are conducted at more than 25 locations in Alaska. About 85% of the harvest is processed for sac roe product (Funk and Savikko 1989, 1990). The objective in these sac roe fisheries is to capture Pacific herring (*Clupea harengus pallasi*) close to their spawning grounds at the prime of their sexual maturity. The Alaska Department of Fish and Game (ADF&G) is mandated to manage these and all fisheries resources based on the sustained-yield principle and in the interest of the economy and general well-being of the state (Alaska Statute 16.05.020; State of Alaska 1983).

In the Gulf of Alaska and the eastern Bering Sea the department manages each herring fishery for a maximum 20% exploitation rate. The time and location of the fishery is established to maximize the roe content of the harvest. ADF&G is only beginning to develop its policy of maximizing roe recovery in herring sac roe fisheries. For example, the Norton Sound management plan, states that the fishery will open once herring are judged "marketable" (greater then 8.5% roe) or spawning is observed (Lean and Bue 1990). By regulation, a primary objective for managing the herring fishery in the Togiak District of Bristol Bay (ADF&G 1990) is to strive for the highest level of product quality.

The seafood industry has created the economic incentive for maximizing roe recovery by adjusting the price per ton paid to fishermen by a fixed value for every percentage point above or below 10% roe recovery. Prices have ranged from $500 per ton at 10% roe ± $50 in Togiak to $1,500 ± $50 per ton in Lower Cook Inlet. The price for sac roe is in sharp contrast to those paid for food and bait herring. During spring sac roe fisheries catches with estimated roe recovery of less than 6%-7% are purchased for food and bait in the eastern Bering Sea. Recent prices for that product have ranged from $50 to $250 per ton. Up to 44% of the spring sac roe harvest in some eastern Bering Sea fisheries has been purchased as food and bait (Hamner 1989). From 1986 through 1990 approximately 100% of the Gulf of Alaska spring herring harvest was purchased for sac roe product whereas only 86% of the eastern Bering Sea harvest was purchased as sac roe herring.

Accurate estimation of roe percentages is vital in maximizing the monetary value of the harvest. Between the time herring appear on the spawning grounds and the opening of the fisheries, managers direct commercial vessels to test fish for herring. These test catches are then distributed to processors for roe recovery estimation. Duration and location of the fishing period is determined by the manager after consultation with the processors and confirmation of the roe recovery of the test samples. The price paid to each fishermen is also based on the buyer's estimation of roe recovery.

The seafood industry uses a standard 10-kg sample of herring (males and females combined) to estimate roe recovery or percent mature roe for all Alaska fisheries. Criteria of color, firmness, and egg size are used to judge whether an egg skein has matured sufficiently to market as sac roe product. Only mature or "marketable" roe is removed and weighed. Roe percentage becomes the ratio of the weight of mature roe over total fish weight in the sample, or 10-kg. The size of herring in Alaskan fisheries varies within its geographical distribution. Therefore, based on average size during the 1989 season, the number of fish actually in a 10-kg sample has ranged from 86 herring in Prince William Sound to 29 fish in Togiak. The estimate of roe percentage is a function of both the sex ratio and the stage of roe maturity for fish in the 10-kg sample. Sampling error, judged by the magnitude of the variance and width of a confidence interval, is a function of the number of fish in the sample.

Understanding the implications of sampling error and underlying biological factors affecting estimation of roe recovery is necessary for establishing herring management policies. Managers have relied on the seafood industry to estimate roe recovery. Current sampling strategies have not always allowed managers to attribute differences in roe percentage among samples to (1) differences between processors grading roe or (2) differences in time and location of collection.

Biological differences among herring stocks affect roe recovery potential. The size of Pacific herring increases with latitude to a maximum in the Togiak stock and decreases northward (Rowell 1986; Fried et al. 1982a, 1982b, 1983, 1984; Lebida and Sandone 1988). Size-specific fecundity is inversely related to latitude (Paulson and Smith 1977). These relationships suggest that roe recovery potentials are stock specific. Hay (1985) found that the gonosomatic index (GSI, the female gonad size expressed as a percentage of total body weight) increases with size of female. This conclusion supports the observation that an increase in fecundity with size and age exceeds growth (Hempel 1979). This trend is also apparent in Atlantic herring (*C. harengus harengus*) stocks where the exponent (b) in the allometric relationship of fecundity with fish length ($F=aL^b$) ranged from 3.4 to 6.8 (Schopka 1971). Lastly, favorable environmental conditions or an increase in food supply can accelerate growth and increase the absolute and relative fecundity (Nikolsky et al. 1973). This would result in interannual variation in roe recovery or differences in roe recovery among herring at different locations.

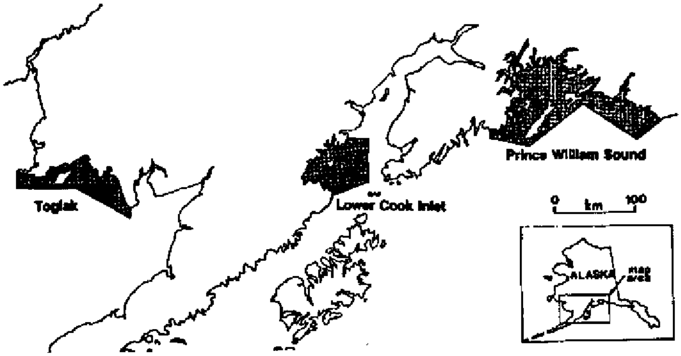

Figure 1. Major stocks in Pacific herring in south-central Alaska.

We were interested in how the biological parameters of two geographically separated Alaskan herring spawning stocks, Prince William Sound (Gulf of Alaska) and Togiak District of Bristol Bay (eastern Bering Sea), (Figure 1) interact to produce stock specific estimates of roe percentage and GSI. These two stocks were selected because of differences in population characteristics. A Prince William Sound herring cohort maximizes it biomass at age 3, stabilizing through age 5. Togiak herring are longer lived and are of a larger size at each age. A Togiak cohort also maximizes its biomass at an older age of 7 to 8 years. For each stock we wanted to (1) estimate the precision of roe percentage calculated from the industry's standard 10-kg sample, and, (2) recommend sample sizes, sample collection design, and harvest strategies that would maximize roe recovery in the harvest.

METHODS AND MATERIALS

The seafood industry estimates roe percentage (R) as a ratio of total weight of mature egg skeins (Σy_i) to total weight of all herring (Σx_i) in a 10-kg sample. This can be described as a ratio of mean gonad weight (Y) to mean total body weight (X), or

$$R = \frac{\sum_{i=1}^{n} y_i}{\sum_{j=1}^{n} x_i} = \frac{Y}{X} \quad . \tag{1}$$

The variance of R, V(R), follows from Cochran (1977) as

$$V(R) = \frac{\sum_{i=1}^{n} (y_i - Rx_i)^2}{n X^2 (n-1)} \quad . \tag{2}$$

We assumed that the sample size (n) was minor compared to the total population size and omitted the finite population correction factor. Sample size was, however, assumed large enough to apply a normal distribution approximation. Confidence limits for R were obtained using a standard normal deviate corresponding to the 95% confidence probability.

ADF&G staff weighted female gonads from Togiak herring from 1985 through 1988 collecting 3,818 (n) mature gonad weights. Gonads were removed from fresh fish and weighed within several hours after collection during annual age, sex, and size sampling. In contrast, Prince William Sound herring egg skeins were similarly sampled but were frozen shortly after collection. The gonads were later thawed and weighed to estimate fecundity. A total of 1,067 gonad weights were collected from 1988 through 1990 in Prince William Sound. During the 1990 season, 65 herring egg skeins were weighed before freezing and after thawing to evaluate potential bias due to freezing.

Togiak and Prince William Sound data sets were created by randomly selecting age and weight data for male herring from historic data files in equal numbers to female mature gonad data by age, year, and location. These data were from fish captured using non-selective gear from commercial and test fishing activities.

The effects of sample size, age composition, sex ratio, and roe maturity on the estimate of roe percentage precision and accuracy were evaluated through simulation. To simulate an age structured population with an age-specific sex ratio, bootstrap resampling methods (Noreen 1989) were used to create artificial samples from which R and V(R) were estimated. Samples were drawn with replacement from historical data using numbers at age obtained from a multivariate random number generator (IMSL 1989). The use of observed data freed us from specifying a bivariate distribution for female gonad and total body weight, acknowledging their potential lack of independence. The probability of occurrence of mature roe was modeled as a binomial random variable. The parameter of interest was the outcome of one Bernoulli trial ($t = 1$ or 0) from a binomial random number generator (IMSL 1989). The mature gonad weight (y^*_i) of female i became the product $y^*_i = t\, y_i$.

Using equation (1) we replaced y_i with y^*_i to estimate roe percentage at each bootstrap replicate (R_b). The average bootstrap roe percentage (R_B) became

$$R_B = B^{-1} \sum_{b=1}^{B} R_b \,, \qquad (3)$$

and its variance, $V(R_B)$, became

$$V(R_B) = (B-1)^{-1} \sum_{b=1}^{B} (R_b - R_B)^2 \,. \qquad (4)$$

We applied a normal approximation to obtain confidence levels for R_B, using a standard normal deviate corresponding to a 95% confidence probability. Precision was defined as the half width of the 95% confidence interval based on the bootstrap variance (equation 4). Estimates of R_B and $V(R_B)$ were calculated from 1,000 bootstrap replications ($B=1{,}000$). Sample size (n in equation 1) was varied from 10 to 500 for each age composition, sex ratio, and gonad maturity combination. For each age composition three levels of female percentage (40%, 50%, and 60%) and 4 levels of gonad maturity (70%, 80%, 90%, and 100%) were evaluated. Sex ratios were held constant over all ages (a) in our parameterization of a multinomial distribution with 2a age-sex categories. These simulations represented the ranges likely to be encountered when sampling herring spawning populations.

We did not evaluate every possible age composition using our Togiak (ages 4-11) and Prince William Sound (ages 4-10) data sets. Rather, we simulated the 1991 forecast age composition, and age compositions representing cases where one-, two-, or three-year classes dominated the population. In addition, roe percentage and its precision were estimated from sampling the Togiak data set when nine age classes were of equal magnitude.

RESULTS

The herring stocks chosen for this study differed greatly in mean weight, fecundity, and instantaneous rate of natural mortality by age (Table 1). Herring that spawn in the Togiak area grow to be nearly double the size of herring that spawn in Prince William Sound by age 7 and have a fecundity nearly three times as great by age 6. Prince William Sound herring show higher average GSI at young ages equaling, those of Togiak herring by age 8. We found an average 0.5% weight loss in frozen ovaries. Any affect this might have on our study would be to slightly underestimate GSI values in Prince William Sound herring.

Table 1. Average fish weight, fecundity, gonosomatic index (GSI) and instantaneous natural mortality rates of herring from Prince William Sound (PWS) and Togiak District, Alaska.

	Mean Weight (g)		Fecundity (x 1,000 eggs)		Mean GSI (%)		Natural Mortality	
Age	PWS[a]	Togiak[b]	PWS	Togiak	PWS	Togiak	PWS[c]	Togiak[d]
3	79	110	8.9			16.0		
4	103	158	12.6	37.3	18.6	15.6	34.3	10.3
5	124	208	16.7	34.6	20.7	18.5	34.3	10.3
6	141	256	20.3	57.1	21.8	19.3	34.4	10.3
7	155	301	22.9	75.1	22.8	21.2	36.5	22.6
8	166	341	24.5	82.3	22.9	22.6	45.0	34.8
9	174	375	25.9	99.8	22.2	23.0	66.7	47.1
10	181	404	26.9	93.7	23.0	22.2	11.1	59.3
11	186	427	29.7			22.5	18.9	71.5
12	190	446	29.0			22.7	31.4	83.8
13	192	461	32.5					

[a] From weight-age relationship 1973 to 1988 (Funk and Sandone, 1990).
[b] From weight-age relationship 1980 to 1989 (Baker, *In press*).
[c] Used to forecast biomass since 1989 (Brannian and Rowell, 1989).
[d] Used to forecast biomass since 1989 (Brannian, 1989).

Average GSI also varied by age class among years. As seen in Prince William Sound (Figure 2), there appears to be a pattern of lower average GSI at younger ages though the relationship is probably not linear. A similar pattern of GSI and age was seen for Togiak herring (Figure 3). A trend of decreasing GSI values over time (1985-1988) was present for Togiak herring and an increasing trend over time for Prince William Sound herring.

Assuming samples comprised of 50% female and 100% mature roe, a range of roe recoveries expected from these stocks would be one-half the age specific GSI values of Table 1 or reading the ordinate of Figures 2 and 3 as half their indicated value. Roe percentages ranged from 8-10% for young herring (<6 years) and averaged 11% for older fish (>8 years).

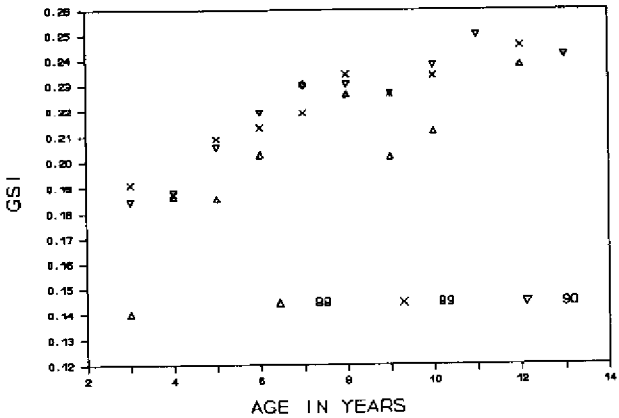

Figure 2. Estimated average female gonosomatic index for Prince William Sound, 1988 through 1990.

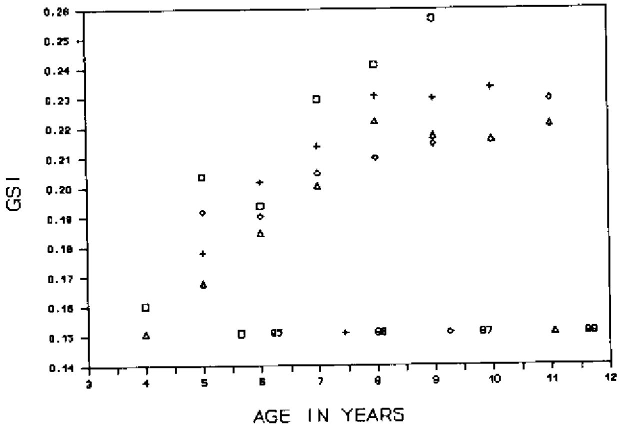

Figure 3. Estimated average female gonosomatic index for Togiak District Herring, 1985 through 1988.

Pacific herring also differ by age or size in their spawning migration timing. There is a consistent pattern of older and therefore larger fish reaching the spawning area first (McBride et al. 1981; Fried et al. 1982a, 1982b, 1983, 1984; Lebida et al. 1985, 1986; Lebida 1987; Lebida and Sandone 1988; and Sandone et al. 1988). Results of our 1990 sampling for age composition in the Togiak District was typical: older-age fish were most prevalent in our earliest sampling stratum and decreased in abundance over time, being replaced by younger fish (Figure 4).

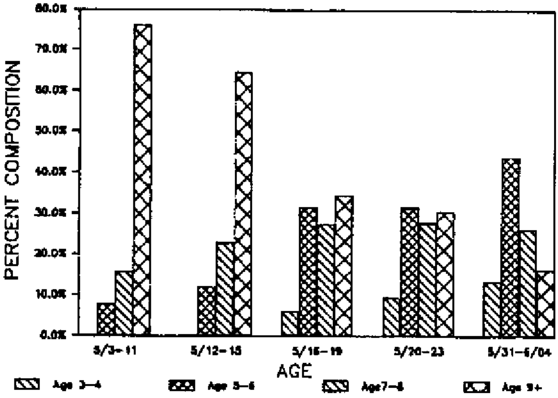

Figure 4. Change in age composition of Togiak District herring sampled in Bristol Bay during spring spawning migration, 3 May through 4 June, 1990.

As expected, our simulations demonstrate that roe percentage decreased as the percentage of mature roe decreased, and increased as the proportion of females in the spawning population increased (Table 2). Roe percentage varied from 6.1% to 13% when sampling 150 fish repetitively from our Prince William Sound data set with an age composition consisting of equal contributions of ages 4, 5, and 6. In contrast, the variance of roe percentage ranged only from 0.64 to 0.94, and the half width of the 95% confidence interval, our measure of precision, were quite similar, ranging from ±1.6% to ±1.9%.

Table 2. Bootstrap estimates of roe percentage and the half width of the 95% confidence interval (1,000 replicates) based on 150 fish selected from the Prince William Sound herring data set with equal numbers of age 4-, 5- and 6-year-old herring. Sex ratios and female maturities were varied.

Percent Female	Percent Mature Roe (Half Width 95% Confidence Interval)			
	70	80	90	100
40	6.1 (1.8)	7.0 (1.7)	7.9 (1.9)	8.7 (1.9)
50	7.6 (1.7)	8.7 (1.9)	9.8 (1.9)	10.9 (1.9)
60	9.1 (1.9)	10.4 (1.8)	11.6 (1.8)	13.0 (1.8)

Precision increased with increasing sample size. Values ranged from about ±7% at sample sizes of 10 to ±0.98% at sample sizes of 500 (Figure 5). The relationship between precision and sample size was very stable over the entire range of percent female and the range of percent mature roe evaluated for each age composition. Also, this relationship did not depend on whether the samples were drawn from the Togiak or Prince William Sound data sets (Figure 5).

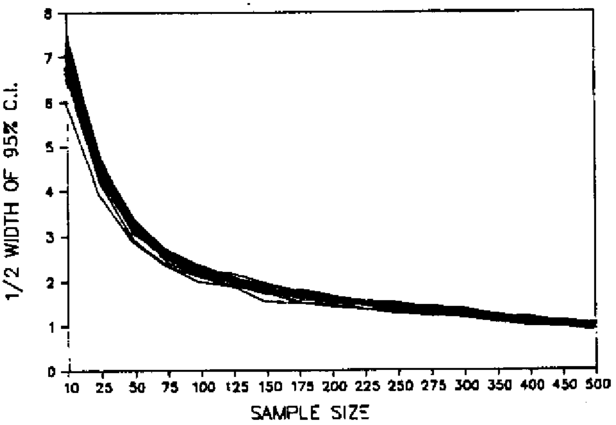

Figure 5. The half width of the 95% confidence interval for estimates of roe percentage (based on 1,000 bootstrap replications) for sample size 10 through 500. Each line represents simulated sampling from either the Prince William Sound or Togiak Districts herring data set with a unique age composition, sex ratio, and percentage mature roe.

The average number of fish in industry's 10-kg roe percent sample varied with the average size of fish in the population. The number of fish in a Prince William Sound sample has decreased from 98 fish in 1988 to a forecast 65 fish in 1991 as herring in the dominant 1988 year class grow larger. The accompanying precisions have also widened from ±2.3% to ±3.0% respectively. The average number of fish in a 10-kg sample of Togiak herring has varied from 29 fish in 1988 to a forecast 27 fish in 1991 because older, larger fish have dominated the age structure of the population. Precision for roe percent estimation for the Togiak District ranged from ±4.2% to ±4.4%.

DISCUSSION

Roe recovery from a herring fishery is a function of the spawning stock's age and sex composition, stage of roe maturity at time of harvest, and the relationship of female GSI to age. Given our goal of maximizing roe percentage we could develop harvest strategies based on biological characteristics of the herring population in question. The stock would be harvested when females are 100% mature and percent female is maximum. An attempt would be made to harvest older fish because roe recovery is lower in younger fish. To accomplish this, fisheries would be conducted at the beginning of the spawning migration to take advantage of the temporal separation of young and old herring.

Universal recommendations concerning sample sizes for the estimation of roe recovery were not possible because not all combinations of herring stocks, age compositions, percent female, and percent mature roe were evaluated. Therefore, we will direct our comments to the 1991 forecast age composition for Togiak District and Prince William Sound herring stocks. We recommend sample sizes for roe percent estimation of 125 (Prince William Sound) to 150 (Togiak) fish. There is evidence that precision is slightly better for Prince William Sound herring than Togiak, and the lower sample size is recommended. Results of our simulations indicate that this would guarantee accuracies of about ±2%. In addition, a serious attempt should be made to randomly select those fish from multiple schools throughout the area to be described by the sample.

Because larger, older herring dominate the Togiak herring population a 10-kg sample contains too few fish to adequately describe roe recovery for the population. This is defined by a 95% confidence interval, of ±4% which could result in a sample being judged of food and bait quality (6% roe) when the true population value was closer to 10%. Ultimately a sample of 150 herring should be used to estimate roe percentage. With time and cost restraints, however, no fewer than 100 fish, or 30 kg of Togiak herring, should be sampled. Yet, remember that at lower sample sizes the calculated roe percentage could have an error of slightly greater than 2 percentage points. Because of the small 10-kg samples used by the industry, most of the differences among roe percentage samples should be treated as sampling error and not ascribed to actual differences in roe percentage by time and area.

ACKNOWLEDGMENTS

We thank Evelyn Biggs and John Wilcock for providing Prince William Sound gonosomatic, fecundity, and age-weight data. Fred Jamsen wrote the computer simulation program, and Tim Baker along with Evelyn Biggs provided the Prince William Sound 1991 forecast age composition. We also thank Virginia Shook for her invaluable clerical assistance. Fritz Funk, Jeff Bromaghin, and other staff contributed many useful editorial and analytical comments. This manuscript represents contribution PP-028 of the Alaska Department of Fish and Game, Division of Commercial Fisheries, Juneau.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

On the Condition and Management of Herring Stocks in the Baltic

E. Ojaveer
Baltic Fisheries Research Institute
Tallinn, Estonia

ABSTRACT

During the recent decades Baltic herring stocks have mainly been influenced by large variations in the natural conditions induced by alterations of the climatic periods. That has resulted in substantial changes in the abundance and growth rate of the populations. Pollution has increasingly affected the condition of the populations, especially their embryonal and larval development and growth.

Intensification of stock exploitation and probably also the increase in biological productivity of the Baltic Sea connected with eutrophication has lead to a considerable growth of Baltic herring catches in the 1950-1970s. Still, certain biological (the mosaic population structure), economic and social reasons have prevented the total stock from falling into depression.

At present the international management of Baltic herring is rather formal. Management should be based on the regulation of the local populations exploitation.

1. STOCK STRUCTURE

Long ago fishermen and fishery scientists (Kessler, 1864) realized the fact that the Baltic Sea is inhabited by a number of herring local populations adapted to their areas including spawning, nursery and feeding grounds and differing from one another by vital characteristics. The transition between them is gradual without any sharp borderlines. The transition areas coincide with larger gradients in important environmental conditions - salinity, temperature, food abundance etc. Depending on changes in

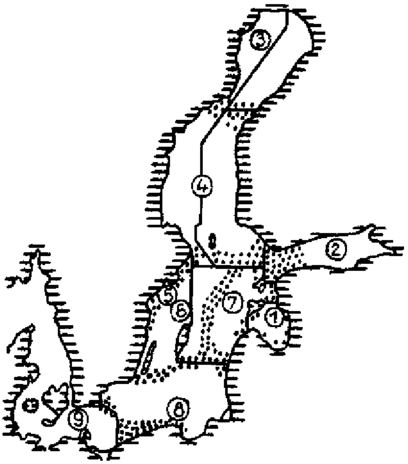

Figure 1. Baltic spring herring populations: 1 - Gulf of Riga; 2 - Gulf of Finland; 3- Bothnian Bay; 4 - Bothnian Sea; 5 - Swedish fjord herring; 6 - Western Central Baltic; 7 - Eastern Central Baltic; 8 - Southern Baltic; 9 - Western Baltic; ⁞⁞ transition areas between the populations; —— borders of herring assessment units of the ICES Working Group on Pelagic Stocks in the Baltic

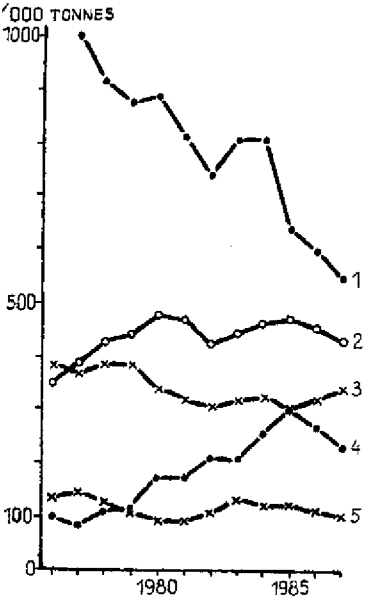

Figure 2. Dynamics of spawning stock biomass in some Baltic herring assessment units (see Fig. 1): 1 - Southern + Western Central Baltic; 2 - Eastern Central Baltic; 3 - Eastern Bothnian Sea; 4- Western Baltic; 5 - Gulf of Finland

the environmental conditions and in the abundance of populations, their borders oscillate from time to time. Differences between the stocks in the dynamics of population biomass (Fig. 1, 2) and growth (in spring herring the W_{∞} varies from 224 g in the Western Baltic to 35 g in the eastern Gulf of Finland) are substantial and constant (Ojaveer, 1988; Hagstrom et al., 1989; etc.). Furthermore, the populations differ significantly in morphological features and embryonal development. In the Gulf of Riga the threshold salinity for spring herring embryonic development is remarkably less than in Rugen spring spawners (2.5% and 4% correspondingly - Ojaveer, 1988).

Taking into account the shortness of the period of herring development in the Baltic Sea (approximately 10000 years) and the wide contact and intermingling of the local units, it is natural that no clear genetic differences between the populations can be found. However, the significant differences found between the gulf herring populations in muscle esterases (Märtinson et al., 1979) hint at their certain genetic inhomogeneity.

As in the Atlantic, in the Baltic Sea spring and autumn herring (that have been treated as sibling species - Blaxter, 1958; Ojaveer, 1988; etc.), occur. Autumn herring dominated in Swedish catches in the 1930s (Alander, 1943). In the 1940s the share of spring herring increased. However, in the Western, Southern and Central Baltic the abundance of autumn herring was high up to the second half of the 1960s and in the Gulf of Riga till the second half of the 1970s. In the Northern Baltic, near the border of its area, the importance of autumn herring has been generally small. In the present period the Baltic autumn spawning stock constitutes probably less than one tenth of the total herring stock. Therefore, below mainly spring herring will be considered.

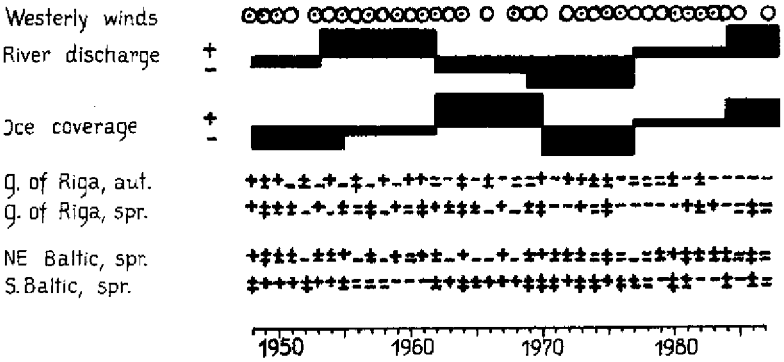

Figure 3. Relative abundance (‡ rich; + above average; ± average; - below average; = poor) of year-classes in some Baltic spring and autumn herring populations in various periods of fresh water inflow, severity of winters and wind direction in January-March (© over 45% westerly winds / O-easterly winds by strength).

2. RECENT DEVELOPMENTS IN YEAR-CLASS ABUNDANCE AND GROWTH

In recent decades periodical fluctuations in the Baltic Sea environment depending on deviations in climate have had the greatest influence upon the Baltic herring stock condition. The fluctuations have exerted their impact both on the abundance of year-classes and growth rate.

In every population a specific mechanism for recruitment formation has established. In Southern Baltic spring herring good year-classes develop mainly in the periods of low river discharge (Fig. 3) when water exchange between

the Baltic Sea and the Kattegat is intense, favouring abundant upmixing of nutrients and rich biological productivity in the spawning area of that stock. In the Gulf of Riga and Gulf of Finland spring herring rich year-classes appear mainly in the years with strong westerly winds before the spawning season creating favourable temperature conditions and enriching the surface layers of coastal larval retention areas with nutrients. In the Baltic Sea abundant autumn herring year-classes have formed in the conditions of mild first winter (Fig. 3). During the periods of severe winters its stock decreases seriously.
In the present period of severe winters, high river discharge and restricted water exchange between the Baltic Sea and Kattegat the abundance of the Southern Baltic coastal spring herring and autumn herring has decreased. That has resulted in important changes in the biomass of Baltic herring populations (Fig. 2, 3).

Changes in the Baltic Sea environment induced by climate have influenced the herring growth. The major factors determining the Baltic herring growth rate are the availability and caloric value of food organisms, suitable temperature and salinity. Commonly, Baltic herring does not feed at low temperatures in winter. Towards north and east its growth rate declines.

At the end of the 1970s and in the early 1980s the weight at age of Baltic herring was probably the highest, at least in the NE Baltic proper (Fig. 4). In general, the

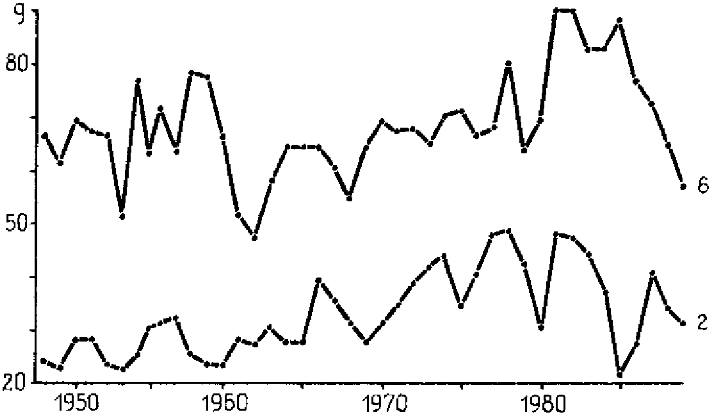

Figure 4. Mean weight of 2- and 6-year-old herring on spawning grounds in the NE Baltic proper.

increasing trend of herring growth rate may be connected with augmentation of the primary and secondary biological productivity based on the clear increase in nutrient concentration (Elmgren, 1989; Kostrichkina et al., 1989; Wulff et al., 1990). In the first half of the 1980s drastic changes appeared in the growth of most of the Baltic herring populations. In 1983-1985 the mean weights at age considerably dropped, excluding the populations of the Gulf of Bothnia (Aro, Kotilainen, 1989; Hagstrom et al., 1989) and since then they have remained on the lower level of the 1960s (Fig. 4).

The situation can be analyzed taking the Gulf of Finland and the NE Baltic spring herrings as an example. In younger herring living on Copepods, the growth obviously depends on the Copepod abundance throughout the year. In 1974-1989 the correlation coefficient between the weight of the 2-year-old Gulf of Finland herring and the Copepod abundance in May of the year and the year before was 0.73 ($P<0.05$). For August the coefficient was 0.61 ($P<0.05$). A good growth of young herring at the end of the 1970s and in the early 1980s in the Baltic proper and the Gulf of Finland coincided with the high salinity of the upper water layers (Kalejs, Ojaveer, 1989) favouring the marine fauna including Pseudocalanus and other herring prey organisms. A sharp salinity decline in the early 1980s that was connected with the beginning in 1977 of the period of high river runoff and low water exchange between the Baltic Sea and Kattegat, resulted in considerable drop of abundance of the herring food organisms mentioned above. Simultaneously a steep decrease in herring growth starting with 1983 (Fig. 5), as well as increased tendency for herring emigration from the Gulf of Finland and the Nothern Baltic, occurred (Fetter, Ojaveer, 1988).

In older herring living mainly on cold water zooplankton, nektobenthos and benthic invertebrates, growth rate is clearly connected with oxygen concentration in bottom layers that determines the area and abundance of the organisms indicated. Therefore, growth rate of the older herring regularly increases after the inflows of Kattegat water improving oxygen conditions in the deeper layers, and decreases in the stagnation periods when oxygen deficiency occurs (Fig. 5). Since the 1950s the only exclusion from that regularity took place during the stagnation from the beginning of the 1980s. Then, as a result of considerable decrease in salinity , and therefore - in permeability of the halocline, oxygen penetrated into deeper layers mainly from above. Its concentration in deep layers was quite satisfactory for deep-water invertebrates. Owing to that, during the first half of the 1980s the growth rate of older herring of the NE Baltic proper has remained on comparatively high level.

From above it can be concluded that considerable decrease in the weight-at-age values in several Baltic herring populations in the first half of the 1980s was mainly due to bad growth of young herring from 1983 onwards and to the intensification of southward emigration of slow-growing populations. The situation was obviously caused by

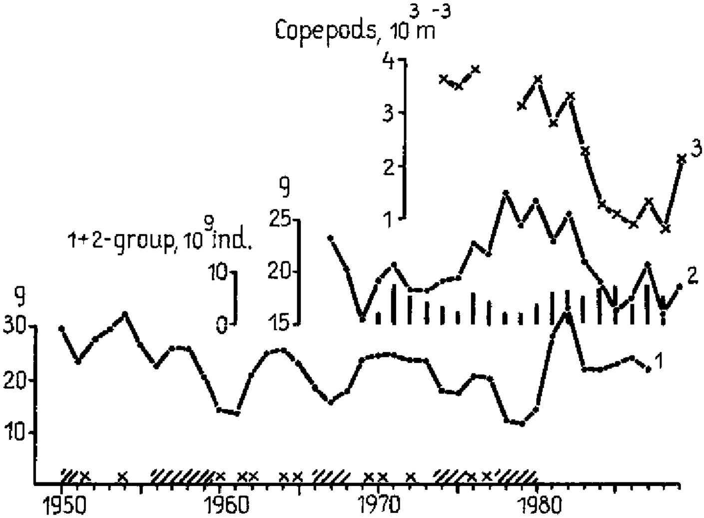

Figure 5. Dependence of Baltic herring growth on environmental conditions. 1 - 3-year sliding averages of weight increment in 4-6-year-old fishes on spawning grounds in the NE Baltic; 2 - mean weight of 2-year-old herring in the Gulf of Finland; 3 - Copepod abundance in the Gulf of Finland in May; x - inflows of modified Kattegat waters; //// - oxygen deficiency in the layers of older herring occurrence; ▮ - abundance of 1+2-year-old herring in the Gulf of Finland.

worsening of herring feeding conditions in the Baltic proper and in the Gulf of Finland and by some increase in the abundance of young gulf herring (Fig. 5).

3. INFLUENCE OF POLLUTION

In the Baltic Sea, that was earlier rather oligothrophic, pollution started to play important role from the 1960s (Kaleis, 1976). The most important and general influence has had eutrophication. Elmgren (1990) and other scientists have stated increase in nutrients content of both surface and bottom layers that has resulted in higher primary, secondary (Kostrichkina et al., 1989) and fish production (Fig. 6). However, that has also brought about higher oxygen consumption and its deficiency in bottom layers - increase of volume of anoxic zone devoid of zoobenthos and plankton, i. e. fish food organisms, especially in the stagnation periods. These changes have contributed to the variations in herring feeding conditions discussed above, growth rate, fecundity, etc.

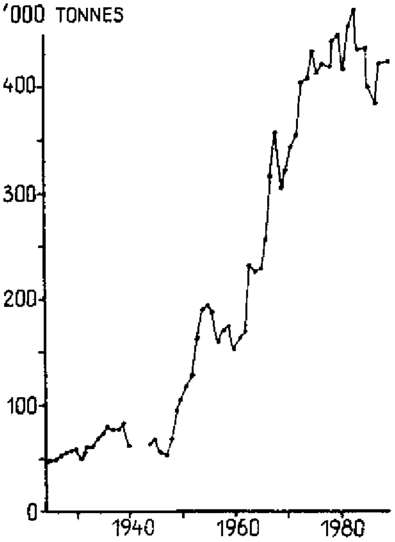

Figure 6. Herring total catches in the Baltic Sea (ICES, 1988, 1989; Ojaveer, 1988).

Usually the concentration of pollutants is the highest in the coastal zone, up to the depth of 20-25 meters, where herring spawning grounds and larval retention areas are situated. Oil spills, oil dispersants, heavy metals, organochloric and other compounds, local sharp oxygen deficiencies (Linden, 1974; Ojaveer, 1988; Aneer, 1989; etc) have essentially increased the herring embryonal and larval mortality.

In addition to the direct influence, herring reproduction conditions have suffered from serious changes in ecosystem induced by pollution. Principal changes have been stated in the structure and area of macrovegetation that constitutes the normal substrate for Baltic herring embryos (Aneer, 1989). That has resulted in higher loss of embryos because of worse development conditions (overcrowding of the retained spawning grounds, spawning on less suitable substratum - filamentous algae, rock, etc.) The effect has been the most obvious in the time periods and areas with the basic natural conditions (temperature, salinity etc.) significantly differing from the optimum. Therefore the embryonic mortality has essentially increased in the latter half of the spring spawning period when the temperature increases over the optimum and in deeper grounds in connection with disappearance of bottom vegetation because of decreased water transparency (Raid, 1990). In heavily polluted parts of the sea important changes and shifts have taken place in herring spawning and retention areas caused by mudding of spawning places, disappearance of spawning substratum and decreasing of larval food abundance (Kääriä et al., 1988; Raid, 1990).

The above shows that at present pollution seriously limits herring in the Baltic Sea. The stability of herring recruitment abundance and of its feeding conditions has decreased. Therefore Baltic herring stock has become more vulnerable and needs proper management.

4. MANAGEMENT

Herring is the most important fish stock in the Baltic Sea. In 1977-1986 its catches fluctuated between 399000 -

471000 tonnes, e. i. 44-50% (on the average 434000 tonnes or 47,5%) of the total catches in the Baltic Sea.

From the 1920s to the Second World War Baltic herring catches varied from 50-60000 tonnes. After the War, from the second half of the 1940s landings increased up to the mid-seventies after which a certain stabilization followed (Fig. 6). The growth was connected with an increase in exploitation rate of stocks that followed to the introduction of new fishing gears - pelagic trawls made of synthetic fibres, fish detection devices etc. The increase in landings also seems to reflect an increase in the nutrients content of the Baltic Sea surface layers since the 1960s allowing higher biological productivity.

Big increase in the Baltic herring catches was not followed by a depression of the total herring resource as has happened in most herring populations in the World Ocean. Probably the main reason for the rather great stability of the Baltic herring total stock under the increase of exploitation is the consistence of the resource of a number of autonomous units. Therefore high exploitation in some part of the sea cannot destroy the whole resource. In keeping down the exploitation intensity, lower economical value (as compared with the Norwegian or the North Sea herrings) of the relatively small-sized Baltic herring has played its role. The market conditions have had serious effect on the exploitation of some slow-growing stocks in the Northern Baltic and the Gulf of Bothnia. Further, collaboration between the Baltic countries in protection of the living resources of the Baltic Sea and the Belts has obviously contributed to the conservation of the herring stocks.

The international cooperation in Baltic herring stock assessment started in 1974 when the first meeting of the ICES Working Group on Assessment of the Pelagic Stocks in the Baltic was held. The principle of the Working Group - to assess the Baltic herring by units with the vital characteristics (abundance dynamics, growth rate) not much varying in the limits of the unit - has never been fully regarded. Nevertheless annually voluminous work has been done and herring stock condition by up to 8 assessment units estimated.

The first TAC recommended by the ICES for the Baltic herring in 1976 was almost equal of the actual catch (Table 1). In 1981-82 the ICES changed its method of presentation of the TAC recommendations to allow to the management bodies more flexibility - in certain cases advicing several options inside of the safe biological limits (IBSFC, 1983) therefore since 1983 no ICES recommendations on the total TAC for the Baltic herring can be presented (Table 1). However, the ICES has annually presented the International Baltic Sea Fishery Commission (IBSFC) with the advice by the assessment units and has recommended fish stock management on that basis.

Table 1. TAC and actual catch (Working Group data) of Baltic herring in 1976-1990 ('000 tonnes, IBSFC, 1983; ICES, 1986, 1988, 1989).

	TAC		Actual
	ICES	IBSFC	catch
1976	400		413.0
1977	400	422	422.2
1978	397	444	418.0
1979	386	405	443.5
1980	374	420.2	448.5
1981	341	418.6	415.8
1982	356	445.1	454.7
1983		474.9	471.1
1984		479.9	433.9
1985		480.2	434.7
1986		489.7	398.9
1987		489.7	383.4
1988		489.7	421.9
1989		489.7	422.3*)
1990		482.7	

*) Preliminary

The IBSFC was created in 1975 for realization of the Convention on Fishing and Conservation of the Living Resources in the Baltic Sea and the Belts signed in 1973. It has provided the forum for discussion between the Baltic Sea fishery managers and fishery scientists on state of fish stocks, fishing regulation measures, quota allocation etc. However, up to now the IBSFC has only partly introduced the resource management recommendations presented by the ICES. The overall TACs adopted by the IBSFC for the Baltic herring have always exceeded these adviced by the ICES. The actual Baltic herring catches have been higher than the ICES recommendations, sometimes surpassing even the TACs set by the IBSFC. From 1984 onwards the actual catches have clearly been less than the comparatively very high TACs established by the IBSFC. Consequently, since then the regulation of Baltic herring exploitation by the IBSFC has been rather formal.

The IBSFC has failed in introduction of Baltic herring management (setting TACs and allocating quotas) by stock units. As the result the most valuable stocks (especially the populations with higher growth rate and larger body size inhabiting the Western and Southern Baltic, also the populations in the Gulf of Riga and Gulf of Finland offering good fishing conditions) are chronically overexploited whereas others (e. g. the stocks in the Gulf of Bothnia) are fished generally on the level recommended by the ICES (ICES, 1988).

In the future proper management of Baltic herring, based on regulation of exploitation by the local populations, should be introduced. For improvement of the quality of assessments it is highly important to develop models considering herring stocks as integral parts of the ecosystem, e.i. with their interrelations with other organisms as well as with abiotic factors including these of anthropogenic origin.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

The Problem of Mesh Size in the Baltic Herring Trawl Fishery

A. Järvik and T. Raid
Baltic Fisheries Research Institute
Tallinn, Estonia

ABSTRACT

Fixing of certain mesh sizes for the codends is one of the common measures in regulation of Baltic herring trawl fishery. Still, the possible effect of different mesh sizes in codend on landings and fish stocks need substantial investigation. In particular, meshing in codend is one of the main factor causing a decrease of efficiency and selectivity in Baltic herring trawl fishery. Also it may affect on fishing mortality of young fish. In 1981 and 1986 a large number of commercial pelagic pair trawl hauls was investigated to estimate the share of meshed herring against the landings. The quantity of meshed herring varied widely and depended mainly upon the relationship - the fish body girth versus the codend mesh size, the trawling speed and the season. The meshing of herring in autumn was highest if the ratio of its maximum body girth to the inner mesh perimeter varied from 1.06 to 1.09. The problem of estimation the optimal mesh size in codend in mixed herring and sprat fishery in the Gulf of Finland is discussed.

INTRODUCTION

It is widely recognized in trawl fisheries management that fixing of certain minimum mesh size for the codend is essential to prevent young fish bycatch (Gulland, 1964; Treschev, 1983) Commonly, the minimum mesh size is fixed at the level, ensuring 50% escape of the captured fish below the minimum permitted size.

In the case of the fixed minimum mesh size in codend, the efficiency of the trawl fishery selectivity regulation is controlled by the fish seasonal distribution, especially by the relation of young and adult fish in captured shoals, but it also depends on the trawling speed, codend construction and several other factors (Treschev, 1974; Shevtshov, 1988; Robertson, 1989). Besides, fish meshing may serve as a factor, responsible for a decrease in the codend selectivity (Treschev, 1974).

Furthermore, on the occasion of a rather large number of fish in meshing, the error of estimated fishing mortality (F) may appear for the reason that the meshed fishes are for the most part shaken overboard being thus not included in F calculation. As a result, the fishing pressure is underestimated.

In the Gulf of Finland the main method of Baltic herring harvesting is the pelagic pair trawl fishery. Hence, high selectivity of the trawl fishery is of urgent necessity. For this purpose, the minimum permitted size of herring, captured in the USSR fishing zone has been fixed at the level of fish body length $l = 11.0$ cm ($l = 0.86L$, Ojaveer, 1976). This is an average length of 1.5 year-old herring (Table 1). However, it is very difficulty to find the optimal mesh size in codend, which would ensure the escape of undersized herring, because, besides the herring, a large number of sprat is captured with pelagic pair trawls as bycatch. But the average length of adult sprat is more less that of adult herring. For instance, the bycatch of sprat decreases considerably if the codend mesh size is used, which ensures the escape of more than 50% of undersized herring - $A = 32$ mm (Jarvik & Suuronen, 1990).

Table 1. Mean length (L) and weight (W) of herring by age groups in trawl catches in the Gulf of Finland in 1986.

Age	L, cm		W, g	
	Spring	Autumn	Spring	Autumn
0	-	9.5	-	5.8
1	10.7	14.1	7.2	14.3
2	14.1	15.0	17.5	23.0
3	15.4	15.5	24.3	24.8
4	16.8	16.3	29.9	29.2
5	18.4	17.1	40.3	33.7
6	20.8	18.3	57.5	38.5
7	21.4	18.9	67.6	41.3
8	23.6	-	87.2	-
9	23.9	-	82.8	-
10+	-	-	-	-

The meshing is quite an important problem as well. Often the codend with mesh sizes in the interval $20 \text{ mm} < A < 28$ mm looks like a "fur-coat". Since, the meshing of herring (and also sprat) in the codend has not been studied in the Gulf of Finland, experimental research was of urgent necessity. The aim of these experiments was to establish an optimal mesh size of pelagic trawl codends for the purpose of rational herring stock harvesting.

MATERIALS AND METHODS

In the years of 1981 and 1986, a large number (n=117) of the commercial pelagic pair trawl hauls were studied to estimate the quantity and peculiarities of meshing of both Baltic herring and sprat in codend in the Gulf of Finland (ICES Subdivision 32). The dependence of fish meshing on the type of trawlers, codend mesh size (diamond mesh) and seasons was investigated (Tables 2 and 3).

Table 2. The rate of herring in meshing by weight and meshed herring length frequencies in the Gulf of Finland in autumn 1981 (experimental data).

Codend mesh size A, mm	The type of tawlers	The rate of meshed herring to codend catch, %	Length (L) frequencies of herring in meshing, %			
			L<11cm	11cm<L <13cm	13cm<L <15cm	15< L
A=28	Small vessels	4.4	1.8	21.7	64.9	11.2
	Medium vessels	16.2				
A=24	Small vessels	0.1	2.8	29.8	67.4	-
	Medium vessels	5.1				
A=20	Small vessels	-	70.4	28.7	0.9	-
	Medium vessels	0.1				

From all the catches (separately from codend and meshing) a sample of 100 or more herring was taken and measured (body length l) - to the nearest two centimeters in 1981 and to the nearest half centimeter in 1986. The catches were quantified by counting the number of boxes of each catch. The hypothetical total number of herring was calculate both in codend (n) and meshed (m) for every size group (i) for two cases: 1)if in 1986 in the Gulf of Finland all the

Table 3. The rate of herring and sprat in meshing in the Gulf of Finland in 1986 (experimental data).

Codend mesh size A, mm	The type of trawlers	Codend catches, tons		Meshed fishes, tons		The rate of meshed fishes, %	
		Herring	Sprat	Herring	Sprat	Herring	Sprat
			S P R I N G				
A=20	Small vessels	7.3	1.5	-	-	-	-
	Medium vessels	20.5	1.6	0.1	0.0	0.5	1.3
A=28	Small vessels	7.3	1.0	0.0	0.5	0.4	46.0
	Medium vessels	12.3	0.2	1.5	0.1	12.2	60.0
			A U T U M N				
A=20	Small vessels	7.4	0.6	-	-	-	-
	Medium vessels	7.0	8.7	0.3	0.1	4.1	0.7
A=28	Small vessels	2.9	0.2	0.0	0.1	0.7	7.0
	Medium vessels	17.9	2.8	0.5	0.8	3.0	26.8

Estonian fishermen had used codends with mesh size only A=20 mm; 2) if in the Gulf of Finland in 1986 all the Estonian fishermen had used codends with mesh size only A=28 mm.

(1) $$n_i = \frac{\sum_c C}{{}_cW_{100}} \, {}_ck_i$$

(2) $$m_i = \frac{\sum_m C}{{}_cW_{100}} \, {}_mk_i$$

where $\sum_c C$ and $\sum_m C$ are the total weights of herring captured by codend and in meshing during the season (spring or autumn), ${}_cW_{100}$ and ${}_mW_{100}$ are the weights of 100 fishes when the size groups are presented as they in the samples collected from codend and meshing during the season, and ${}_ck_i$ and ${}_ck_i$ are the average season frequencies of size group i in all the samples from codend and meshing.

To estimate the probability of herring to be meshed, in dependence of total length (L) and maximum body girth (G), in autumn 1981 a sample of 172 fishes from meshing was measured, both L and G to the nearest millimeters. Taking into account that usually G is not measured, the linear regression $G = a + bl$ was calculated.

RESULTS

Commonly, the meshing of both species, herring and sprat, took place at the whole length of the codend, but most abundantly in its end. In the majority of cases, 1/3 to 2/5 of the fish body (measured from the head) had passed through the mesh, stomachs were torn, scales and skin down from backs and sides.

Despite remarkable variation, the meshing of herring was lower in the catches by small trawlers (< 150 HP) at a speed of 2.2-2.6 kn against the catches by medium trawlers (225-300 HP) at a speed of 3-3.6 kn. On the occasion of small vessels, only single specimens were found meshed in the codend with the mesh A=20 mm. By weight, more herring (up to 16.2 %) of its total quantity in the catch was found in the codends with A=28 mm in the autumn of 1981 (Tables 2 and 3).

Although, the meshing of herring in the codend was controlled by the ratio of its maximum body girth (G) to the inner mesh perimeter (2A), the dependence was not so prominent as revealed by traditional gillnet selectivity studies (Baranov, 1948; Holt, 1963). In one case (spring 1986; A=20 mm) the frequency of herring length groups did not coincide with the normal value (P=0.05). The similar results has been obtained by the research into the meshing of Atlantic herring in gillnet by Winters and Wheeler (1990). Nevertheless, the analysis of the effect of the ratio G/2A on herring meshing in codend, carried out in the autumn of 1981, enables to state that the probability of meshing is highest for herring if

(3) $1.06 < G/2A < 1.09$

The relation between the herring's length L and G in the autumn of 1981 may be revealed by the linear regression:

(4) $G = 0.57L - 2.05 \quad 0.77$

Solving (3) and (4) with respect to L, we attain that in dependence of the codend mesh size, the probability of meshing was in 1981 theoretically higher for the following herring length groups:

(5) $A = 20$ mm - 9.7 cm $< L <$ 12.6 cm
$A = 24$ mm - 11.2 cm $< L <$ 14.1 cm
$A = 28$ mm - 12.5 cm $< L <$ 15.6 cm

The calculated values of L are in a relatively good agreement with the frequency of meshed herring length groups obtained by experimental data (Table 2).

In the spring and autumn of 1986, the frequency of herring length groups in codends with A=20 mm and A=28 mm is presented in Table 4. The probability of meshing is highest

Table 4. The frequencies of meshed herring in Gulf of Finland in 1986 in codend by size groups.

Body length l, cm	Codend A = 20 mm		Codend A = 28 mm	
	Spring	Autumn	Spring	Autumn
6.5		0.053		
7.0		0.096		
7.5		0.145		
8.0		0.217		
8.5		0.283		
9.0	0.022	0.050	0.001	0.053
9.5	0.146	0.079	0.032	0.015
10.0	0.447	0.099	0.120	0.098
10.5	0.221	0.001	0.041	0.190
11.0	0.124		0.256	0.183
11.5	0.031		0.314	0.083
12.0	0.009		0.180	0.098
12.5			0.049	0.189
13.0			0.001	0.068
13.5				0.001
14.0+				0.015

for the following length groups (L=1.161):

(6) $A = 20$ mm - $11.0 \text{ cm} < L < 12.8 \text{ cm}$
SPRING
$A = 28$ mm - $11.6 \text{ cm} < L < 13.9 \text{ cm}$

$A = 20$ mm - $8.1 \text{ cm} < L < 11.6 \text{ cm}$
AUTUMN
$A = 28$ mm - $10.5 \text{ cm} < L < 15.1 \text{ cm}$

The comparison of (4), (5) and (6) shows certain, however, slight coincidence. The variations in spring may be accounted for by the absence of specimens with L<11.0 cm in captured herring shoals. The herring with L>14 cm is, as rule, mature and the relation between its G and L is no longer controlled by the regression equation (4) due to the enlargement of gonads. The variation observed with A=20 mm in the autumn of 1986 (and, partly, with A=28 mm as well) is evidently due to relatively high abundance of 0+ (L<10 cm) and relatively small increase in the body weight in the summer period (Table 1).

By age groups, in the codends with A=20 mm the 1-group herring dominated in spring and 0-group herring in autumn. In the codends with A=28 mm 1-group herring prevailed in spring, however, beside 1-group herring there were found also single specimens of 2-group herring in autumn (Table 1, equations (5) and (6)).

In order to estimate potential error on calculating fisheries mortality (F) in herring meshing and to determine the optimal codend mesh size in view of the rational use of herring stock, hypothetical seasonal herring quantities were calculated by the equations (1) and (2) in meshing and in the codends catches of 1986 (Tables 5 and 6). It appeared that in that case with A=20 mm the share of meshed herring would have been lower in spring (1.1% in meshing, 98.9% in codends catches). In autumn it would have been more purposeful to use the mesh size A=28 mm (8.4% and 91.6%).

Table 5. The hypothetical quantity of herring in codends catches and in meshing in numbers (*1000) if the mesh size A=20 mm alone had been used in the Gulf of Finland in 1986.

Body length l, cm	Spring			Autumn		
	Codends catches	Meshed	Total	Codends catches	Meshed	Total
6.5						
7.0				454	1242	1696
7.5				454	1699	2153
8.0				515	2546	3061
8.5	3450		3450	423	3321	3744
9.0	5160	80	5240	1059	232	1291
9.5	2160	520	2680	1274	926	2200
10.0	8240	1610	9850	2209	1159	3368
10.5	18310	790	19100	2958	1	2959
11.0	53920	440	54360	7009		7009
11.5+	227880	110	227990	56554		56554
	319120	3550	322670	72909	11756	84665

DISCUSSION AND CONCLUSIONS

Unlike several other catch objects (Treschev, 1974) including Central Baltic herring (Shevtsov, 1988), the meshing of herring in codend may be high enough in the Gulf of Finland. The quantity of meshed herring is highly variable in comparison with that in codend catch, depending on the physiological conditions of the fish (stage of gonads' development, feeding), but also on the frequency of herring length groups in the shoal, codend mesh size. The abundance of the factors, controlling the meshing of herring is indicative of the fact that the meshing of herring in the codend is statistic in character. Therefore, the relation (3) shouldn't be considered as a universal indicator. It only shows that within the boundaries $1.06 < G/2A < 1.09$ is valid, the probability of herring meshing is higher than beyond these limits.

In consideration of the results, presented in Tables 2, 3, 5 and 6, codends with A=20 mm should be used in spring and those with A=28 mm in autumn to ensure rational use of

Table 6. The hypothetical quantity of herring in codends catches and in meshing in numbers (*1000) if the mesh size A=28 mm alone had been used in the Gulf of Finland in 1986.

Body length l, cm	Spring			Autumn		
	Codends catches	Meshed	Total	Codends catches	Meshed	Total
7.0				2		2
7.5				261		261
8.0	919		919	701		701
8.5	616		616	306		306
9.0	922	66	988	732	333	1065
9.5	1542	1061	2603	371	94	465
10.0	5695	3978	9673	341	616	957
10.5	15783	1359	17142	3837	1188	5025
11.0	48531	8486	57017	8202	1144	9346
11.5	61387	10442	71829	9781	522	10303
12.0	70604	5967	76571	8841	616	9457
12.5	32040	1624	33664	14239	1188	15427
13.0	43902	232	44134	7885	427	8312
13.5	12611		12611	6748	44	6792
14.0	16095		16095	3552	94	3646
14.5+	32943		32943	2372		2372
	343580	33216	376796	68171	6264	74435

herring stock in the Gulf of Finland. However, one as to take into account that in the Gulf of Finland both herring and sprat are caught by means of trawls, and the sprat bycatch is rather profitable. And therefore, while choosing the optimal mesh size for codends one has to consider the potential meshing of sprat and the selectivity of codend with respect to both of the species.

In 1981 and 1986, the meshing of herring and sprat were studied in parallel. The results showed that the meshing of sprat was highest in the codends with A=24 mm (more than 20% in the catch) In 1986 the number of sprat meshed in codends was determined. It appeared that about 25.1% and 11.3% of the individuals in codend catch were meshed in codends with A=28 mm in spring and autumn, respectively. For the codends with A=20 mm these figures were 3.8% and 0.2%.

At the same time the codend mesh size A=20-28 mm does not provide sufficient selectivity on herring catch, since $l_{50\%}$< l min =11.0 cm (Table 4). As for sprat, the mesh size A=20 mm will be already enough - $l_{50\%}$< l min = 8.0 cm. With the mesh size over A=28 mm the sprat bycatch declines and the efficency of trawling decreases.

On choosing an appropriate mesh size one has also to consider the mortality of fish cased by their passing through the net. The studies show that in the Gulf of Riga, 10-20% of young herring and sprat (for 0-group the percentage is even higher) may perish having passed through the codend (Efanov, 1981).

The mesh size A=20 mm has been recommended for pelagic trawling in the Gulf of Finland since 1987. The validity of the recommendation was confirmed by the stabilization of herring stock size and catches and an increase in sprat stock and catches in the course of the following years.

The use of the mesh size A=20 mm, prevailingly, seems to have contributed to lessening of the error on calculating F on the basis of 1-group herring, whereas on the occasion of 0-group herring it seems to have increased. The results presented in the paper refer to the underestimation of F on young fish if their meshing in codends will not be taken into account.

Massive meshing of young fish in codends lowers the selectivity of trawls, since the number of meshes in codend, through which fish could escape, decreases considerable.

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Human Uses and Impact on Herring

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Assessing the Risk to Pacific Herring from Offshore Gas and Oil Development in the Southeastern Bering Sea

R.M. Meyer
Minerals Management Service
Anchorage, Alaska

ABSTRACT

The U.S. Department of the Interior (USDOI) began the presale process for conducting an offshore gas and oil lease sale in the southeastern Bering Sea (North Aleutian Basin) during 1973. Due in part to potential environmental effects from gas and oil operations, an offshore gas and oil lease sale--Sale 92, North Aleutian Basin--was not held in this area until October 1988. As a result of this sale, 23 leases were issued for gas and oil exploration. The USDOI's Minerals Management Service (MMS) has spent approximately $235 million to gather information needed to identify resources potentially at risk from offshore gas and oil exploration and development. The MMS is continuing to support studies concerning these resources and is focusing on species of specific concern near areas currently under lease.

During the prelease process for Sale 92, concern was expressed about the potential effects of gas and oil activities on Pacific salmon (all five species), Pacific herring (Clupea harengus pallasi), and king crab (Paralithodes camtchatica).

Gas and oil activities or accidents that have the greatest potential for affecting these species are chronic or acute discharges of pollutants, such as oil and associated fluids. Studies conducted for MMS and others indicate that early lifestages of these species are vulnerable to spilled oil and other pollutants. The "Window of Maximum Vulnerability" (WMV) is considered to be that period when the early lifestages are most sensitive to pollutants, e.g., spilled oil. Studies results show that the WMV for Pacific herring in the southeast Bering Sea falls between May and July, when early lifestages are found in shallow coastal waters. A numerical simulation conducted for MMS by the National Marine Fisheries Service and a synthesis report (Thorsteinson, 1984) evaluating the potential effects of spilled oil on offshore fisheries resources indicated that even during the WMV, gas and oil activities pose minimal threat to offshore fisheries resources. This report also concluded that an offshore oil spill poses a minimal threat to herring stocks spawning in Port Moller, Alaska. The findings are consistent with findings that the Exxon Valdez oil spill had no measurable effect on herring eggs and larvae in Prince William Sound, Alaska.

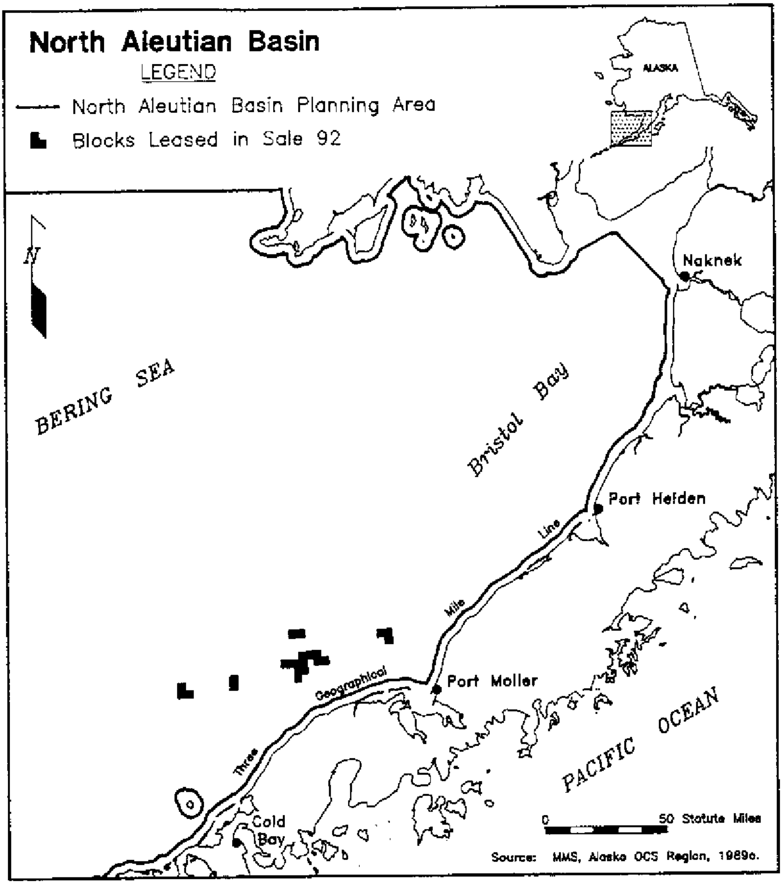
INTRODUCTION

The U.S. Department of the Interior (USDOI), Minerals Management Service (MMS), began leasing submerged lands on the Outer Continental Shelf (OCS) off Alaska for gas and oil exploration in April 1976 with OCS Lease Sale 39 in the northeastern Gulf of Alaska. Since then, MMS has conducted 14 OCS lease sales and leased 3.2 million hectares, and industry has drilled some 67 exploration wells in Federal waters offshore Alaska. Oil in economically producible quantities has been found under State waters in Cook Inlet and under Federal and State waters in the Beaufort Sea--some 8 wells as of May 1990 have been classified as producible in the Federal OCS portion of the Beaufort Sea near Prudhoe Bay.

MMS began preparing for an gas and oil leasing program in the southeastern Bering Sea in 1974, with the first lease sale (Sale 51) scheduled for October 1977 (USDOI, MMS, 1985a). After several delays and sale cancellations, 23 leases from Sale 92 were let in 1988 (Fig. 1). Exploration of these tracts has been suspended pending court review (USDOI, MMS, 1990a).

In addition to recognizing legal mandates guiding the Department's activities, Departmental managers are aware that the harvest of marine resources--primarily fish (Pacific salmon, Pacific herring, and walleye pollock) and crab (king and tanner crabs)--plays an important part in cultural and commercial activities within Alaska. They, therefore, have directed considerable resources to assessing potential conflicts between traditional uses of these resources and the exploration for gas and oil resources.

In 1973, MMS initiated the Environmental Studies Program (ESP) to support the OCS oil- and gas-leasing program off Alaska. The purpose of the ESP is to develop information needed to assess and mitigate potential effects that proposed gas and oil leasing and development might have on the human, marine, and nearshore environments. Since its inception, the ESP has conducted some 521 environmental studies in Alaska at a cost of over $235 million (1973-1990). Over half of these studies have focused on fisheries-oceanography issues. Information



Source: MMS, Alaska OCS Region, 1989a.

Figure 1. North Aleutian Basin Planning Area.

acquired through this program is in the forefront of subarctic and arctic research and is used to support offshore leasing and management decisions.

Fisheries resources in the Bering Sea have been exploited for well over a century, with annual harvests exceeding 1.2 million metric tons (mt) during the past decade. Walleye pollock, flounders, and Pacific cod account for the majority of this harvest. Other important fisheries include salmon, Pacific herring, and crab (king and snow). With the exception of the salmon and Pacific herring fisheries, most fisheries occur offshore, well away from the coast. The salmon and Pacific herring fisheries occur near shore and in estuaries in Bristol Bay and along the Alaska Peninsula.

In 1975, MMS funded the Alaska Department of Fish and Game (ADF&G) to conduct a resource-assessment survey of Pacific herring and other fishes spawning in coastal waters of the eastern Bering Sea (Barton, 1972) from Cape Charikof on Unimak Island to the Seward Peninsula (Barton, 1972). Annually, ADF&G conducts areal surveys throughout the region to estimate spawning-herring biomass. In addition to the spawning surveys discussed above, MMS has supported several projects to synthesize available environmental information concerning the southeastern Bering Sea and to develop information pursuant to potential gas and oil in the region. These projects have included a synthesis of environmental information (Thorsteinson, 1984); a forage-fish workshop (USDOI, MMS, 1987); a monograph of eastern Bering Sea resources (Hood and Calder, 1981); an open-file geologic report (USDOI, MMS, 1983a); an exploration and development report (USDOI, MMS, 1985b); Environmental Impact Statements (EIS's) for gas and oil lease sales (USDOI, MMS, 1982a,b; 1983a,b; and 1985a,c,d); a study of the fish use of inshore habitats (Isakson, 1986); and an environmental characterization of the nearshore zone (LGL, 1987).

PROBLEM STATEMENT

Pacific herring, because of their general life history, are considered to be at considerable risk from spilled oil. This perceived risk was well stated by Rice et al., 1986, when they suggested that the spawning strategy of herring made them particularly vulnerable to the effects of an oil spill because spawning adults and their maturing gonads could be exposed to spilled oil, and the spawned eggs and larvae would be subjected to an oil-contaminated environment.

Background

MMS is charged with managing the exploration for and development of offshore gas and oil resources in an environmentally sound manner. To accomplish this goal, MMS evaluates the potential environmental effects of gas and oil exploration and development on marine resources. MMS has, for example, evaluated the potential effects from offshore gas and oil activities on eastern Bering Sea Pacific herring in EIS's prepared for each of the five gas and oil lease sales in the Bering Sea (USDOI, MMS, 1982a,b; 1983a,b; and 1985a,b,d). Evaluations contained in these documents were based, in part, on results from studies that simulated the potential effects of spilled oil on fisheries resources in the southeastern Bering Sea (Laevastu and Fukuhara, 1984, and Thorsteinson, 1984).

These evaluations and simulations concluded that spilled oil would have minimal or no measurable effect on offshore fisheries resources, including Pacific herring. However, because site-specific information on many of the fisheries resources in coastal waters was not available, the simulations were unable to evaluate the potential effects of an offshore oil spill on certain coastal resources, e.g., herring eggs and larvae.

Following the 1989 Exxon Valdez oil spill in Prince William Sound, Alaska, MMS funded a study to determine the potential effects that spilled oil may have had on Pacific herring eggs and larvae. Developing eggs and larvae were collected from areas that appeared to have been heavily oiled as a result of the oil spill and compared with samples collected from areas that were not exposed to the spilled oil. Results from these studies indicate that the oil spill had no measurable effect on herring eggs and larvae in Prince William Sound in 1989 (McGurk, 1990a,b).

Status of Gas and Oil Exploration

The tracts that currently are under lease for possible gas and oil exploration are offshore of and upstream from Port Moller, Alaska. This estuary supports a large spawning stock of herring that may be at risk from an offshore oil spill.

This report provides an evaluation of the risk to the herring resources in Port Moller from an offshore oil spill and builds on information developed by numerous other authors.

PORT MOLLER--PHYSICAL ENVIRONMENT

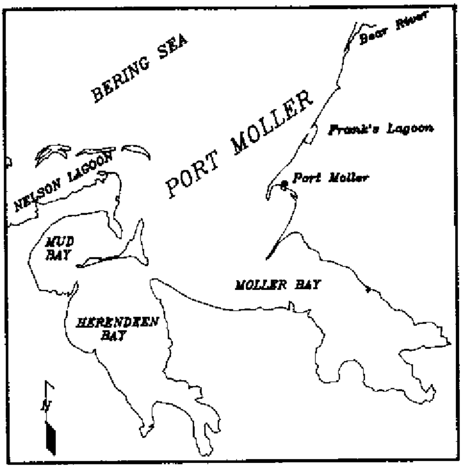


Figure 2. The Port Moller Estuary (McGurk, 1990).

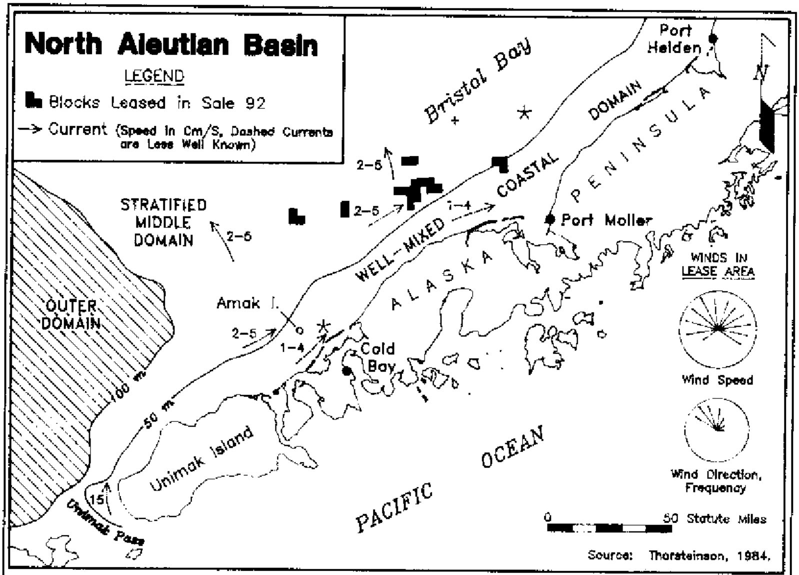
The Port Moller estuary (lat. 56° N. long. 160° 35' W.) is located on the north side of the Alaska Penin-sula (Fig.1). The largest (876 square kilometers [km^2]) coastal estuary in the southeastern Bering Sea, it consists of Nelson Lagoon, Mud Bay, Herendeen Bay, and Moller Bay (Fig. 2). The estuary is shallow, 4 to 17 meters (m), and is characterized by extensive shallow mud flats drained by narrow dendritic drainage channels. Herendeen Bay, however, is deeper (>100 m) and is connected to the remainder of the estuary by the relatively narrow and shallow (<30 m) Johnson Channel. Tidal range within the estuary is about 3 m, and current velocities in the channels can exceed 140 centimeters per second (cm/s).

Circulation of water into and through the Port Moller complex has been described by Greengrove, 1990, as being dominated by tidal forces and major regional storm events. During each tidal cycle, marine water tends to enter on the west of the estuary and exit on the east side, and there is a net discharge from the estuary of about 13 cm/s. Waters within the estuary tend to be well mixed; however, waters in Herendeen Bay may become stratified during periods of low winds.

Prevailing winds are from the southeast and average 8.9 knots. Summer temperatures range from 6 to 18 °C, and winter temperatures range from 6 to -20 °C (Brower, 1988). Although sea ice seldom extends as far south and west as Port Moller, the estuary freezes over each winter.

The Eastern Bering Sea is separated into three hydrographic regions--the outer shelf, the middle shelf, and the coastal region--which are separated by the shelf-break front, the middle front, and the inner front, respectively. Coastal circulation during the ice-free period generally is east along the Alaska Peninsula and to the northeast along the inner-front boundary (Fig. 3). The mean flow past Port Moller appears to be northeastward along the Alaska Peninsula with a velocity of about 2 to 5 centimeters per second (cm/s). Circulation along the coast is dominated by tidal currents (Schumacher and Kinder, 1983). Only about 3 percent of the kinetic energy within the coastal region is associated with weather events.

The Port Moller biota is dominated by large stands of eelgrass (Zostera marina) and rockweed (Fucus distichus). The area is an important staging area for water-



Wind Roses represent the winds used to develop oil-spill trajectories for the Sale 92 EIS and this report (Liu and Leendertse, 1982).
+ represent oil-spill-site D1 in the Sale 92 EIS (USDOI MMS, 1985).
*** represent oil-spill sites in Thorsteinson (1984).**

Figure 3. Prevailing coastal circulation during typical summer conditions. Redrawn from Thorsteinson (1984).

fowl and supports spawning populations of Pacific herring (Clupea harengus pallasi) and red and blue king crab (Paralithodes camtchatica and P. platypus, respectively).

BIOLOGICAL NOTES

Pacific herring are found throughout the eastern Bering Sea at various times of the year. Fish appear to overwinter in the central Bering Sea (Thorsteinson, 1984, and Funk, 1987) and return to coastal spawning sites in late spring-early summer (Wespestad and Barton, 1981). Figure 4 shows the relative abundance and timing of herring spawning in the eastern Bering Sea. Wespestad and Barton (1981) estimated that the eastern Bering Sea herring biomass ranges from 0.374 to 2.75 million metric tons (mt). Results from aerial surveys in 1978 indicated that the coastal spawning biomass for the eastern Bering Sea was 432 to 864 thousand mt. Laevastu (1985) used biomass estimates of 1,409 and 1,121 (kg/km^2) for juvenile and adult herring, respectively, occurring in Port Moller when conducting his analysis. A recent study by McGurk (In Press) suggests that the minimum herring biomass spawning in Port Moller during the 1989 spawning period ranged from 1,764 mt (based on aerial surveys) to 1,788 to 2,241 mt (based on larval abundance).

Spawning occurs subtidally (McGurk, 1989) on marine vegetation (eelgrass and rockweed) throughout Moller and Herendeen Bays (Fig. 5) between early May and

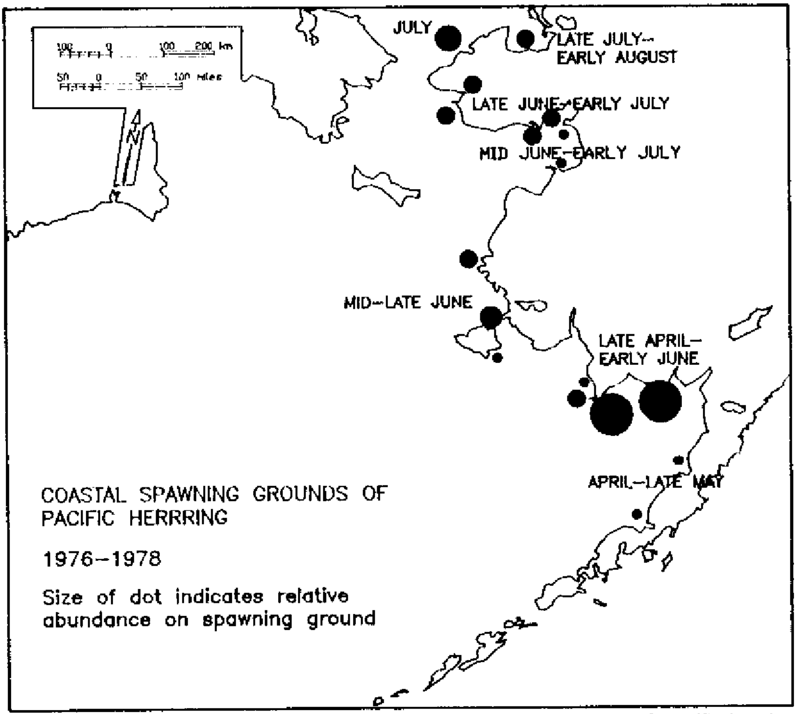


Figure 4. Distribution, spawning time, and relative abundance of Pacific herring in the eastern Bering Sea. Redrawn from Wespestad and Barton (1981).

late June. Winter-ice scour removes most of the intertidal vegetation in Port Moller. High-water turbidity within the Port Moller complex and poor weather conditions in the region make spawning surveys, both aerial and shipboard, difficult. As a result, shoals of pre- and postspawning adults are seldom seen for more than one or two tidal cycles, and clouds of milt in the water indicating active spawning are seldom observed. To date, efforts to collect developing herring eggs spawned within the estuary have not been successful (McGurk, 1990, pers. commun.). Therefore, the actual spawning beds have not been mapped, and the extent of potential spawning beds has been determined only by estimating the areal extent (using aerial photos of the area) of marine vegetation in areas where herring larvae have been collected.

Three cohorts of herring eggs hatched in Port Moller between May 10 and June 30, 1989 (McGurk, 1989). Initial observations indicate that three cohorts also hatched during the same time period in 1990 and that yolk-sac larvae that were collected in July suggested the existence of a fourth cohort (McGurk, 1990, pers. commun.); these data are currently being analyzed. Herring larvae collected in Moller Bay appear to grow faster than those collected from Herendeen Bay; this may be related to the warmer water temperatures observed in Moller Bay (Fig. 6) (McGurk, 1989).

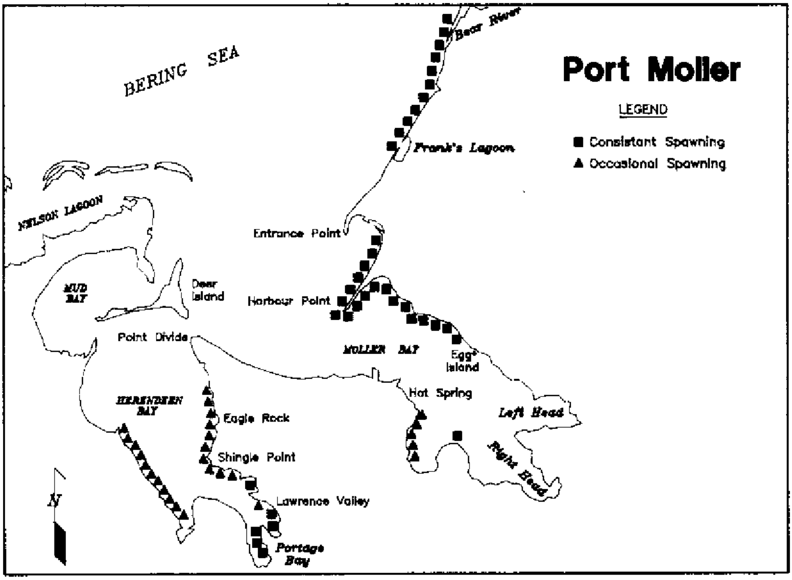


Figure 5. Distribution of herring spawning locations in Port Moller, Alaska. Redrawn from McGurk (1989).

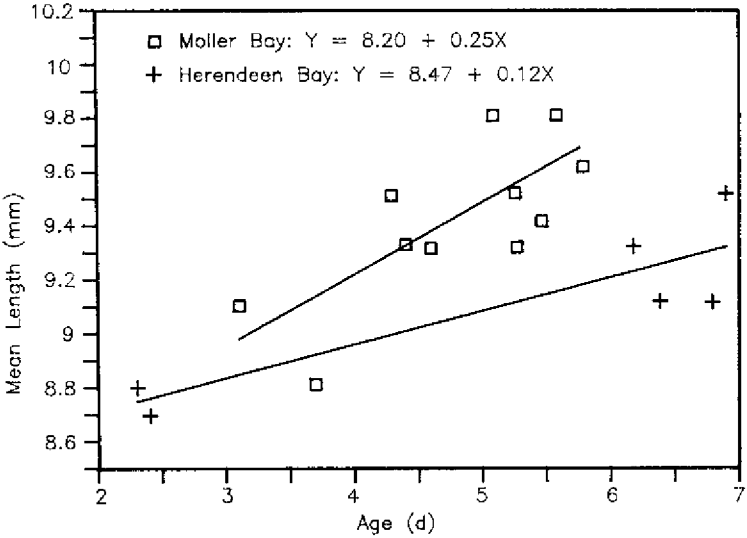


Figure 6. Growth Rates for Pacific herring larvae collected from Herendeen and Moller Bays, Port Moller, Alaska, in 1989 (McGurk, 1989).

Herring larvae undergo diurnal vertical migrations, apparently following their prey field (McGurk, 1989a). The younger larvae are found primarily in the top 15 m of the water column, whereas older, larger larvae have been found as deep as 35 m. At night, smaller larvae tend to be most abundant in the 5 m of the water column and the larger larvae in the top 25 m (McGurk, 1990, pers. commun.). Robertson, 1988, reported that herring larvae in British Columbia waters tended to be most common at depths between 5 and 10 m. The vertical distribution of larvae in the Port Moller estuary (McGurk, 1990, pers. commun.) is controlled in part by the degree of stratification or mixing within the water column. Off Harbor Point, a well -mixed area, larvae were collected throughout the water column, 0 to 25 m, whereas in Herendeen Bay--an area of limited vertical mixing--few larvae were captured below 15 m (larger larvae were found at the deeper depths). McGurk found herring larvae to be most abundant near the eelgrass beds off Right Head in Moller Bay and south of Bluff Point in Herendeen Bay. Other studies suggest that the herring will begin schooling and move out of the estuary as the season progresses, possibly by September.

RISK ASSESSMENT

The probability of an oil spill affecting a significant portion of the herring population or spawning and rearing habitat is expressed by the relationships presented in Table I. The effects (P_{effect}) that spilled oil may have on Pacific herring resources

Table I. Information needed to evaluate the potential effects of an oil spill on herring resources in Port Moller, Alaska.

$P_{effect} = P_{threat} \times P_{transport} \times O_{amount} \times O_{fate} \times T_{toxicity} \times R_{resource}$ where

$P_{threat} = P_{spill} \times P_{WMV}$

$P_{transport} = T_{shore} \times T_{PM}$

$O_{fate} = O_{floating} + O_{in\ water\ column} + O_{in\ bottom\ sediments}$

$T_{toxicity} = O_{concentration} \times D_{time}$

$R_{resource} = H_{spawning} + H_{rearing} + B_{biomass}$

P_{effect}	Probability of a significant effect on herring resources and habitats in Port Moller, Alaska.
P_{threat}	Probability of an oil-spill event occurring during the window of maximum vulnerability (WMV).
P_{spill}	Probability of a spill event occurring.
P_{WMV}	Probability of a spill event occurring during the WMV.
$P_{transport}$	Probability of oil spilled on or near tracts currently under lease for oil and gas exploration being transported by winds and currents into Port Moller.
$T_{to\ shore}$	Probability of being transported to shore.
T_{PM}	Probability of being transported into Port Moller.
O_{amount}	The amount of oil spilled.
O_{fate}	The fate of spilled oil, that portion that is floating or stranded, that is dispersed and dissolved in the water column, and that is deposited in bottom sediments.
$O_{floating}$	The portion of oil floating or stranded.
$O_{in\ water\ column}$	The portion of oil dispersed and dissolved in the water column.
$O_{in\ bottom\ sediments}$	The portion of the oil incorporated into the bottom sediments.
$T_{toxicity}$	The concentration of hydrocarbons and duration of exposure to the hydrocarbons needed to have a lethal or sublethal effect on herring.
$O_{concentration}$	The concentration of hydrocarbons on the surface, floating or stranded, in the water column, and in bottom sediments.
D_{time}	The duration of exposure to concentrations of hydrocarbons.
$R_{resource}$	The resources and habitat at risk from an oil spill.
$H_{spawning}$	Area of potential spawning habitat in the Port Moller estuary.
$H_{rearing}$	Area of potential rearing habitat in the Port Moller estuary.
$B_{biomass}$	Biomass of herring spawning within the Port Moller estuary.

in Port Moller are related to the probability of a spill occurring (P_{threat}); the joint probability that spilled oil will reach the coast and also will enter the Port Moller estuary ($P_{transport}$); the amount of oil spilled (O_{amount}); the time required for the spilled oil to reach the resource at risk (O_{fate}); the toxicity ($T_{toxicity}$) of the oil when it reaches the resource at risk [toxicity is a function of the amount of hydrocarbons dissolved or suspended in the water column ($O_{concentration}$)], the duration of exposure to oil ($O_{duration}$), and the herring's sensitivity to specific hydrocarbon compounds; and the resource at risk ($R_{resource}$), which in this evaluation include the spawning habitat ($H_{spawning}$), rearing habitat ($H_{rearing}$), and biomass of herring spawning in Port Moller ($B_{biomass}$). Other possible effects, i.e., bioaccumulation, reduction of prey density, etc., are considered minor (Varanasi and Malins, 1977; Cimato, 1980; and USDOI, MMS, 1990b) and are not considered in this evaluation.

Table II. The probability of an oil-spill event occurring during the WMV.

	Probability
Oil-Spill Event	57%
Oil Spill Occurring During WMV	19%

The WMV is 3 months long (May to July)

Source: USDOI, MMS, 1985c.

P_{threat} (Table II). The probability (P_{spill}) of an oil-spill event occurring as a result of gas and oil leasing in the area was evaluated in the Sale 92 EIS and also in the Environmental Assessment (EA) (USDOI, MMS, 1985a and 1985b) and the North Aleutian Basin Synthesis Report (Thorsteinson, 1984). The Sale 92 EA estimated that under the offshore-loading scenario, the most likely number of 1,000 barrels (bbl) or greater oil spills occurring is less than one; for spills greater than 100,000 bbl, the most likely number is 0. The probability of one or more spills of 1,000 and 100,000 bbl occurring is 57 percent and 7 percent, respectively.

The WMV for herring spawning in Port Moller is assumed to be 3 months, May through July, based on the time that spawning herring, spawned eggs, and larvae are most vulnerable to spilled oil. Information needed to determine the most probable season during which an oil spill is most likely to occur is not available. However, the author assumes that the probability (P_{WMV}) is related to the proportion of the year that is identified as the WMV (Table II).

Table III. Transport probability.

Probability of Spilled Oil Contacting the Coast Within 30 Days	
1,000-barrel spill	27%
100,000-barrel spill	2%
Probability of Spilled Oil Contacting Port Moller Within 30 Days	6%
Probability of Spilled Oil Contacting Coast (Port Moller) Within 4 Days	13%
Probability that Spilled Oil will Enter Port Moller Thorsteinson, 1984	20%

Sources: Liu and Leendertse, 1982; Thorsteinson, 1984; and USDOI, MMS, 1985a

$P_{transport}$. Table III indicates that the probability of a 1,000-bbl oil spill occurring and contacting the coast within 30 days is 27 percent. For a spill of over 100,000 bbl, the probability of coastal contact is 2 percent. There is a 6-percent probability of the spilled oil contacting the Port Moller area within 30 days following a 1,000-bbl spill. Figure 7 shows the simulated trajectories for an oil spill occurring at release point D-1 (near the area currently under lease) under summer (June-August) conditions (Liu and Leendertse, 1982). These trajectories indicate that the most likely path for spilled oil will be toward the east along the Alaska Peninsula. The trajectory analysis also indicated that sustained onshore winds (13% probability) could drive the oil onshore within 100 hours.

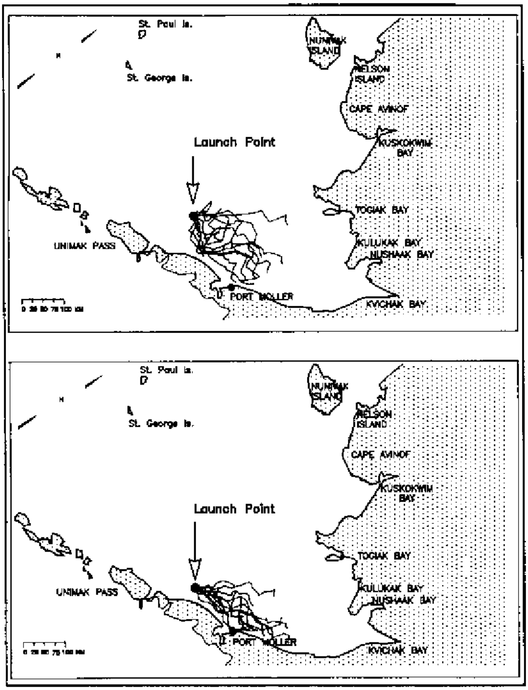


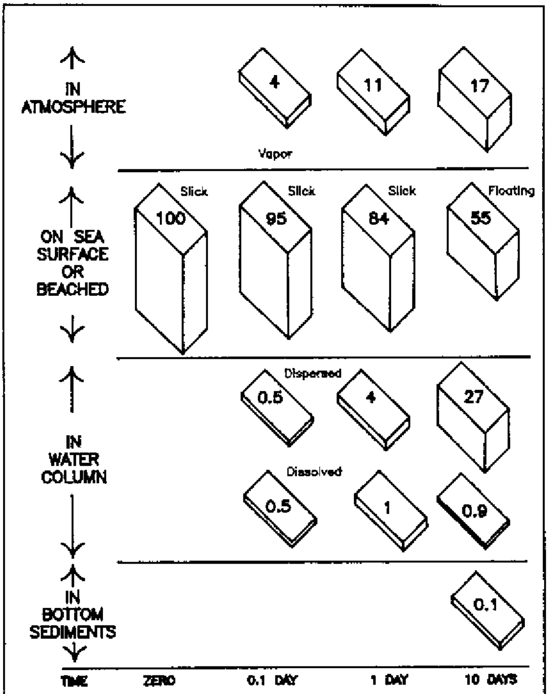
Figure 7. Simulated 30-day trajectories for oil spilled from launch points near tracts currently under lease (Liu and Leendertse, 1982). Redrawn from Thorsteinson, 1984.

Participants in the 1982 synthesis meeting chose to assume that 20 percent of the oil that reached the coast would enter Izembek Lagoon. Since similar conditions prevail off Cape Seniavin (Port Moller), they assumed similar probabilities for spilled oil reaching the coast in this area.

O_{amount}. The median-size spill for OCS platforms and pipelines is 7,000 and 6,000 bbl, respectively, and 9,000 and 11,500 bbl for U.S. and Alaskan tankers, respectively (LaBelle, 1990). Using similar statistics, participants in the North Aleutian Basin Synthesis Meeting in March 1982 decided to evaluate the potential effects of a 10,000-bbl spill (2,000 bbl spilled per day for 5 days) on regional resources.

O_{fate}. The rate of oil weathering is dependent on environmental conditions, wind, air temperature, water temperature, etc., and the specific composition of the spilled oil. Figure 8 summarizes the weathering process or partitioning of spilled Prudhoe Bay crude oil under subarctic conditions. Within the first 24 hours following a spill, 11 percent of the oil--mostly the volatile, highly toxic compounds--will have evaporated; 4 percent will have dispersed into the water column as small droplets; 1 percent will have dissolved; and the remainder, 84 percent, will be present on the surface as a slick or water-in-oil mousse. By the fourth day following the spill, only some 70 percent of the oil will remain on the surface (Thorsteinson, 1984). Under prevailing June wind conditions, the spilled oil will not persist as a contiguous slick but will form streaks or windrows, thereby increasing the area covered by the spilled oil (a 10,000-bbl spill may cover about 16 km^2).

By the 10th day following a spill, approximately 55 percent of the oil will remain on the surface as floating or stranded oil ($O_{floating}$). Once floating oil reaches the coast, it tends to be blown and washed ashore, where some will be incorporated into the beach sediments and the remainder will be remobilized during high tides and storm events. Twenty eight percent of the oil will be dispersed or dissolved in the water column ($O_{in\ water\ column}$), and a small fraction (1%) of the oil will have become incorporated in bottom sediments ($O_{in\ bottom\ sediments}$).



Distribution of an initial 100 vollums of oil, assuming winds of 5 m/s and temperature of 0°C at various times after release (Manen and Pelto, 1984).

Figure 8. Speculative mass balance for Prudhoe Bay crude oil (USDOI, MMS, 1985a).

$T_{toxicity}$. The Sale 92 EIS (USDOI, MMS, 1985a) reported that lethal effects on larvae and eggs were observed at concentrations of 0.1 to 1.0 ppm and that sublethal effects were observed at 0.01 to 1.0 ppm (Table IV).

Results from oil-effects studies are difficult to compare because of the differing experimental and analytical methods employed (Neff, 1990). More contemporary studies are exposing organisms to the water-soluble fraction (WSF) of crude oil (only a small fraction of the crude oil is soluble). The parameters used by Neff, 1990, are similar to WSF parameters used by other authors.

Rice et al., 1986 (Table V), concluded that larvae are the most sensitive lifestage, and they were killed by lower concentrations and shorter exposures than eggs or adults.

Table IV. Marine-organism sensitivity to seawater-soluble-petroleum fractions.

Concentration	Effect	Lifestage
1-100 ppm	lethal	adult
0.1-1.00 ppm	lethal	larvae, some eggs
0.01-1.0 ppm	sublethal	adult, larvae

Sources: Moore and Dwyer, 1974; Thorsteinson, 1984; USDOI, MMS, 1985a; and Laevastu et al., 1985.

The adhesion of oil droplets on developing herring eggs appeared to result in an increase in the occurrence of larval deformities, suggesting that developing eggs with adhering oil droplets may be exposed to higher concentrations for a longer period of time than those exposed to low levels (<4.7 ppm) of WSF (Pearson, 1985).

Laevastu et al., 1985, surveyed the oil-effects literature and concluded that for marine eggs and larvae, mortalities and serious sublethal effects can be observed at WSF concentrations of 100 parts per billion (ppb).

$O_{concentration}$ (Table VI). This variable can be divided into three components, floating oil, i.e., on the sea surface or stranded; oil in the water column as dispersed and dissolved oil; and oil in bottom sediments.

Table V. Results of herring-oil challenge experiments conducted by Rice et al., 1986.

Lifestage	Duration	Concentration	Result
Prespawn Adult	2 days	2.3 ppm	LC_{50}
	12 days	2.3 ppm	LC_{50}
Eggs in Adult	12 days	1.6 ppm	Normal Hatching
Eggs	2 days	5.3 ppm	Normal Hatching
	12 days	1.5 ppm	LC_{50}
Yolk-sac Larvae	<6 hours	6.0 ppm	Survived
	16-144 hours	2.8-2.3 ppm	LC_{50}
Larvae	7 days	1.8 ppm	LC_{50}
	21 days	0.36 ppm	LC_{50}
	7 days	0.3 ppm	Growth Reduced
	NA	NA	Growth Rates Not Reduced by a Diet of Oil-Contaminated Prey

An oil slick is broken into discontinuous patches by wind and wave action. The area covered by the oil patches is much greater (10-100 times) than the area covered by the initial oil slick. In the experiment conducted by Payne et al., 1984, Prudhoe Bay crude oil formed a stable emulsion within 48 hours under simulated wind conditions of 2 m/s.

Table VI. Maximum area affected by a 10,000-barrel oil spill, assuming that 100 percent of the oil remains on the surface, in the water column, or deposited in bottom sediments.

Floating Oil Slick, Contiguous[1]	.16 km^2
Floating Oil Slick, Noncontiguous[2]	16 km^2
Oil in Water Column[3]	546 km^2
Oil in Bottom Sediments[4]	2,730 km^2

[1] A contiguous slick 1 mm in thickness.
[2] A water-in-oil emulsion dispersed to 100 times the initial size.
[3] Oil in the water column (dispersed and dissolved) at a concentration of 0.1 ppm, 5 m thick.
[4] Oil in bottom sediments at a concentration of 0.1 ppm.

Figure 9 indicates that the concentration of petroleum hydrocarbons in the water column reaches a maximum within the first 24 hours following a spill. The concentration then decreases rapidly over the next 12 days. After 9 days, the concentrations of hydrocarbons in the water column will decrease to less than 0.1 ppm.

Observations made following the <u>Exxon Valdez</u> oil spill showed that the concentrations of volatile aromatic hydrocarbons (VOA) in the water column had returned to near background levels, 0.20 ppb (Fig. 10), within a month. Continued weathering of the oil and flushing of water from Prince William Sound were considered important factors in reducing the concentration of VOA in the water column.

Table VII. Estimated time that herring eggs and larvae could be exposed to concentrations of hydrocarbons exceeding 0.1 ppm.

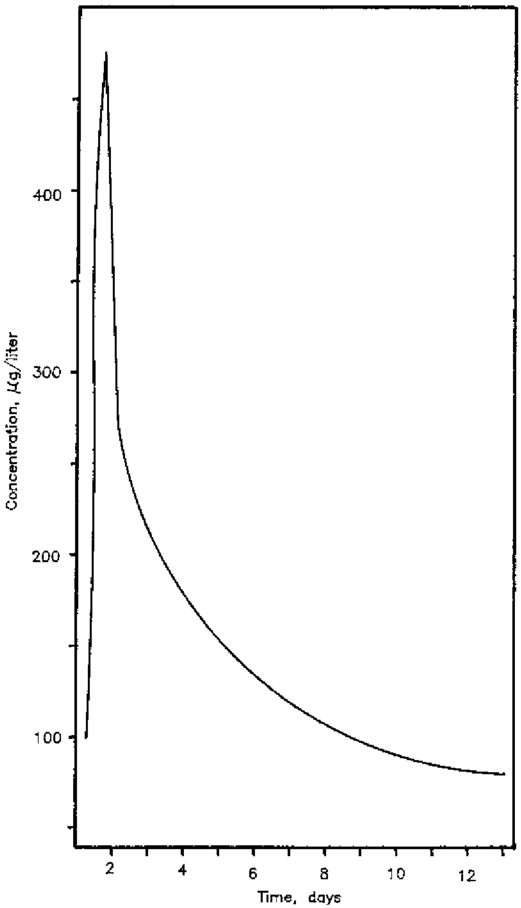
Source	Duration (Days)
Floating Oil	0 (<1)
Oil in Water Column	5
Oil in Sediments	> 1-Year

Sources: Payne, 1984; Thorsteinson, 1984;
and Neff, 1990.

D_{time}. Table VII provides an estimation of the length of time that herring eggs and larvae could be exposed to levels of hydrocarbons exceeding 0.1 ppm.

Herring eggs can be directly affected by contact with floating/stranded oil (smothering of eggs), dispersed or dissolved oil (toxic effects), and oil in bottom sediments.

Few if any herring eggs spawned in Port Moller will be exposed to floating oil because they are deposited subtidally, on marine vegetation. Exposure to floating oil is further reduced because floating oil tends to become stranded high in the littoral zone during high tides and storm surges, where it is incorporated in beach sediments. The oil, however, may persist as pancakes or tarballs for over a year and could expose to floating oil a portion of two year-classes of herring spawning in Port Moller.



Note: Observations were made by spilling Prudhoe Bay crude oil in outdoor flowing seawater wave tanks at Kasitsna Bay Alaska.

Figure 9. Observed concentrations of petroleum hydrocarbons in a moving water column under a slick of crude oil (Payne et al., 1984).

The length of time that eggs and larvae could be exposed to concentrations of dispersed and dissolved oil is a function of the oil-weathering and -flushing rate for Port Moller. Neff, 1990, observed a similar process in Prince William Sound when within 30 days following the spill, the concentration of toxic compounds returned to background or near-background levels. Therefore, the duration of exposure to maximum levels of hydrocarbons in Port Moller is expected to be less than 30 days. Observations by Payne, 1984, suggest that the concentration of hydrocarbons in the water column will decrease to less than 0.1 ppm within 9 days following a spill.

Oil that is incorporated in bottom sediments is weathered and contains low levels of VOA's and PAH's. The residence time for significant amounts of sedimented oil in offshore areas appears to be about a year. Inside the Port Moller estuary, resident times are expected to be shorter in shallow areas because of the comparatively higher energy and approaching a year in deeper areas because of comparatively lower energy levels (Thorsteinson, 1984).

$R_{resource}$. Estimates of herring resources at risk in Port Moller are presented in Table VIII.

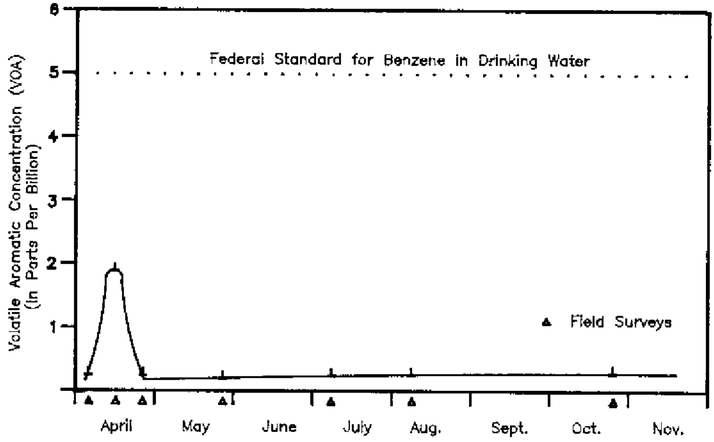


Figure 10. Average volatile aromatic concentrations from primary sites in Prince William Sound (Neff, 1990).

Table VIII. Potential spawning and rearing habitat and spawning biomass that could be affected.

Spawning Habitat ($H_{spawning}$) (Estimated Spawning Habitat)	**24 km²**
Rearing Habitat ($H_{rearing}$) (Estimated Area of Moller and Herendeen Bays)	**438 km²**
Estimated Herring Spawning Biomass	
Based on 1989 aerial survey	**1,764 mt**
Based on larval abundance	**1,764 to 2,241 mt**

Sources: McGurk, 1989b, and McGurk, In Press.

$H_{spawning}$. Information provided by McGurk, 1989, was used to estimate the aerial extent of eelgrass and rockweed beds (24 km^2) in Moller and Herendeen Bays that have been associated with spawning herring in the past (Table VIII).

$H_{rearing}$. Specific information on the amount of optimum rearing habitat for herring larvae in the Port Moller estuary is not available. However, information provided by McGurk, 1989, indicates that larvae tend to concentrate in Moller and Herendeen Bays. Therefore, these bays are considered prime rearing habitat. These two bays cover over half of the estuary, or about 438 km^2 (Table VIII).

$B_{biomass}$. Estimates of the biomass of herring spawning in the Port Moller estuary range from 1,764 to 2,530 (Laevastu, 1985) and 1,788 to 2,241 (McGurk, In Press). The adults have been observed throughout the estuary (Table VIII).

OIL-SPILL ASSUMPTIONS

Table IX lists the assumptions used in analyzing the potential risk to spawning Pacific herring and herring eggs and larvae in Port Moller, Alaska, from an offshore oil spill. This evaluation is based on the assumption that a median-sized oil spill will occur during the WMV and that it will occur on or near tracts currently under lease by MMS for oil and exploration (Fig. 1). The joint probability (Table II) of a median-sized oil spill occurring and that it would occur during the WMV were not factored into this analysis.

Table IX. Oil-spill-evaluation assumptions.

P_{event}	
$P_{oil\ spill}$	1 Spill
P_{WMV}	19%
$P_{transport}$	
$P_{to\ coast}$	13%
$P_{into\ estuary}$	20%
O_{amount}	10,000 bbl
$O_{floating}$	7,000 bbl
$O_{in\ water\ column}$	2,800 bbl
$O_{in\ bottom\ sediments}$	100 bbl
$O_{concentration}$	
$O_{floating}$	1 mm thick x 100 (dispersion rate)
$O_{in\ water\ column}$	0.1 ppm to a depth of 5 m
$O_{in\ bottom\ sediments}$	0.1 ppm per m^2
O_{fate} (partitioning)	
$O_{floating}$	11.2 km^2
$O_{in\ water\ column}$	153 km^2
$O_{in\ bottom\ sediments}$	27 km^2
$D_{exposure}$	30-Day Maximum
$O_{floating}$	0-Days
$O_{in\ water\ column}$	5-Days
$O_{in\ bottom\ sediments}$	0-Days
$H_{spawning}$	24 km^2
$H_{rearing}$	438 km^2
$B_{biomass}$	1,764 mt

It is assumed that there is a 13-percent probability that oil could reach the coast within 4 days and that the probability of oil entering Port Moller is 20 percent (Table IV).

A 10,000-bbl oil spill was assumed to be representative of the median-sized oil spills occurring on the OCS and is similar in size to a spill evaluated in the North Aleutian synthesis report (Table V). Based on information provided in Figure 5, 70 percent (7,000 bbl) of the oil would be floating or stranded after 4 days. After 10 days, 28 percent (2,800 bbl) would be dispersed or dissolved in the water column and 1 percent (100 bbl) would reside in bottom sediments.

Assuming that northeasterly winds prevailed for at least 4 days following the spill, 13 percent (1,300 bbl) of the oil could reach the coast. Of this amount, 70 percent or 910 bbl of the oil could be floating (based on 4 days of weathering), 28 percent or 364 bbl of the oil could be dispersed and dissolved in the water column (based on 10 days of weathering), and 1 percent or 130 bbl could be in bottom sediments (based on 10 days of weathering). The 4- and 10-day partitioning estimates were used to provide conservative estimates of the size of the areas that could be affected by an offshore oil spill.

For the purpose of this analysis, the area directly affected by floating oil was estimated by assuming that the oil spread to a uniform thickness of 1 mm and that the oil was dispersed into patches or windrows affecting an area about 100 times the undispersed size of the oil slick. The author assumes that the majority of the floating oil that enters Port Moller will be in the form of a stable water-in-oil emulsion and that it will become stranded along the high-tide line, where it will become incorporated in the beach sediments to slowly release petroleum hydrocarbons into the marine environment. Because the amount of oil that could be released into the estuary is assumed to be negligible, considering the weathered state of the oil and the amount that could be involved, it is not considered in this analysis.

The critical, i.e., lethal, concentration of oil in the water column and bottom sediments was assumed to be 0.1 ppm (Table V). To provide a conservative estimate of potential effects, oil dispersed and dissolved in the water column was assumed to be concentrated within the top 5 m. McGurk (1990, pers. commun.) observed concentrations of young herring larvae in this depth strata at night.
Port Moller herring resources that could be affected by an oil spill were divided into three lifestages: pre-spawning adults, spawned eggs, and larvae. The maximum

period of time that pre-spawning herring adults, spawned eggs, and larvae could be exposed to concentrations of oil exceeding 0.1 ppm is assumed to be about 30 days (Figs. 9 and 10). Since herring eggs in Port Moller are deposited subtidally and larvae do not reside on the surface, it is assumed that the duration of their exposure to floating crude oil would be minimal (0). Figure 9 indicates that pre-spawning adults, eggs, and larvae could be exposed to 0.1-ppm levels of dispersed and dissolved hydrocarbons for up to 9 days following an oil spill. Since in this analysis spilled oil would take about 4 days to reach Port Moller, the expected duration of exposure of fish, eggs, and larvae to oil in the water column would be shortened to about 5 days. Adult and larvae herring are not associated with bottom sediments; therefore, their exposure is assumed to be minimal (0). Since herring eggs are deposited primarily on marine vegetation and not on bottom sediments, their exposure to oiled sediments is also assumed to be minimal (0). However, a small but unknown portion of the eggs may be deposited on bottom substrate during the mass spawning process and, therefore, could be exposed to contaminated sediments.

The portion of the herring resources considered to be at risk from an offshore oil spill was assumed to be that portion of the habitat occupied by pre-spawning adults, eggs, and larvae. A conservative biomass estimate (1,764 mt) of pre-spawning adult herring in Port Moller was used in this analysis. The habitat occupied by the pre-spawning adults is expected to be similar to that used by the larvae (438 km^2). The aerial extent of potential spawning and rearing habitat was used to estimate the portion of spawned herring eggs and larvae that could be exposed to spilled oil. The estimate of spawning habitat available was based on an estimate of the aerial extent of marine vegetation (24 km^2) in areas where large numbers of herring larvae were collected and where spawning had been observed in the past. The extent of rearing habitat was based on the observation that most herring larvae were observed in Moller and Herendeen Bays; and because the bays account for about half of the area of the Port Moller estuary, the rearing habitat was estimated to include about half of the estuary, or about 438 km^2.

Table X. Potential effects of a 10,000-barrel crude-oil spill on herring resources in Port Moller, Alaska.

P_{event}	
$P_{oil\ spill}$	57%
P_{WMV}	19%
$P_{transport}$	
$P_{to\ coast}$	13%
$P_{into\ estuary}$	20%
$O_{amount\ entering\ Port\ Moller}$	260 bbl
$O_{floating}$	182 bbl
$O_{in\ water\ column}$	73 bbl
$O_{in\ bottom\ sediments}$	3 bbl
O_{fate}	
$O_{floating}$	0.5 km^2
$O_{in\ water\ column}$	4 km^2
$O_{in\ bottom\ sediments}$	1 km^2
$D_{exposure}$	30-Day Maximum
$O_{floating}$	0 Days
$O_{in\ water\ column}$	5 Days
$O_{in\ bottom\ sediments}$	0 Days
$H_{spawning}$	24 km^2
Potential portion of spawning habitat affected	17%
$H_{rearing}$	438 km^2
Potential portion of rearing habitat affected	1%
$B_{biomass}$	1,764 mt
Potential portion of spawning biomass affected	1%

[1] Based on the assumption that the spilled oil will reach Port Moller within 10 days and that it will have reached a stable water-in-oil emulsion by the fourth day.

RESULTS

Table X presents a summary of the potential effects that could result from a 10,000-bbl oil spill offshore, off of and upstream from Port Moller.

Assuming that northeasterly winds prevailed for at least 4 days following the spill, 13 percent (1,300 bbl) of the oil could reach the coast. Of this amount, 20 percent (260 bbl) would enter the Port Moller estuary. Of this 20 percent, 70 percent (182 bbl) of the oil would be floating, 28 percent (73 bbl) would be in the water column, and 1 percent (3 bbl) would be in the sediments. Floating oil could cover an area of about 0.5 km^2, oil dispersed and dissolved in the water column could affect an area of about 4 km^2, and 1 km^2 of bottom sediments could be affected. The duration of exposure of the herring resources to floating oil and oiled sediments was assumed to be zero, and exposure to oil in the water column was expected to be about 5 days. The analysis also indicates that approximately 17 percent of the spawning habitat and 1 percent of the rearing habitat could be exposed to critical levels of oil in the water column.

DISCUSSION

While it is possible that large quantities of oil from an offshore oil spill could enter the Port Moller estuary and could affect herring resources, results of this analysis suggest that if an oil spill occurred on or near offshore areas currently under lease for gas and oil exploration in the southeastern Bering Sea during the period when herring resources were most vulnerable to the potential effects from spilled oil, the probability of a significant effect to these resources is quite low. The primary variables that reduce the probability of a significant effect to the herring resources are distance and time.

The distance separating the spill site and the resource at risk determines the minimum time required for the spilled oil to reach the resource in question. This in turn determines the maximum amount and condition of the oil that could reach the resource at risk. The condition and amount of oil reaching the resource determines the toxicity of the oil and the portion of the resource that could be exposed to toxic levels of spilled oil.

The probability of an offshore oil spill having a significant effect on herring resources in Port Moller is probably less than that described in this analysis because the analysis did not consider the probability that the spill would occur during the WMV, that dispersed and dissolved oil would be distributed throughout the mixed layer rather than just the top 5 m, and that there are multiple herring spawnings each year.

Considering the oceanographic dynamics of the estuary, all of the herring resources in the estuary could be exposed to varying concentrations of dissolved and dispersed oil in the water column for varying periods of time. Observed concentrations of hydrocarbons seldom would approach 0.1 ppm and would generally be much less. Therefore, the observation that specific portions of the resources could be exposed to 0.1 ppm for up to 5 days is considered to be a worst-case possibility.

Results from studies of herring eggs and larvae conducted following the <u>Exxon Valdez</u> oil spill indicated that the presence of spilled oil had no measurable effect on hatching success, occurrence of abnormal larvae, or larval growth and mortality rates (McGurk, 1990a,b). These results suggest that the developing eggs and resulting larvae were exposed to levels of dissolved and dispersed oil less than that needed to elicit an acute response, i.e., death, deformity, or reduced growth rates.

Although results from histopathological studies conducted following the <u>Exxon Valdez</u> oil spill have not been released, it appears that even though fishes examined exhibited no overt response to the presence of spilled oil, hydrocarbons metabolites in liver bile and elevated levels of mixed function oxidases (MFO) were detected (anonymous comments made during discussions following the presentation of this paper). Therefore, even though hydrocarbons could be present in Port Moller following an oil spill at levels to low to elicit an acute response, sublethal effects could be observed for an extended period of time. Sublethal amounts of hydrocarbons could leach into the estuary from crude oil stranded in the littoral zone or be resuspended from bottom sediments during storm events. The presence of sublethal concentrations of hydrocarbons could probably be detected as elevated levels of hydrocarbons metabolites in liver bile and MFO enzymes. The long tern effects from exposure to sublethal concentrations of hydrocarbons is unknown. However, the observation that spawning populations of Pacific herring are found in areas where chronic hydrocarbon pollution is endemic, i.e., San Francisco Bay, Pudget Sound, etc. suggests that herring populations are able to tolerate exposure to sublethal concentrations of hydrocarbons that exceed those expected to occure in Port Moller following an offshore oil spill.

The study upon which much of the information used in this analysis is based was developed through the MMS-funded study, "Fisheries Oceanography of the Southern Bering Sea and North Aleutian Basin: Relationship of Larval Dispersion and Mortality of Herring Larvae to Environmental Conditions in the Port Moller Estuary," by Michael McGurk of Triton Environmental Consultants Ltd., Sidney, British Columbia (McGurk, 1990c).

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Impact of an Oil Spill on Herring Stock

L. Urho
Finnish Game and Fisheries Research Institute
Helsinki, Finland

ABSTRACT

In February 1987 the tanker Antonio Gramsci ran aground near the Söderskär Islands in the Gulf of Finland (Baltic Sea); 570 tons of oil spilled into the sea, remained between the ice two months before spreading, then "disappeared". Abnormal herring larvae were frequent near the Söderskär Islands in 1987 and 1988. The occurrence of herring larvae with curvature in posterior notochord revealed oil-affected areas. Prespawning herring were collected from commercial catches and the changes in gonadosomatic (GSI) and liversomatic (LSI) indices among herring from the affected area were compared with those from the control area. In the affected area the mean size of herring livers in 1987 was twice that in the control area, while almost the opposite was noted for the mean size of ovaries. In 1987 and 1988 the differences in the means between the areas were very significant, but decreased with time; in 1989 there was no significant difference. The absolute levels changed in both areas, partly due to dissimilar samples. However, the normal seasonal reduction of enlarged livers during gonad maturation did not occur in herring from the affected area, which resulted in smaller gonads.

The results demonstrated that while the oil spill affected local herring population in the Gulf of Finland, its effect on stock as a whole is not clear.

INTRODUCTION

Oil spills are common, but the impacts on fish stocks and fisheries have seldom been demonstrated. Fish are known to become contaminated, but to a lesser extent than zooplankton and benthic invertebrates (Teal & Howarth,1984). A clearly detectable impact on fish stocks was demonstrated after the Amoco Cadiz accident in 1978 when 250 000 tons of oil were released (e.g. Conan,1982). The effects on fisheries are easily masked under variable catches partly due to the year class fluctuation (Jones,1982).

The amount of oil spilled is not the only factor governing the damage caused, the type of oil, physiography and biota of the area, weather conditions, season, previous exposure of the area to oil and other pollutants, and the treatment of the spill are also important (Straughan,1972).

In the laboratory fish eggs exposed to hydrocarbons have most commonly yielded foreshortened larvae at hatching (Eldridge et al.,1978, Linden,1978, Smith & Cameron,1979, Stene & Lønning,1984, Tilseth et al.,1984). Several types of abnormal body curvatures have also been observed (Mironov,1969, Struhsaker et al.,1974, Lønning,1977, Smith & Cameron,1979). However, abnormal larvae have seldom been reported after an oil spill.

In the Baltic Sea oil spills have been frequent in the 1970's; the largest the Thesis in 1977 (1 100 tons released) and Antonio Gramsci in 1979 (5 000-6 000 tons released), were well documented (Kineman et al.,1980, Pfister,1980). Diminished spawning and hatching success was noted after the Thesis spill (Nellbring et al.,1980) and increase in the frequency of sprat larvae with damaged notochord ends after the Antonio Gramsci spill in 1979 (Parmanne & Axell,1980), but the results raised some doubts as to whether these were due to oil spillage. Notochord end damage and other abnormalities of herring larvae were observed after the Eira spill (300 tons released) in 1984 (Hudd et al.,1987, Urho & Hudd,1989).

On February 6, 1987 the tanker MT Antonio Gramsci ran aground in the Gulf of Finland and about 570 tons of crude oil were released into the ice-covered sea. The aim of this paper is to demonstrate how the herring stock in the Gulf of Finland was affected.

MATERIAL AND METHODS

The Occurrence of Oil

The spilled crude oil remained among the ice in the outer archipelago near the islands of Söderskär and Kalbådagrund (accident site) and drifted around the nearby sea area for more than two months, spreading over an estimated 2 500 km^2, before "disappearing" (Fig. 1). Small amounts of oil were deposited on shore by mid-May; floating oil was last seen on June 3 west from the accident site between Kalbådagrund and Helsinki. This area is also the most probable location where the sunken oil ended, since the main currents are westward and the winds were not capable of affecting the distribution of oil before ice breakup in late April.

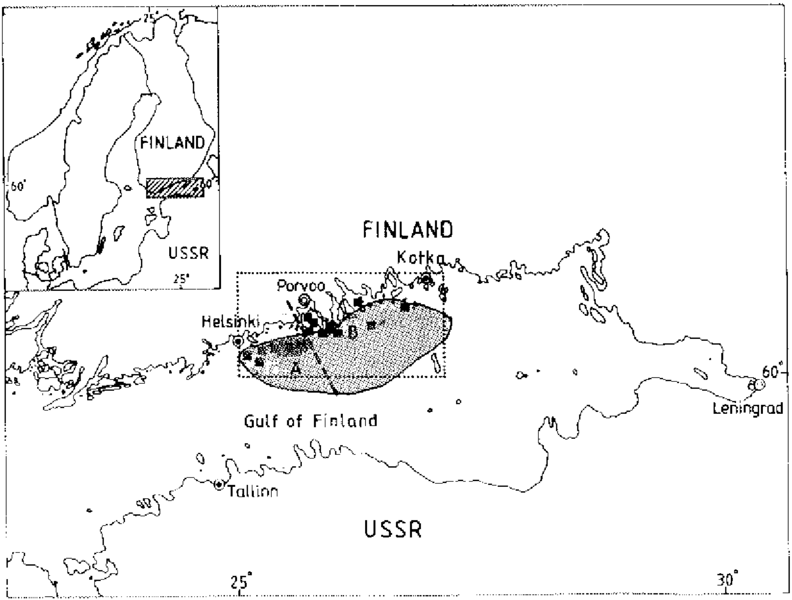

Figure 1. Study area. .... ★ Accident site. ░ Area where oil was observed. ▓ Area where oil affected for the longest time. ■ Sampling stations.

The Study Area and Herring Samples

The study area covered the entire area from Helsinki to Kotka (Fig. 1) where oil had been observed. This was divided into two subareas: Area A, west from the accident place (=affected area) and area B, east and north-east from the accident site (=control area). Unfortunately, area B also had oil after the first samplings in mid-May, when some oil returned.

Herring samples were collected from trawl and trapnet catches between April 20 and July 4 in 1987-90 at 14 stations (Fig. 1). In the final analyses the samples were grouped by stations into areas A and B. In 1987, 1988, 1989 and 1990 respectively 18, 9, 3 and 1 samples were taken, each containing 50-200 fish. Total length, weight, gonad weight, and liver weight were measured and the liver color, fin damages, sex and maturation stage (according to Kesteven,1960) were determined from individual fish (n = 2 820). Gonadosomatic (GSI) and liversomatic (LSI) indices were calculated in relation to total weight (grams) and multiplying by 100. Since the gonad weight and GSI increase with gonad maturation and body length only fish with maturation stages 4 or 5 (before spawning runs) with total lengths of 15-22 cm were used for the analysis.

Differences between the areas were tested with ANOVA. Discriminant analysis was used to show how the female

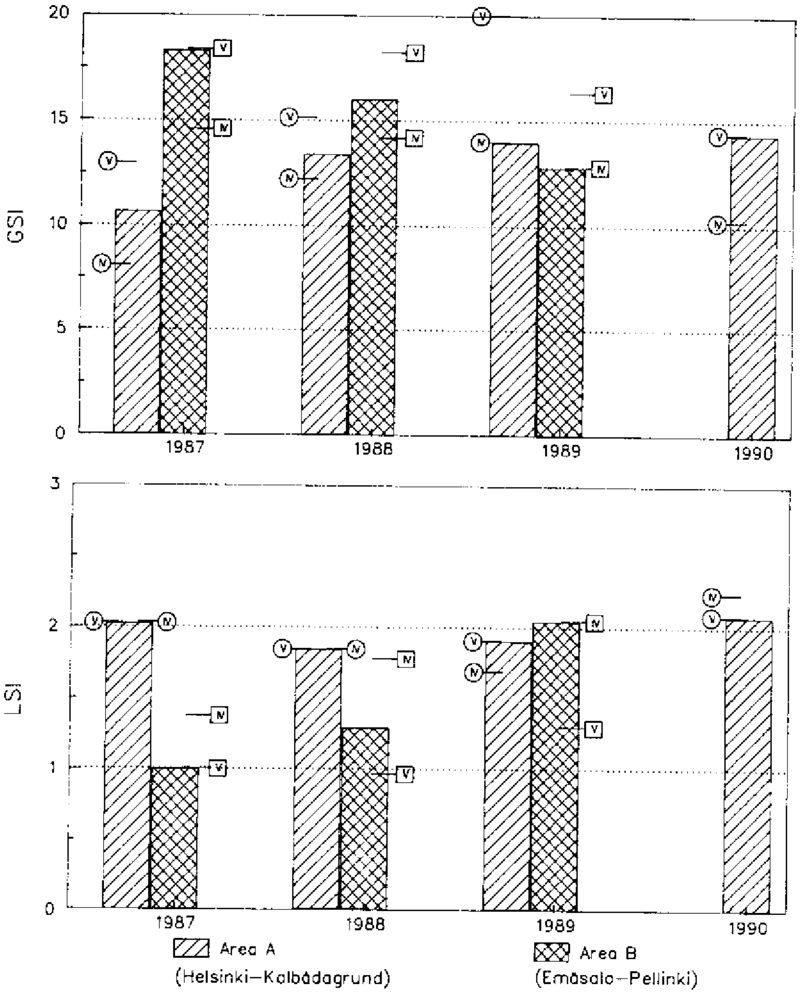

Figure 2. Mean GSI and LSI among herring females in areas A and B in 1987-90. Separate means for maturation stages IV and V, numbers encircled.

Difference between areas according to GSI and LSI. In 1987 it was possible to differentiate female herring area A from those of area B almost totally on the basis of LSI and GSI (Fig. 3). In 1988 there were still statistical differences in GSI and LSI values between the areas and discriminant analyses showed that about 70 % of the individuals could be assigned to their own areas (Table 1). In 1989 there was a totally mixed group of female herring. Individuals with high GSI and especially with low LSI had disappeared or were replaced by individuals with smaller ovaries or enlarged livers.

Table 1. Female herring assigned to areas A and B according to GSI and LSI in 1987-89 by discriminant analyses.

	1987		1988		1989	
	Area A	Area B	Area A	Area B	Area A	Area B
Area A	90	10	68	32	58	42
Area B	9	91	21	79	41	59

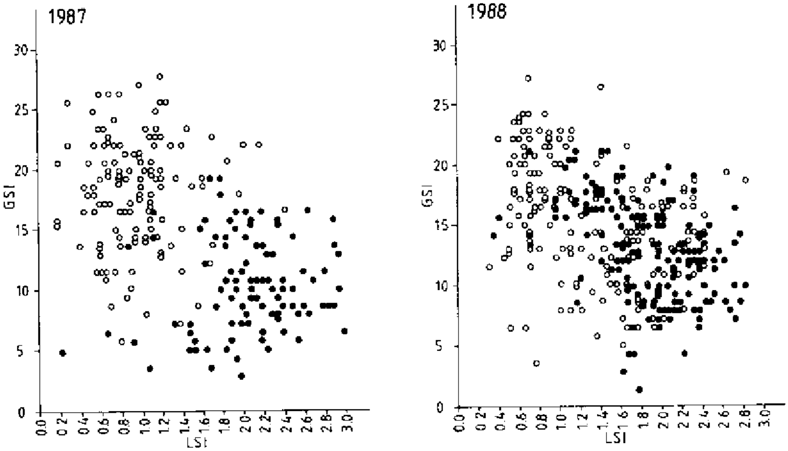

Figure 3. Female herring from areas A (filled circle) and B (open circle) plotted using GSI and LSI values in 1987-88.

<u>Liver color</u>. In area A over 30 % of the herring livers were yellowish in 1987 compared to 7 % in area B of all size groups. In female livers differences between the areas were less pronounced (Fig. 4) because the material used was selected (maturation stages 4 and 5 and length group 15-25 cm). Yellow livers were more common in small and less mature individuals in both sexes. However, the proportion of red livers increased in both areas during 1988-89.

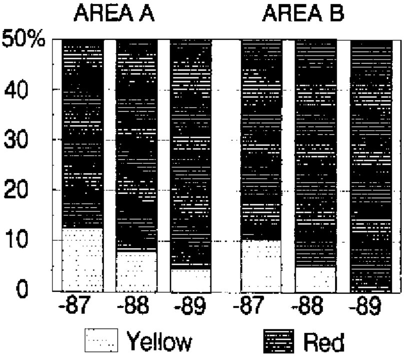

Figure 4. Liver color in herring females in areas A and B in 1987-89.

Damages in Herring Larvae

Length distribution. Captured larvae were 3-30 mm in length. The length distributions of herring larvae revealed that relatively foreshortened larvae were numerous in the samples of both years, while 10 % were less than 7 mm in 1987 and 5 % in 1988.

Deformed notochord ends. Curvatures in the posterior end of the notochord were the most common damage in herring larvae (Fig. 5), occurring mostly in herring less than 20 mm in total length. The mean frequency of this damage was 42 % of all larvae less than 15 mm in length in 1987 and 34 % in 1988. However, in both years over 50 % of the larvae between 7 and 12 mm had some curvature in the notochord end.

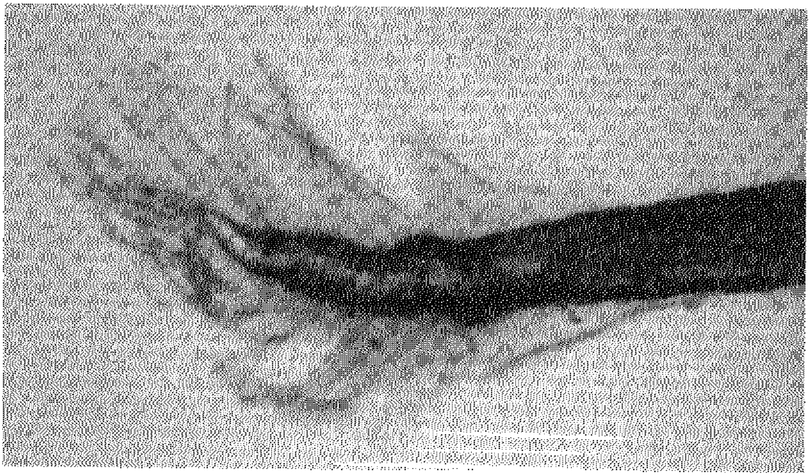

Figure 5. Caudal peduncle of a herring larva with deformed notochord end.

The highest frequencies (60 - 73 % of larvae less than 20 mm) of larvae with deformed notochord ends occurred west and northwest from Söderskär in both years and about 50 % of the larvae in some other areas, e.g. near Sköldvik (oil refinery) and off Helsinki. In areas east of the accident site (between Emäsalo and Pellinki) the mean frequencies were about 30 - 40 % and farther east about 10 - 30 %. However, in the easternmost area the mean frequency was 39 % according to samples taken with oblique hauls in 1987. The occurrence of herring larvae with deformed notochord ends decreased from 1987 to 1988 in most of the areas.

Abnormal, compressed, short-bodied herring larvae. Some of the larvae were abnormally curved, although the most common abnormality was a compression of some body part (Fig. 6). This compression (and apparently also deletion) of several myotomes shortened the total length, occasionally to half the normal body length. In the area of myotomal compression the body depth was often increased locally. Very often this abnormal body part was also mechanically damaged so that the myotomal structure was partly destroyed. However, the abnormally developed body part was not usually difficult to distinguish from purely mechanical damages.

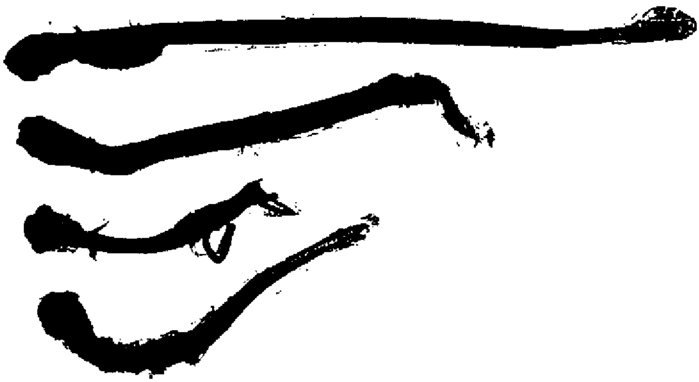

Figure 6. One normal herring larva (L=7 mm) and three abnormal, compressed larvae sampled near Söderskär after the oil spill in 1987.

The large proportion of foreshortened herring larvae can be partly explained by the occurrence of abnormal herring larvae. Larvae with compressed bodies occurred among herring up to 17 mm in length, but were most common in larvae of less than 7 mm.

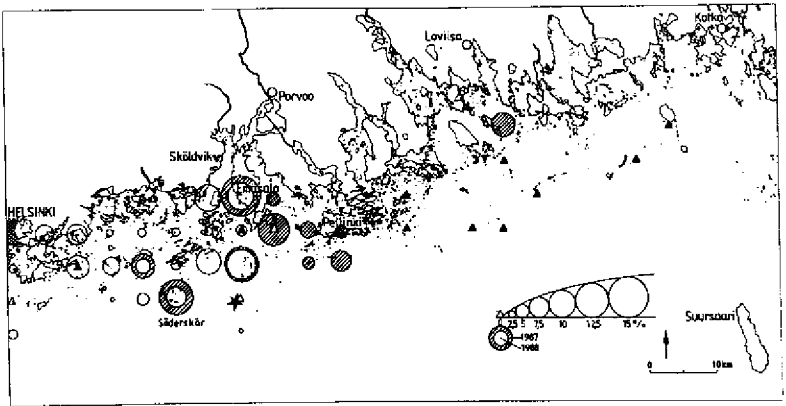

Figure 7. Occurrence of abnormal herring larvae in 1987-88 expressed as frequencies among larvae of less than 10 mm TL.

The highest mean frequencies (15 % in 1987 and 11 % in 1988) occurred near Såderskär and Emäsalo, west and north of the accident site (Fig. 7). The frequency decreased from 1987 to 1988 in most of the squares with sufficient amounts of larvae in both years. The only exception was the area northwest from Söderskär where the mean frequency went up to 8 % in 1988. In 1987 in (Pellinki) the area northeast of the accident site the frequency of larvae with compressed bodies was 5 % and in the area farther east the damage occurred only occasionally. In the Gulf V samples from the Valko field station the mean frequency was 3.1 %. In the Söderskär area the proportion of damaged larvae/haul exceeded 20 % at some stations.

DISCUSSION

Herring Larvae Detect Oil in the Water Column

After the previous Antonio Gramsci oil spill in 1979, Parmanne & Axell (1980) observed that sprat (Sprattus sprattus) larvae with deformed notochord ends were more common after the spill than in previous years. By regrouping and calculating the frequencies it was found that among larvae less than 15 mm in length 48 % were damaged in 1979; for 1975-78 damage frequencies varied 12-17 %. After the Eira oil spill 29 % of the herring larvae in the Northern Quark had some notochord end damage and in the size class of 7.5-15.5 mm 40 % (Hudd et al.,1987, Urho & Hudd,1989). In the same study a preliminary laboratory test confirmed that a drop of water-soluble oil fraction of oil is able to make the notochord end of certain size smelt larvae deformed (Hudd et al.,1987). In the Gulf of Finland 42 % of the herring larvae less than 15 mm in length sampled in 1987 had curves in the notochord end and during 1988, 34 %. The prevalence was highest near the area where oil remained for the longest time. However, fairly high damage frequencies also occurred in some other areas with busy shipping routes as well as off the oil refinery. After the oil slicks had disappeared no increased hydrocarbon concentrations could be detected from water samples, suggesting that the frequency of herring larvae with deformed notochord ends can be used as a sensitive indicator of the presence of oil in a certain water area. The larvae may, however, be over-sensitive so that the effects of oils of different origins cannot be distinguised (i.e. fish larvae in shipping lanes are more easily exposed to hydrocarbons). The method needs more testing in both the field and laboratory.

Enlarged Livers and Small Ovaries Reflect Exposure of Adults to Oil

After the spill mature herring ovaries in the affected area never reached the size of those in area B which appeared normal. The reduction of relative gonad weight in areas polluted by oil has also been observed in previous investigations (Miossec,1981, Hudd et al.,1987) and is also consistent with laboratory studies (Payne et al.,1978, Rowe et al.,1983).

Other factors may also affect GSI, leading to biased results (e.g. in Whipple et al.,1978). That GSI increases with fish size was already taken into consideration by selecting the fish lengths of 15-21 cm; however, GSI still correlated with length. Since the length distributions of herring collected from the two areas were not identical the difference between the areas was confirmed by inspecting all size classes separately (Table 2.).

Table 2. The mean GSI of female herring in 1-cm size groups from the areas A and B in 1987-89.

	1987				1988				1989			
	Area A		Area B		Area A		Area B		Area A		AreaB	
TL (cm)	GSI	n	GSI	n	GSI	n	GSI	n	GSI	n	GSI	n
< 17 cm	9.7	41	14.5	33	9.0	41	11.5	95	10.1	6	11.4	45
17 - 18	10.1	22	16.8	10	13.0	37	15.7	45	13.3	6	11.5	23
18 - 19	12.5	15	18.0	19	13.6	33	15.1	51	15.2	6	10.8	14
19 - 20	15.2	2	20.1	11	13.2	27	18.4	21	14.8	2	13.2	9
> 20 cm	10.3	5	20.9	52	15.6	53	19.4	78	15.2	11	13.5	28

The GSI increases with maturity (e.g. Hay,1985). This observation invalidates the contradictory results presented by Whipple et al. (1978). The mean GSI values in Figure 2 also exaggerate the difference between the two areas, but in spite of this gap between the maturation stages the difference between the areas still exists and is real. The GSI among female herring in area A was lower in both maturation stages in 1987.

The reduced GSI in area A coincides well with the enlarged livers observed in the area compared to the more normal sized livers in the area B. The difference in LSI between the areas is, however exaggerated because of the low proportion of maturation stage 4 females area B in 1987. According to Krivobok (1964) the LSI of herring decreased sharply during maturation stages 4 to 5. Some compounds in the liver are mobilized for egg maturation (see e.g. Love,1970, Dodd,1983). In area A there was no difference in LSI between stages 4 and 5, which suggests that liver material had not been exploited normally for reproduction. In Brittany exceptional values in the LSI cycle were also observed in plaice exposed to spilled oil (Miossec,1981). The author associated the smaller eggs with less yolk and reduced gonad weights with liver metabolism.

The enlarged livers and gonads of incomplete size in area A lend support to the theory that detoxification of oil components in the liver inhibits the mobilization of energy and liver material used during egg maturation in gonads. Similar observations of GSI and LSI values after the Eira spill in the Northern Quark also support this theory (Hudd et al.,1987).

Payne et al. (1978) reported the occurrence of liver discoloration after exposing fish to crude oil for 1-2 weeks. Except for enlarged livers Hudd et al.(1987) also noticed exceptionally pale or yellow livers in perch taken from the oil contaminated area. In the Gulf of Finland the proportion of herring with yellow livers decreased during

1987-89, which could indicate a state of recovering was in progress.

Reproductional Losses and Recovery

That gonads in area A were smaller may indicate reduction in the number of viable larvae available for hatching, as indicated by laboratory tests (Kühnold et al.,1978). To estimate the amount of herring larvae in area A was impossible. The prevalence of abnormal larvae was easier to estimate, although the mean frequency is influenced by the proportion of samples between areas A and B.

In the southern Baltic Sea the frequency of abnormal sprat embryos increased from 12 % in 1979 to 50 % in 1981 while abnormal sprat and flounder larvae with foreshortened caudal peduncles were also found (Grauman & Sukhorukova,1982). According to the authors all the observed deformations in embryos were analogous to the results of experimental investigations on the toxic influence of detergents and oil-products toxic influence on eggs. Although the Antonio Gramsci spill in 1979 was not directly associated with the results, the anomalies in Baltic Sea fish eggs were assumed to be brought about by oil pollution (Grauman,1986). Abnormalities, such as foreshortened and curved bodies in herring and gobiid larvae were reported as sublethal effects of the Eira spill in the Northern Quark (Urho & Hudd,1989). The abnormalities observed in herring larvae in the Gulf of Finland (Fig. 6) after the crude oil spill of Antonio Gramsci were not exactly the same as in the Eira spill (heavy bunker oil). Various oils and oil fractions cause different effects (Lønning,1977).

The proportion of abnormal herring larvae in the Gulf of Finland was only up to 20 %. The sampling was mainly done in surface waters, which suggests that the probability of occurrence of abnormal larvae with reduced swimming ability in the samples may be lower than that of normal larvae. As expected, high frequencies of abnormal larvae were observed in area A. The frequency of abnormal larvae decreased from 1987 to 1988. Adult herring with reduced gonads and enlarged livers were also sampled in this area.

The increase in GSI in area A seems to indicate a process of recovery, while the changes in area B suggest that herring spawning in that area might also have been affected after sampling in 1987. The unusually high damage frequencies in the notochord end in 1987-88 agree these findings. Another possibility is mixing of populations; herring in the Gulf of Finland migrate from different spawning areas into feeding areas where the spawning populations mix while a part of the stock even migrates out from the Gulf during winter (Parmanne, 1990). However, this can hardly can explain the changes in GSI and LSI if the spawning populations from area B should home to their own spawning grounds, where yearly sampling took place.

CONCLUSIONS

Relatively small oil spills may also cause effects on fish, which can be demonstrated. The shallowness of the area, as well as the proximity of the spawning season and spawning grounds may have contributed to the impact.

The Antonio Gramsci oil spill in 1987 was relatively small, but did affect herring stock in the Gulf of Finland since the occurrence of low GSI, high LSI, affected herring larvae correlate with occurrence of the spill while no environmental changes in the area other than the oil spill are known to have occurred.

The severity of the impact cannot yet be judged. It is already known that herring catches in the Gulf of Finland were about their usual level in 1987. Remarkably reduced GSI values and the occurrence of severely abnormal larvae indicate reduced reproduction, but high natural mortality during the larval period may also cover up the losses of less viable offspring. Whether the year classes 1987-88 will be "normal" or not remain to be seen.

ACKNOWLEDGEMENT

I express my thanks to all the colleagues, graduate students and friends who helped in the field works and those who assisted in development of the ideas presented here. I am especially grateful to Richard Hudd for his ideas and support during the study years, to Sari Laurila for her assistance and critical comments on the manuscript, to James Thompson who revised the language, and to Ritva Lehtonen, Pia Åkerman and Jyrki Lappalainen for drawing the figures.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

How Much Is Herring Spawn Worth? Potential Economic and Ecological Consequences of Impacts on Herring Spawning Areas

D.E. Hay
Department of Fisheries and Oceans
Nanaimo, British Columbia, Canada

ABSTRACT

The protection and preservation of established herring spawning areas is essential for the maintenance of abundant stocks. A detailed examination of records of herring spawning collected for 50 years in British Columbia has assisted in the identification and classification of all major spawning areas. The direct economic value of herring spawning areas can by estimated by comparing the worth of the fishery to the linear length of annual spawn. In addition to its direct economic contribution to the fishery, there also are indirect economic contributions because, as an abundant prey species, herring also contribute to the support of other commercial and recreational fisheries. In British Columbia, the average present annual economic (landed) value of herring is about $50 million (Cdn.). With a total linear distance of spawn of about 440 km, the average value of spawn is then worth about $110,000.00 per km per year (or about $110.00 per meter per year). This is the average value for all spawning areas. Some prime spawning areas would be much more valuable, perhaps 10 times more. Using this as a guide, economic cost of impacts can be estimated. Impacts that remove areas as potential spawning sites have a direct economic cost in terms of lost potential revenue that would have been gained if the impacts had not proceeded.

INTRODUCTION

The gradual industrialization of the British Columbia coastline has raised concerns from Industry and government about possible environmental impacts on herring spawning areas. There also are concerns about impacts on herring roe-fishery sites which occur mainly in the vicinity of spawning areas. Decisions affecting the integrity of herring spawning habitat are made routinely but it is not always clear whether the decision makers are aware of the real value of spawning habitat.

This paper points out that virtually all of the herring spawning habitat of the 20,000 km British Columbia coastline has been identified and classified (Hay et al. 1989a-f). On the basis of this analysis, it is possible to estimate the relative magnitude of spawn deposition of various locations. Further, the economic value of these spawn areas can be determined in terms of the worth of the roe fishery that is dependent on spawn areas. The paper presents a brief review of the methods and results used in the 1989 analyses and then presents a simple method to calculate economic worth of spawning areas.

METHODS

Since 1937 the annual deposition of herring has been measured and published for most parts of the British Columbia coast. In some locations, the data collections started in 1929. For most areas of the British Columbia Coast, there are records indicating, within a distance of 1 km, the date and quantity of spawn deposition. The detailed methods and results are described fully in Hay et al., 1989a-f). For the present analyses, total length of spawn is the most useful measurement. Impacts that affect shorelines, and therefore spawning habitat can be quantified in terms of the distance of shoreline impacted.

The economic value of the annual herring catch, between 1982 and 1986, was taken from the Annual Summary of British Columbia Catch Statistics (Anon. 1982, 1983, 1984, 1985, 1986). The value can be estimated as the worth of the 'landed' catch (Table 1). The years chosen, 1982-1986 are representative of the herring roe fishery. Also, the review of the geographical analyses of spawn distribution considers the 50 year period between 1937 and 1986. The economic value of herring spawning locations was estimated by comparing the annual cummulative lengths of spawns with the landed value of the catch.

RESULTS

When the entire British Columbia coast is considered, over 4400 km of shoreline (about 22 % of the total coast) have been used as spawning habitat at least once during the 50 years between 1937 and 1986. About 3700 km (17%), has been used 2 or more times and about 1200 km (6%) has been used 10 or more times. Some specific locations have been used almost continuously, (i.e. 50 times in 50 years) since the records were first

Table 1. Spawn deposition, landed value of catch and estimated value of herring spawning areas, 1982-1986.

Year	Spawn length (kms)	Landed value ($000)	Value per m/year
1981-82	486.7	$35,929	$ 73.82
1982-83	465.2	$53,393	$114.77
1983-84	410.6	$44,365	$108.05
1984-85	404.4	$63,105	$156.05
1985-86	434.8	$46,209	$106.27
Average	440.4	$48,600	$110.35

started. Approximately 77% (or 3400 of the total 4400 km) of known spawning areas have supported repetitive spawnings. These areas must be considered as important spawning areas, worthy of stringent conservation.

Based on the data in Table 1, an average of about 440.4 km of spawn, between 1982 and 1986, supported a sustained fishery worth over $48 million Canadian dollars (or about $40 million U.S.). (Note: it is coincidental that the average length of spawn, 440 km, is exactly 10 % of the total recorded spawning range of 4400 km). The wholesale value of the roe fishery is substantially greater, usually 2 to 3 times the landed value. The value of a unit length (i.e. km) of spawning area can be estimated by dividing the total average value by the average length of spawn (or $48 million/440 km). Therefore as an approximation, herring spawn is worth about $110,000 per km per year (or $110 per linear m per year), based on the landed valued. If wholesale value were used, spawning areas would be worth more than $200.00 per year per linear m of coast. These estimates represent the average worth for the entire coast. If the analyses were restricted to selected spawning areas with the greatest widths and egg densities, then the value of these areas would be much greater, by at least a factor of 10, for a worth of about $1000 (landed) or $2000 (wholesale) per year per linear m.

DISCUSSION

Economic Value of Herring Sawn

The estimate of $110 per m per year as the annual economic value of herring spawn is an approximation. If the industry had to pay annual rent for the herring spawning area, it would cost as much as $110,000 per km. If the present fishery for herring roe were worth less, then the estimated value of spawning habitat would be less, and vice versa. Clearly, the exact value will change between years (Table 1). However, the intent of this analyses is to show only that herring spawning habitat has tangible and substantial economic value. Even if there were no herring fishery, herring spawning grounds would remain valuable because herring are a vital component in a trophic web, and as such, they support other commercially valuable species. For instance, in British Columbia, chinook and coho salmon are of particular importance to the recreational salmon fishery and these species rely heavily on herring in their diet. There also is a value to herring that transcends economic considerations. Herring provide a food base to non-harvested species of birds and marine mammals that are protected and prized, but not harvested. This form of value is self-evident.

Ecological Consequences of Impacts on Spawning Areas

At the present time, there are no satisfactory methods of replacing lost spawning habitat or enhancing existing spawning habitat. Attempts to move eggs between spawning areas, while successful in the production of larvae, did not lead to the establishment of new spawning runs (Hay and Marliave 1988). An important conclusion from this work is that at the present time there is no reliable way to enhance existing spawning areas or create new ones. Therefore, if herring stocks are to be sustained, it is vital that existing spawning habitat be maintained and protected.

The economic value of herring spawn in each year is based on the assumption that actual and potential herring spawning habitat is limited (although this is not to say that herring spawning habitat is a factor limiting population size at the present time). It also is assumed that the total amount of spawn deposition each year is required to produce the stock which sustains the present fishery. If reproductively mature Pacific herring are harvested at a rate of 20% a year, a figure suggested by Doubleday (1985) and Ware (1985) as one that can maintain relative stability, then theoretically, at least 80% of the available spawning habitat should be maintained. Obviously, this assumption assumes a simple relationship between the stock (as represented by eggs) and the subsequent recruitment. Such as assumption is certainly an oversimplification because most fishery models assume that at very high stock levels (or high spawn depositions) recruitment may be impaired. Nevertheless, in some circumstances, substantial areas of spawning habitat could be removed without any noticeable decrease to recruitment. However, such habitat loss could result in a decrease in the resilience of a stock to maintain normal abundance levels.

Research on Herring Spawning Habitat

In recent Symposia on herring, little attention has been paid to issues concerned with quality of herring habitat. This was true of the 1968 ICES conference in Copenhagen (Saville 1971), the 1980 Alaska herring Symposia in Anchorage (Melteff and Wespestad 1980), and the 1983 Pacific herring Symposium in Nanaimo (Brett 1985), with the exception, perhaps, of a paper on the effects of eutrophication by Aneer (1985). This is an observation, not a criticism. I suggest that the trend may be changing in the present Symposium which has at least 5 contributions related to habitat issues. However this still is a small proportion of the total effort. As herring biologists and managers, we may overlook habitat considerations at the peril of the stability and preservation of the resource.

Recognition of the importance of habitat research

The recognition of the economic significance of spawning habitat for marine species like Pacific herring has been slow to develop. In terms of the effort for managing the fishery for Pacific herring, and other herring populations throughout the world, there is considerably more effort directed at estimating parameters of population dynamics (age, growth, gear selectivity, etc.) than there is in the effort to define, control and protect habitat. The relative lack of interest in habitat, as a component of fishery science, may be because the subject lacks the 'rigor' of other scientific approaches. If so, it may simply be a reflection of the lack of support and activity for research in habitat related issues. Another reason for the low level of effort directed at habitat research could be and implicit assumption that habitat issues are inconsequential, ecologically and economically. I believe this to be false. Hopefully, some readers might agree.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Kokechik: The Making of "Just a Small Fishery"

H. Sparck
Harold Sparck and Associates
Bethel, Alaska

Joe Paniyak
Kokechik Corporation
Bethel, Alaska

ABSTRACT:

For the villagers of Hooper Bay and Chevak, development of a commercial herring fishery in Kokechik Bay was both a challenge to their subsistence way of life and an opportunity to secure an economy in a cash poor section of Alaska's Bush without salmon opportunities. Their efforts to construct a working system to protect longterm conservation and subsistence values, and provide much needed cash is a model for other undeveloped fourth world communities buried in a developed nation's economy. If and when the eastern Bering Sea herring resource recovers from its current low period of productivity and ocean interception, the apparatus to continued the local fishery is in place.

During a twelve year period, village fishermen in Hooper Bay and Chevak struggled against foreign fishing empires, insensitive State and Federal governments, and nomadic non-local boats intent of capturing the entire commercial product. Concerned for subsistence use, and herring as a prey species for preferred subsistence resources like salmon and marine mammals, these villages initially attempted to repeal State commercialization of the resource. Their efforts failed at both the administrative and judicial level. They next engaged in a meticulous effort to limit fishing competition by seeking strong conservation goals for resource managers, funding for research, a loan on their own labor to construct a fishing fleet, and preferential harvest privileges to capture economic benefits from the resource.

SUBSISTENCE USE OF HERRING IN KOKECHIK AREA

Unlike Nelson Island, which maintained its reliance on herring in spite of overfishing by foreign fleets in the early 1970's, Kokechik area villages switched to chum salmon as their principle fishfood. Nelson Island does not have salmon as an alternate marine fish. Subsistence surveys taken by
(N.K. 1974)
Nunam Kitlutsisti in 1974 during a period of low herring abundance found that salmon was the dominate fish harvested. Fish accounted for 70% of the harvested protein. Salmon amounted to 35% and herring 6%. of that total. Occasional studies conducted by the Alaska Department of Fish and Game's
(Bergstrom. 1988;Hamner,988)
[ADFG] Commercial Fisheries and Subsistence Divisions on annual subsistence herring take confirms a lower per family herring harvest in the Kokechik area.

Herring spawn in Kokechik, a bay now uninhabited. Three distinct runs of herring, separated by size and age, cycle through both Hooper Bay and Scammon Bay on their way to spawn, and are fished for subsistence. Both bays are closed to commercial fishery due to local wishes. Villagers from both bays journey to Kokechik Bay to harvest herring roe on rock kelp after the 2nd run of herring has ended. Local villagers agree that fluctuations in the annual size of herring requires multiple gear sizes. Herring quality can also differ due to fat content. Since drying time is short, villagers prefer herring with little body fat. Living in the marine environment, and without refrigeration, herring are air dried. With warm weather comes bugs, and their larvae. Villagers must take their herring just after the ice goes out, and before the sun and winds appear so that drying is completed to prevent the fat from turning rancid.

THE COMMERCIAL FISHERY

Historic Eastern Bering Sea Commercial Fisheries

Herring operations existed in Norton Sound at Golovin and in the Aleutian Islands from 1909 to the mid-1940. Herring was brined in salt and pickle spices in first the Norwegian, then the Scotch method, and were also reduced. Alaskan Natives were involved in the commercial fisheries in the Golovin area in 1940, and in the general Norton Sound area beginning again in the 1960's.

Japanese/Soviet Exploitation at Sea and Near Shore

Once overfishing began to reduce Western Bering Sea herring stocks, Soviet scientists began acoustic surveys in the Eastern Bering Sea in 1960. Their research paved the way for the Soviets to expand their 1959 commercial operations, and peaked in 1969-70 and again in 1973-74. Japanese herring fishing took place as by catch until 1964 when the International North Pacific Fisheries Commission [INPFC] waived herring as an abstention species. Large stern trawl operations reportedly began in 1968, and peaked in the early

1970's. The Japanese gillnet fleet began to harvest roe bearing herring in the Eastern Bering Sea in 1968 after being expelled by the USSR from its Western Bering Sea operations under the USSR-Japanese Joint Fisheries Agreement. Indifferent record keeping, and the absence of U.S. observers made the reported tonnages suspect.

During this period of time, Kokechik villages noticed the decline in herring spawn on kelp during the 1970's. During harvest of roe bearing kelp in the Kokechik Bay, these estuary fishermen noticed Japanese gillnet boats fishing close enough to the beach to have the faces of their crew "seen through binoculars," a violation of the 1966 Bartlett Act. U.S. Coast Guard investigators appeared on Nelson Island in 1973 to check on reported illegal fishing by Japanese boats in the Etolin Straits, net debris on the beach, and a dramatic decline in older age herring in the spawning biomass.

1976 Magnuson Fisheries Conservation and Management Act

Working in conjunction with Nelson Island, Kokechik villagers asked the Alaskan Congressional Delegation in 1973 to support a 200nm zone in the bill introduced by Senators Magnuson and Stevens. They urged the Congress to take immediate action to conserve the dwindling Eastern Bering Sea herring stock.

North Pacific Fisheries Management Council

NPFMC's 1977-78 decisions: Representatives of the Kokechik villages appeared before the North Pacific Fisheries Council in its first set of meetings in late 1976 in Anchorage to plead for an elimination of the foreign directed fisheries for herring, citing their dependence on herring for subsistence, and its critical position in the food web for marine mammals and salmon as a prey species. The Council responded by closing the area north of 58° N and east of 168° W in 1977 to the Japanese spring gillnet fishery, and in 1978, closed the area south of 58° N and east of 168° W. Villagers agreed that spawning runs began to improve following the 1977-78 seasons, but still rejected any offshore fisheries for herring.

Herring Fisheries Management Plan: Kokechik and Nelson Island representatives participated in the Council's development of its initial FMP. Throughout this effort, they opposed offshore directed fishing in any form fearing resource depletion of their small discrete substock, a memory of the late 60's foreign effort. Their spokesmen cited the uncertainty associated with the location of their small stocks during the clockwise post-spawn migration of the much larger Togiak substock. As a group, they feared that their small substock could be disproportionately intercepted in a directed fishery, or as by catch. At the time, foreign fisheries could retain and sell herring taken as by catch, but without observers, were free to target and under-report herring tonnage.

Napoleon v. Commerce: In December, 1980, the NPFMC recommended in a split vote that the Secretary of Commerce authorize a directed fishery for herring by a pioneer joint venture trawl firm. In addition, the NMFS chose to act on the request as an emergency regulation, by passing public comment. Kokechik and Nelson Island villagers "passed the hat", and sued in Federal District Court. A subsistence taker in Hooper Bay, George Napoleon, complained, acting as a class for other subsistence takers. The court ordered that offshore fishing for herring in the FCZ was prohibited, requiring all herring taken to be discarded. The Council then established a special Herring Winter Savings Area reporting zone for foreign fleets northwest of the Pribilof Islands, between 58° North and 59° 30'N latitude, and 172° W to 175° W longitude. Foreign fishing within this zone had to report detailed target species catch, and herring bycatch from September 1 though April 30. Rather then comply, foreign fleets reduced their effort in this area.

State of Alaska's In-Shore Commercial Sac Roe Fishery

OCSEAP surveys: Atlantic herring stocks began to their most recent decline in the early 1980's, causing a shortage in the Japanese sac-roe market that could not be replaced by existing Pacific Coast fisheries in British Columbia, California, Oregon, Washington, and Alaska. The Department of Commerce's NOAA had an agreement with the Department of Interior's Minerals Management Service to conduct pre-OCS sale biological baseline and inventory work. A portion of these funds were directed towards Eastern Bering Sea herring spawning substocks beginning in 1975. These reports demonstrated a harvestable surplus throughout Western Alaska. At no time did the OCSEAP programs examine or seek input from Western Alaskan villages that used herring for subsistence. Representatives of Nunam Kitlutsisti traveled to Kokechik and Nelson Island villages to explain State procedures, and the push at the Alaskan Board of Fisheries to open these bays to commercial fishing. These villages voted to oppose commercial use of herring. They cited the dramatic decline of herring from former abundance, and the most recent trawl induced decline in the early 1970's as reasons to prevent a new round of resource depletion.

State commercial fishery: Following twenty years of inactivity, the domestic sac roe fishery began to pick up in the eastern Bering Sea during the 1960's, with sales exclusively to Japan. Based on the OCSEAP studies, and a failed Atlantic stock, an expanded effort was predicted for Togiak in 1977, where 2,535 tons were taken. That effort by non-local fleets expanded north to Security Cove (1978), Goodnews Bay and Norton Sound (1979), and Cape Romanzoff (1980).

Efforts by state officials to convince Nelson-Nunivak Islands to allow commercial fisheries at the expense of their subsistence fisheries were unsuccessful. Nelson Island and Kokechik representatives argued against State Board of Fisheries proposals for a 40% inshore exploitation rate.

They argued that conservation threatened by offshore by catch and inshore subsistence use dictated a 20% exploitation rate won out.

Local efforts to close fishery: Following the pioneer effort in Togiak in 1977, and Security Cove in 1978, Western Alaskan coastal villages organized their first pan-Western Alaskan meeting of herring fishing villages in Kipnuk, Alaska In August, 1978 to oppose State herring fisheries.

Twenty seven villages from Bristol Bay to Kotzebue Sound attended, and passed a resolution calling on the State to suspend all commercial fishing pending resolution of biological studies, an end to high seas interceptions, and resolution of the subsistence allocation issue. The Bering Sea Fishermen's Association was birthed at this meeting. This grouping of Western Alaskan regions has acted as a unifying voice for village goals and herring conservation throughout the period of commercial development.

The State backed down on its efforts to commercialize Nelson Island, then the center of Federal socio-economic attention in its initial Herring FMP study. The State was attempting to restrict the exploitation of Eastern Bering Sea herring stock to state waters. Conservation of stocks and subsistence utilization were the State primary reason for this fishery. With reluctance, the "boomers" within the State Board of Fisheries and the Division of Commercial Fisheries recognized that an obdurate Nelson Island suing the State over commercialization of its resource would not help achieve state objectives with the Federal manager.

The State did not back off on Kokechik's similar objections. Cape Romanzoff was open in 1979, but no effort took place. The next year saw the first commercial effort, with few local participants. The fishery opened after two years of regulatory and legal objections by Kokechik villages.

In 1978, when the State first exposed its commercial fishing plan, Kokechik representatives at the Lower Yukon Fish and Game Advisory Committee [LY-FGAC] obtained a unanimous decision opposing the fishery. That opinion was expressed to the Board in Fall, 1978 with no reaction. No commercial fishery took place in 1979, in that non-local effort concentrated its activity in Norton Sound.

In 1979, the LY-FGAC, again prodded by Kokechik, opposed the fishery, and gave similar testimony to the Alaska Board of Fisheries. This time, "boomers" on the Board told the villagers that the fishery would take place, in spite of local objections.

When commercial activity was imminent in the Cape Romanzoff in 1980, the Chairman of the LY-FGAC attempted to convene a majority of the Lower Yukon Fish and Game Advisory Committee to use its emergency authority under State regulations to close the Cape Romanzoff fishery. State biologists objected to the use of State funds for this purpose, and no meeting took place. State biologists confirmed that socio-economic condition prevented a local fleet from participating, minimizing local benefits but that there was no biological reason for the closure. Kokechik raised the question in State Superior Court whether there was any limit of the advisory committee to close a season. The State responded that its interpretation of statute required closures to be based on biological reasons. The State Court rejected Kokechik request for a restraining order, and held over the case on its merits until after the season. In the fishery, local fishermen expended 70% of the effort, but took only 40% of the harvest.

Following the fishery, Kokechik was prepared to challenge the State's interpretation of the statute, but a decision by elders in Kokechik villages for Kokechik to take over the fishery suspended this effort.

Local Efforts at Beneficial Commercial Fishery

The village people of the Kokechik area have never looked at herring as a short term economy. They put herring into their worldview perspective of resource renewal and ecology. Conservation of the resource was the first order chosen by the elders of this area when confronted with state and federal commercial fishing designs in 1976. The elders feared that herring would disappear again as they had in the late 1960's, and with them the other marine species that use herring as prey: mammals, seabirds, and salmon, complicating subsistence. The elders also wanted to retain herring as a secondary subsistence resource. The direction of the elders were explicit.

Conservation: Kokechik elders directed the commercial fishermen to protect the species away from the spawning grounds.

Both Scammon Bay and Hooper Bay were closed to commercial fishing to protect subsistence utilization. The take of herring eggs on kelp for commercial use was similarly banned to protect spawning substrate. Kokechik fishermen have appeared throughout the 1980's before the State Legislature asking for additional funds for ADFG research, and State support for Federal limitations on herring by catch. In addition, these same representatives have asked the Congress for similar research funds.

Kokechik representatives were instrumental in the Council placing the first limitations on directed take of herring by foreign gillnet fleets seeking roe bearing herring in 1976 and 1977. They helped stimulate Federal socio-economic investigations in the Council Herring FMP effort, sponsored the Napoleon V. Commerce litigation that made herring a prohibited species, and ended efforts by domestic fleets to take herring at sea. Kokechik was instrumental in the Council's 1982 decision to impose by catch caps for all prohibited species, including time/area closures once each nation went beyond its allocation. When domestic fleets successfully excused themselves from these controls in 1983, Kokechik appeared before the Council to cite DAP herring bycatch, and declining Eastern Bering Sea herring substsocks as a reason to impose a DAP herring by catch regime.

The most difficult conservation issue in the State's commercial fisheries was exploitation rate. Several herring seine "boomers" held leadership positions on the Board of Fisheries in the late 1970's. These individual advocated a 40% exploitation rate. Working in concert with other local, state, and national groups, Kokechik advocated a 20% exploitation rate. The 1979 conference on herring biology, sponsored by the NPFMC, the State, and NMFS had developed a consensus for the lower rate as the prudent exploitation index. Reluctantly, the "boomers" agreed to this figure.

Capitalization: In early fall, 1980, the Kokechik area villages held a joint meeting to discuss the commercial herring program. With elders in attendance, and giving direction, the villages decided to change their focus to dominate the local fishery. Having witnessed the failed legal challenge in the spring, Kokechik leadership gave authorization to approach State government for development capitol before the end of the 1980 Legislature just in case the elders changed their minds.

State Senators George Hohman and John Sackett realized that per capita income in the Wade-Hampton Census District was the lowest in the state. The three villages in question did not have lucrative Yukon River or Bristol Bay commercial salmon fisheries, and were the poorest of villages in this district. All three villages were on townsites conveyed by the State but land possession was retained "in trust" by the Bureau of Indian Affairs. Houses were rented with 25 year mortgages from Federal and State agencies. Under this system, villagers were without equity, and had no experience with private commercial loans from lending institutions.

The senators teamed to invest funds in the Alaska Renewable Resources Corporation [ARRC], a unique venture-capitol fund for high risk Alaskan natural resource businesses. Supported by the Hammond Administration and regional Alaskan Native groups, the Stuknaarvik Fishermen's Cooperative, named for a point in Kokechik Bay, was established. That group then negotiated an agreement with ARRC, forming the Kokechik Corporation, to manage a $300,000 development loan, and a $42,000 technical assistance grant to construct a fleet.

ARRC retained a marine architect to design a utilitarian boat that would carry 8,000 lbs (4 short tons) of herring, and further serve as a subsistence vessel.

ARRC next contracted with a boat yard in Port Townsend WA. on the Olympic Peninsula to build a prototype boat, and rig outlines for local village construction crews to follow in building a local fleet on site. Aluminum was preferred but rejected in favor of wood. State liability insurance required fabrication take place in fire proof buildings which do not exist in Bush villages. Villages agreed to put up a building for winter construction of the boats.

Technical support was offered by Nunam Kitlutsisti, an Alaskan Native environmental and subsistence advocacy group in the Yukon-Kuskokwim Delta, and Yupigtak Bista, an Alaskan

Native Federal Manpower Program.

An application was filed with the Federal VISTA program administered out of Anchorage. Three positions were sought for "local village VISTA's" who would act as foremen in a construction program to build a local fleet. Until this time, all VISTA were recruited from the lower 48, their skills matched up to local needs. Each village choose its VISTA. That individual would in turn travel to Port Townsend to participate in the prototype construction, then return home and foreman the construction of ten boats in their own villages. Alcoholism claimed one village VISTA, but he was quickly replaced due to the seriousness of the project. The foremen returned, the boat outlines and pre-cut wood arrived in due time, and by the 1981 fishing season, fifteen boats had been built. An additional fifteen boats joined the fleet in 1982. By 1987, over 70 local boats fished in Cape Romanzoff.

The pro-forma statement prepared by ARRC did not predict ex-vessel herring prices correctly. In addition, one of the three participating villages which had salmon permits refused to make boat payment. They choose to skip the arduous journey over ice to the herring grounds. Instead they used their Kokechik boats in the salmon fishery, and claimed no herring payments were due. Hooper Bay and Chevak fishermen who had paid each year complained about double billings made by Koekchik to make up for the non-paying boat owners but the Kokechik Board did not seize the boats. ARRC agreed that re-payment schedules be stretched out. Eventually, the State settled for $.63 repayment on its investment dollar after ARRC's dissolution.

<u>Preferential fishing regulations</u>: Over an eight year period of time, the Kokechik group was able to reduce the State commercial fishing area in Cape Romanzoff to the protected inside waters of Kokechik Bay, and limit gear use in its "stone aged fishery". Both procedures gave the small boat, labor intensive local boats a competitive advantage over the nomadic commercial herring fleet.

In 1980, the Cape Romanzoff commercial fishing area contained Kokechik Bay proper, and a semi-circle 1 mile wide stretching from Dahl Point on the seaward side of the southernmost spit to Point Smith on the north side in Scammon Bay. Non-local boats fished the outside waters, and the small boat local fleet fished within the bay's protected waters. The fishery was then open to both gillnet and seine fishing.

Capitalizing on a report to the Board by ADFG biologists that they were unable to monitor fishing activity beyond the bay given their limited equipment, the Kokechik group proposed reducing the fishing district. Over three annual Board meetings, they were finally able to have the fishing district reduced to Kokechik Bay proper.

Again focusing Board attention on the short term values being aggressively pursued by the seine fleets, uncertain biology, and promotion of local economic development, Kokechik worked in concert with other Western Alaskan fishing groups in

1980 to eliminate the use of seines north of Security Cove. Seine boats bypassed Cape Romanzoff in 1979 when they pioneered the third generation of Norton Sound fishing when their spotter pilots reported that Kokechik Bay and its immediate seaward environs were muddy, and herring school could not be observed. But in 1980, spotter airplanes sighted clear water in Point Smith, and two seine boats did exploratory fishing, but did not report to ADFG. At the same Board meeting, seine interests made the mistake of pushing the Board to open Nelson-Nunivak Islands in spite of outstanding subsistence objections. These islands, like Togiak and Norton Sound, are not located near a major river with sediment load. The area seaward of the spawning zone is deep and clear, ideal for seining. But by this time, Board of Fish membership had changed. The herring seine "boomers" were silenced.

In 1981, a new problem revealed itself. With the elimination of seines, a large fleet of nomad herring skiffs participated in the Cape Romanzoff fishery. These boats began fishing herring in December in San Francisco, and worked the coastline to Norton Sound in June. They appeared again in 1982, outfishing the hand-pulling local boats with two man, fully hydraulic boats and spotter airplanes.

At the winter, 1982-83 Board of Fisheries meeting, a new Board of fisheries sat. They agreed to use the principle of super-exclusive registration to reduce nomad competition in the herring fisheries. This principle had been applied to the crab fisheries to prevent large boats dominating many small fisheries, and had withstood court challenge. Ideally, herring gillnet skiffs would now have to pick and choose among the super-exclusive fisheries. In most years, the idea worked. Effort by local boats increased, as did the percent harvested by local fishermen.

Chart #1 Commercial herring fishing data, Cape Romanzoff District 1980-1988

	1980	1981	1982	1983	1984	1985	1986	1987	1988
Catch(st)	611	720	657	816	1185	1299	1865	1342	1119
Estimated Value ($ millions)	0.13	0.21	0.22	0.37	0.31	0.55	1.14	1.00	1.02
# of Fishermen	69	111	75	63	66	73	97	157	113
% Effort by Local Fishermen	70	81	85	92	98.5	94	70	53	103
% Harvest by Local Fishermen	40	60	84	88	99.8	94	70	33	91
Exploitation Rate	20.4	14.7	13.4	14.8	19.4	18.6	24.3	18.6	17.0

Source: ADFG, Division of Commercial Fisheries

The chart above shows two glitches with this theory. In both 1986 and 1987, nomad boats successfully fished in Cape

Romanzoff. In 1986, fourteen outside boats traveling to Norton Sound joined the local fleet in the last period, pushing that season's harvest to its highest tonnage and an exploitation rate of 24.3%. Repetitive failure of the State's Attorney General in the Nome District Court to prosecute super-exclusive use violations, and a lack of Fish and Wildlife Protection [FWP] enforcement encouraged the nomads to take chances. For a period of five years, there were too many bad guys, and too few cops.

Without effective deterrents, there was no inducement for the nomads to obey super-exclusive use. The lack of bonded storage yards in Western Alaska north of Togiak was a limiting factor. FWP refused to seize violators of super-exclusive use, for its supervisors did not want to take an officer out of service to physically watch a seized vessel. Area legislators responded with additional funds and manpower, dedicating a large enforcement vessel with deck space for seized vessels. FWP patrolled these northern herring fisheries, and in both 1987 and 1988, seized vessels. Court mechanics released the 1987 vessel in time for the Norton Sound fishery, but the 1988 vessel was confiscated, and sold.

Problems still exists with complaints from locals that FWP makes the "easy busts" on locals for violations, but has failed to pursue more serious misdemeanor level conspiracies by nomad fleets to evade detection, like multiple boat listings, and under- and non-reporting of harvest.

The last major effort by Kokechik to conform the fishery to its own needs was gear modification. Citing the efficiency of the nomad fleets, a declining biomass, and the cops and robbers difficulty of checking on super-exclusive use violators in season, Kokechik proposed the elimination of hydraulic aids to harvest, called "shakers", and reduction of gear to one 50 fathom shackle. In the words of the chairman of the Board of Fisheries, when the Board agreed to Koekchik's proposal, "we have created the first stone-age fishery in Alaska." The Board Chair was worried that Kokechik was locking itself out of expanded fishing opportunities.

For Kokechik, reduction of the fishing area, elimination of seine and hydraulic aides to gillnet gear, and super-exclusive use gave the small boat fishermen a good chance to dominate the fishery. Joe Paniyak, leader of the Kokechik group, told the Board with no investment capitol, but lots of sons with strong arms, a better chance to catch the fish and collect the cash to supplement his subsistence way of life.

<u>Limited entry</u>: Recognizing that FWP, and ADFG cannot be responsive each year to guarantee locals benefitting from the fishery, Koekchik used the 1986 and 1987 documented "invasion" by nomad boats to petition the Alaskan Commercial Fisheries Entry Commission [ACFEC] to impose limited entry into the fishery. Hearings were held that fall, and a decision to limit entry to 100 fishermen was made public in spring, 1988. A point system was developed over the next year, and limited entry permitting will be completed in time for the 1991 season.

The ACFEC took this action even though a constitutional challenge to the super-exclusive use authority of the Board of Fish is pending before the Alaskan Supreme Court. In the event that suit in successful, the existing limited entry permit system would be amended, and new permits re-issued. Under the current plan, 94 permits will be given to local fishermen. Kokechik expects that the six non-local permits may soon sell out, given the super-exclusive use, gear and effort limitations

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Subsistence-Herring Fishing in the Eastern Bering Sea Region: Nelson Island, Nunivak Island, and Kuskokwim Bay

M.C. Pete
Alaska Department of Fish and Game
Bethel, Alaska

ABSTRACT

This report summarizes information on the subsistence use of herring in the Nelson Island and Etolin Strait region of Alaska. Data were gathered in annual surveys from 1986 through 1988. All fishing families were surveyed each season to arrive at total harvests. Qualitative information on community experiences with depletions of herring stocks in the late 1960s and early 1970s is included. A brief description of subsistence-herring use by five other communities in the Nunivak Island and Kuskokwim Bay areas supplements the more detailed information presented for Nelson Island communities.

Herring is a central component of the subsistence economy of the communities in the Nelson Island area. It comprises the highest proportion of all species harvested of the total subsistence outputs -- 40 percent by weight in Tununak in 1986. Participation, both by individuals and households, in subsistence-herring production is high.

Subsistence harvest estimates for Nelson Island communities in recent years (1986 through 1988) have shown substantially higher annual harvests than those recorded in previous years. The recent estimates indicate that herring harvest effort and use was considerable. Over 200 short tons of herring were harvested annually for subsistence use by communities in the Nelson and Nunivak Island districts and the Kuskokwim Bay area combined. This is considerably greater than earlier estimates from the late 1970s which projected that the combined harvest by communities in the eastern Bering Sea region was approximately 110 short tons of herring taken annually for subsistence use. Smaller sample sizes and reduced numbers of fish probably account for much of the difference.

Declines in herring stocks within the past two decades have been attributed to offshore foreign fishing in the 1960s and 1970s. Depletion of herring returning to the Nelson Island area has created hardship for the area residents. They have had to make adjustments. Current projected declines understandably cause concern.

INTRODUCTION

This report primarily summarizes information from a three-year research project, conducted from 1986 through 1988, in the Nelson Island area communities. The multi-year study was conducted to document the level of subsistence use of herring by the residents of these communities, to monitor the effects of the commercial herring sac-roe fishery initiated in 1985, and to develop a cost-effective means of annually estimating the subsistence-herring harvest. Findings from this project were described in two reports -- one completed in 1986 (Pete and Kreher, 1986) and another in 1987 (Pete, Albrecht, and Kreher, 1987). The present report also briefly describes effects to subsistence use of declines in herring numbers in the late 1960s and early 1970s. Finally, the scant information on subsistence-herring utilization by other communities in the Nunivak Island and Kuskokwim Bay area is summarized.

The importance of the subsistence use of herring to residents of Nelson Island and vicinity has been reported in many sources (Lantis, 1946; Barton, 1978; Hemming, Harrison, and Braund, 1978; Lenz, 1980; Skrade, 1980; Fienup-Riordan, 1983; Pete, 1984; Pete and Kreher, 1986; Pete *et al.*, 1987), including the North Pacific Fishery Management Council's Bering-Chukchi Sea Herring Fishery Management Plan (1981). Between the early 1970s and 1984, proposals to open Nelson Island herring stocks to commercial fishing were met with intense opposition by Nelson Island area residents, primarily because of their experience with effects of previous offshore commercial harvests by foreign fisheries (Hemming *et al.*, 1978; Pete, 1984).

In 1984, with an understanding that commercialization was inevitable given state and federal mandates to authorize use of harvestable surpluses of fish, the people of the Nelson Island area submitted proposals to open the Nelson Island herring stocks to commercial harvest. The regulations they requested and obtained for the commercial herring fishery were designed to favor participation by local fishermen and to protect the important subsistence fishery. Equipment was small-scale, like that used in the subsistence fishery, and area closures to commercial fishing were established to protect subsistence fishing and herring spawning sites. Local residents requested documentation of their subsistence use of herring in order that minimal disruption occur due to commercial activity, hence this three-year research project was developed.

The research substantiated the importance of herring in the subsistence economy of Nelson Island area residents. The scope and timing of surveys for this project was notable for several reasons. A complete census of fishing families in all communities was surveyed during the subsistence fishing season each year. At the time of the studies herring stocks were plentiful, thus effort and participation in the subsistence fishery was reported to be similar to earlier years (those prior to the mid-1960s) when herring were typically abundant. Harvest surveys that were conducted previously, during the late 1970s and early 1980s, were limited by an inability to contact many fishermen, and those surveys also took place during years that stock abundance was considered to be improving from low levels.

Projected returns of herring for the 1990 season are below the thresholds at which commercial harvests are allowed to occur in Nelson Island and Nunivak Island districts (Hamner, 1989). Nelson Island residents have expressed concern about loss of opportunity and reduced productivity of subsistence-herring fishing in the near future. Furthermore, the commercial herring fishery became an important option for generating income as well as providing a significant, if fluctuating, financial contribution to the local economy (Pete, 1985).

METHODOLOGY

Information was collected using a survey questionnaire which was administered in person. Harvest times, personnel involved in fishing, types of gear used, areas fished, and harvest levels were recorded. In all years of the project, a census (100 percent) sample of fishing families was surveyed to arrive at total community harvests of herring for subsistence use.

Information on results of declines in the late 1960s and early 1970s in Nelson Island herring stocks was derived predominantly from interviews with members of approximately 50 percent of Tununak fishing families during the 1986 survey and between one to five elders in each of the other three communities. Furthermore, Tununak was the subject of a comprehensive subsistence harvest study and elderly residents were systematically asked about herring production during the time of declining stocks. The survey team specifically asked knowledgeable elders in the other communities about what happened when herring were not plentiful. The topic was discussed informally with many other individuals at other occasions subsequent to the 1986 survey season. Although the information was qualitative compared to in-season harvest data, it was highly consistent among individuals and communities.

COMMUNITIES USING HERRING FOR SUBSISTENCE USE

Nelson Island District

There were four communities that utilized Nelson Island district herring stocks for subsistence use that participated in the three-year project. From north to south, these communities were Newtok, Tununak, Toksook Bay, and Nightmute (Fig. 1). These communities and Chefornak, approximately 20 miles south of Nelson Island, constituted a discrete regional and societal group, called *Qaluyaarmiut* (Fienup-Riordan, 1983; Shinkwin and Pete, 1984). They traditionally were united by a network of kinship ties, formed a marriage universe, and cooperated in important social, religious, and political ceremonies. This intercommunity relationship has persisted to current times; the communities still were intertwined through kinship and in the late 1970s, they formed a regional political organization through which they interact with outside agencies.

Newtok, the only community not situated on Nelson Island proper, is along the Keyalivik River, just north of the island (Fig. 1). Tununak, Toksook Bay, and Nightmute are all on Nelson Island. Newtok and Nightmute are riverine communities; their residents relocated to coastal camps to produce herring and other subsistence foods. Newtok residents used to go to Niliklugak until the late 1970s, when cumulative erosion and deposition made their settlement there unsuitable. They camped at Tununak to fish for herring until the early 1980s. With faster outboard motors and longer nets, they often harvested their herring in one tide and returned to the village to process their catch. Umkumiut, a sizable seasonal camp is still used by residents of Nightmute and Toksook Bay. Families used to move to Umkumiut prior to ice breakup for spring seal hunting and stay until August for marine fishing and drying. Throughout the study period, its occupation by families was generally limited to the herring season, although hunters used the camp throughout the year.

The present locations of Tununak and Toksook Bay have been noted as influential in their current levels of herring use. Located along the coast near herring spawning areas, they were most advantageously situated to harvest and process herring. Furthermore, their locations made trips to traditional winter harvesting areas prohibitive because of costs in fuel, time, and equipment, thereby contributing to an increased dependence on herring (Hemming *et al.*, 1978).

Prehistoric evidence and historical records (Okada, Okada, Yajima, Miyaoka, and Oka, 1982; Fienup-Riordan, 1983) demonstrate that Tununak was a spring and summer camp for harvesting sea mammals, herring, salmon, and other marine resources. In winter, Tununak residents moved eastward on Nelson Island, nearer to Chakchak, or to small, extended, family-based settlements along northern Nelson

Island or east of Newtok. From these settlements, they harvested pike, burbot, whitefish, blackfish, and other resources throughout the winter. The establishment of Tununak as a permanent settlement occurred to facilitate use of the school, church, and stores.

Toksook Bay, previously another customarily used summer camp, was established as a permanent settlement in 1964 when some of the residents of Nightmute whose homes had been threatened by erosion settled there, because there was little area for expansion in Nightmute (Hemming *et al.*, 1978; Fienup-Riordan, 1983). Winter resource use areas of Toksook Bay residents were still focused in the vicinity of Nightmute and areas south and east of Nelson Island.

Community populations and numbers of households remained relatively stable over the three study years, 1986 through 1988, with only a three-percent increase in the regional population. According to our censuses, in June 1988, the four villages had a combined, permanent-resident population of 1,110 persons in 207 households (Table 1), an overall average household size of 5.4 persons, with a range of 1 to 11 persons per household. More than one-half (58 percent) of the households ranged in size of 5 to 11 persons. Toksook Bay, the largest village in terms of population, also had the largest average household size. Close to 99 percent of the permanent residents were Alaska Native, primarily Yup'ik Eskimo, and most, including children, spoke Central Yup'ik as their first language. Many elders did not understand English.

TABLE 1. NELSON ISLAND POPULATION AND PARTICIPATION IN SUBSISTENCE-HERRING PRODUCTION, 1988

Community	Population	Total number of households	Number of participating households	Number of fishing families
Newtok	207	40	27 (68%)	16
Tununak	318	63	54 (86%)	37
Toksook Bay	422	77	65 (84%)	37
Nightmute	163	27	20 (74%)	14
Totals	1,110	207	166 (80%)	104

The local economy of these communities is characterized as "a mixed, subsistence-based economy" referring to their use of local, wild resources obtained by hunting, trapping, fishing, and gathering, with some income secured by primarily seasonal, though intermittent, wage employment, commercial sale of halibut, salmon, herring, and furs, and cottage industries (Wolfe and Walker, 1987). None of these communities were linked by road. Air and water transportation were the primary means of access. Cost of living was typically high because of the expense of importing goods and services. In economies such as these, the subsistence sector is generally the most stable, therefore, the most reliable. Adjustments are made in subsistence production based on fluctuations in abundance, availability of resources, and personal circumstances. However, drastic and unexpected reductions in abundance of critical species, such as herring in the Nelson Island area, have caused difficulties.

Nunivak Island and Kuskokwim Bay

Other communities situated on Nunivak Island and along Kuskokwim Bay use herring for subsistence purposes. These include Mekoryuk, located on the north shore of Nunivak Island, and Chefornak, Kipnuk, Kwigillingok, and Kongiganak along Etolin Strait and Kuskokwim Bay (Fig. 1). Population and household data are

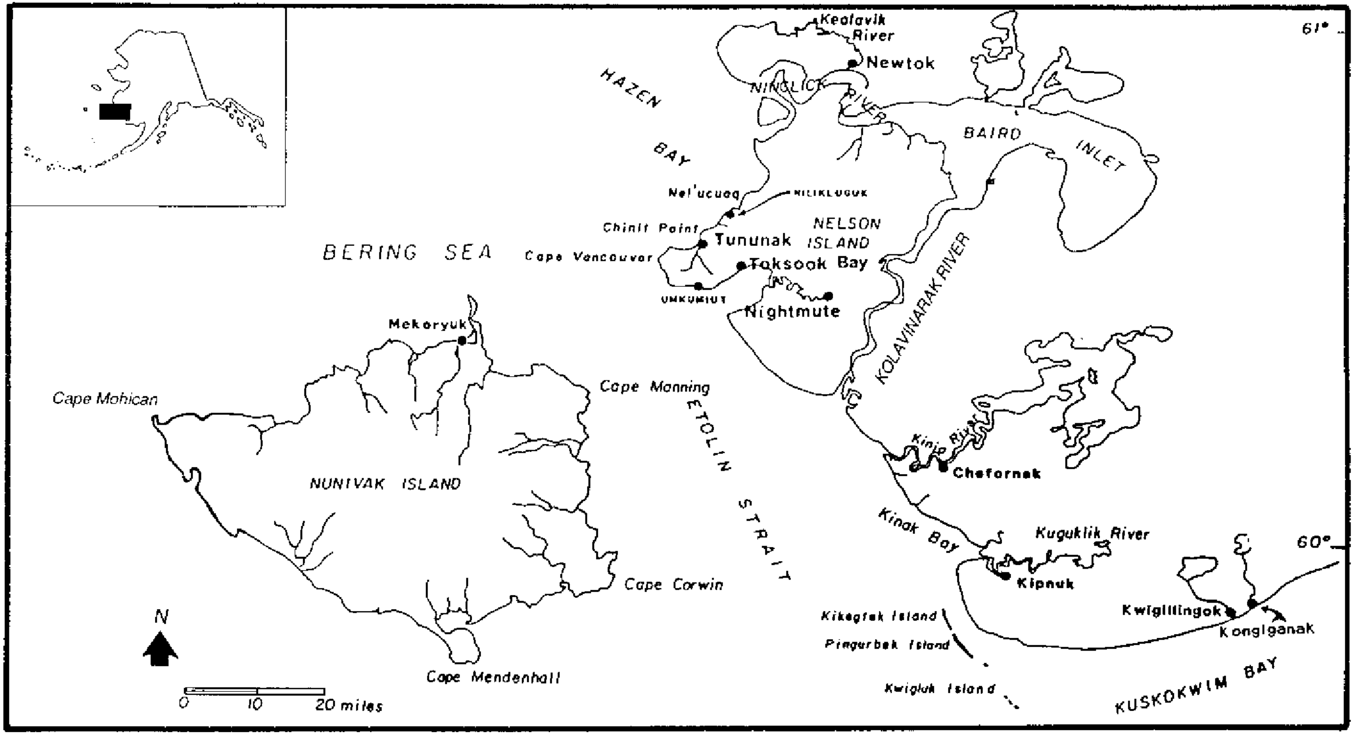

Fig. 1. Location of communities in the Nelson Island, Nunivak Island, and Kuskokwim Bay areas.

presented in Table 2. Community size ranged between 180 and 500 persons, most of whom were Yup'ik Eskimo.

Kipnuk participated in subsistence-herring harvest surveys in 1985 and 1987. Surveys in both years were administered to 100 percent of the subsistence-herring fishing families (Pete *et al.*, 1987). Information on subsistence-herring use by the other four communities was based on existing literature and reports (Hemming *et al.*, 1978; Stickney, 1984; Pete, 1984; Anderson, 1985; Bue, 1986; Alaska Department of Fish and Game, 1987).

TABLE 2. POPULATION FOR NUNIVAK ISLAND AND KUSKOKWIM BAY AREA COMMUNITIES, 1986 AND 1980

		1980[b]		
Community	1986 Population[a]	Population	Number of households	Percentage Alaska Native
Mekoryuk	173	160	44	95.6
Chefornak	310	230	38	96.1
Kipnuk	498[c]	371	81	96.5
Kwigillingok	257	205[d]	35[d]	96.9
Kongiganak	295	239	48	96.7
Totals	1,533	1,205	246	--

[a] Alaska Department of Labor, 1989.
[b] U.S. Department of Commerce, 1983.
[c] This is 1987 data (Pete *et al.*, 1987).
[d] This is 1981 data (Stickney, 1984).

SUBSISTENCE-HERRING FISHING

Nelson Island District

Previous reports (Pete and Kreher, 1986; Pete *et al.*, 1987) include detailed descriptions of harvest times, gear used, fishing areas, personnel involved, and methods of processing and storing of herring. Most aspects of the fishery remained very similar throughout the three years of the project. The following is a brief summary of information in the two earlier reports.

Kin-based, subsistence-herring production units, or fishing families, organized the complex of activities necessary to harvest, process, and store herring for the winter. Most fishing was done by men and most processing was done by women. Fishing families were often composed of members from more than one household. Commonly, adult children cooperated with their parents who lived in separate households to produce herring for subsistence use. Participation in subsistence-herring production by households throughout the three years was typically high. There was an annual average involvement by 80 percent of all households which included over 40 percent of the regional population and approximately 85 percent of the people between the ages of 15 to 70 years. Persons as young as six years of age were involved in some aspect of subsistence-herring production.

Each community used traditional fishing areas which were located in proximity to the settlements (Fig. 2). Set gill nets with mesh sizes of 2 to 2-3/4 inches were the most common gear. Nets were typically between 60 and 150 feet long with some as long as 300 feet in length. Locally made, wooden, and industrially manufactured, aluminum boats between 14 to 28 feet long were used for subsistence-herring fishing. Most boats were between 18 and 22 feet in length.

Herring season from fishing, through aging, cleaning, drying, and storing of the herring began as soon as the adjacent ocean became ice free, generally in late May, and lasted for about two months. It was a very busy time of year with many other subsistence activities occurring around those involving subsistence-herring production. Herring roe-on-kelp (*elquat*) was also collected. Other fish species sought throughout this time included halibut, Pacific cod, wolf fish, five species of salmon, capelin, smelt, and many species of shellfish and marine invertebrates. June

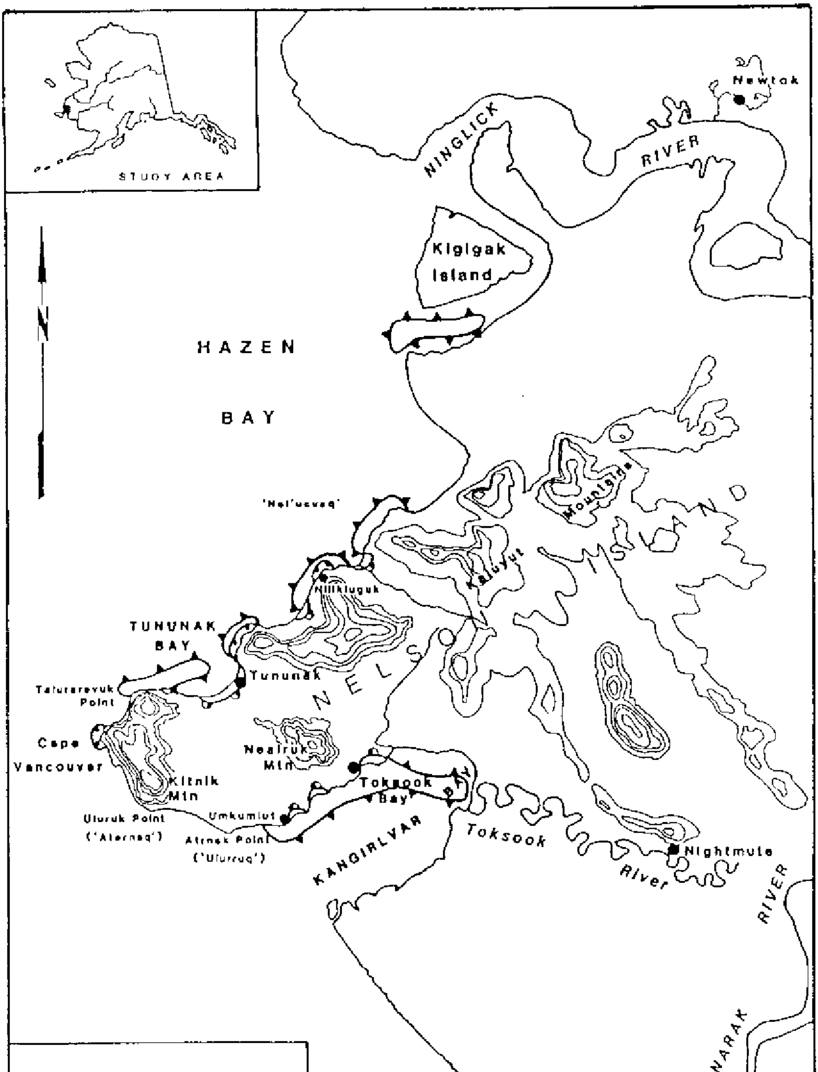

Fig. 2. Areas used by Nelson Island residents for subsistence-herring fishing and spawn-on-kelp, beach grass, and *kelugkaq* collecting in 1987.

through August was the most common time to get seasonal wage employment, often outside of the communities. Most subsistence fishing occurred after the local commercial herring season was over, except for Tununak; they fished as soon as herring occurred in the area. The other communities preferred the smaller-sized, "less-fatty" herring. In spring and fall (June and September), beach grass, called *tapernat* was gathered to use in braiding herring into strings (*piirrat*) to dry. Throughout the season, assuring adequate numbers of herring on the drying racks was always a priority task.

Harvest Levels. Throughout the three years of the surveys, subsistence-herring harvest levels for the four Nelson Island communities ranged from 124 to 166.8 short tons (Table 3). The numbers of fishing families involved in producing herring for subsistence use has remained relatively constant -- over two-thirds of all households have fished in most years (Tables 1 and 3). Average multi-household harvests ranged from three-quarters of a ton to two tons, depending on the community and year (Pete and Kreher, 1986; Pete *et al.*, 1987). The harvest levels and degree of involvement described by this study were significant. Prior to these findings, most managers and policymakers involved with herring fisheries assumed that all communities along the eastern Bering Sea coast, from Pilot Point in Ugashik Bay to Golovin in Norton Sound, only utilized up to 110 short tons of herring for subsistence. The four Nelson Island area communities exceeded that estimate themselves.

By all criteria, herring are a crucial part of the economy of Nelson Island area residents. Total subsistence harvests demonstrate its importance in the subsistence sector. Based on a household harvest and income survey of 52 percent of all Tununak households in 1986, the per capita subsistence production was 1,091 pounds, placing it within the top 10 percent of communities statewide (Wolfe and Walker, 1987). As many as 90 species of fish, shellfish, marine invertebrates, marine mammals, large and small game, birds, berries, and plants were listed as commonly harvested by Tununak residents. Still, herring accounted for 40 percent by weight of the subsistence output in Tununak that year. Per capita pounds of herring harvested in all four communities from 1986 through 1988 was considerable (Fig. 3).

Nunivak Island and Kuskokwim Bay

Gear used for subsistence-herring fishing by Kipnuk fishermen was similar to that used by Nelson Island fishermen (Pete and Kreher, 1986). In Kipnuk, outboard powered boats ranged in length from 12 to 24 feet. Locally constructed, wooden, and aluminum skiffs were utilized. Drift or set gill nets ranged from 12 to 450 feet

TABLE 3. ESTIMATED NELSON ISLAND SUBSISTENCE-HERRING HARVEST LEVELS (IN SHORT TONS) AND HOUSEHOLD PARTICIPATION, 1986-88

	1986		1987		1988	
Community	Short tons	Number of participating households	Short tons	Number of participating households	Short tons	Number of participating households
Newtok	12.6	18	10.0	22	12.5	27
Tununak	63.3	56	48.0	56	49.3	54
Toksook Bay	69.5	64	51.0	63	58.5	65
Nightmute	21.4	18	15.0	19	16.0	20
Totals	166.8	156	124.0	160	136.3	166

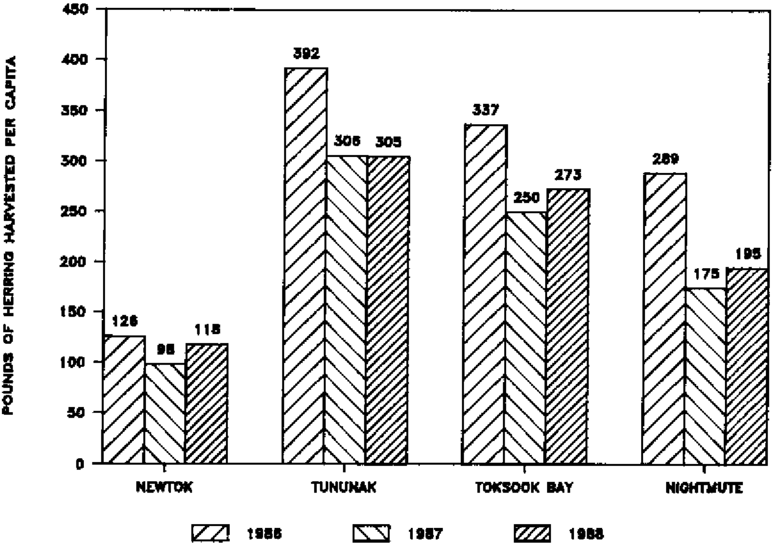

Fig. 3. Pounds of herring harvested per capita for subsistence use by Nelson Island communities, 1986-88.

in length with stretched mesh sizes from 1 to 2-3/4 inches (Anderson, 1985; Pete *et al.*, 1987).

Herring caught for subsistence use were processed in a manner similar to that described for Nelson Island. They were gutted, cleaned, and braided into strings to dry for winter food. It is likely that harvesting and processing of herring was similar in the other communities, although no recent studies have been conducted.

Most subsistence-herring fishing areas of each community were in nearby waters, with the exception of Mekoryuk where people fished along the entire eastern coast of Nunivak Island (Fig. 1; Pete, 1984) or within the Nunivak Island fishing district. The communities from Chefornak, south and east to Kongiganak, fished in the Cape Avinof district. A few people from Chefornak joined relatives in Toksook Bay and at Umkumiut, to fish for, and process herring for subsistence in 1986 through 1988 (Pete and Kreher, 1986; Pete *et al.*, 1987). In contrast to past years, Kongiganak residents fished near their community in 1985, rather than in the area used by Kwigillingok (Anderson, 1985). There are no data on Kongiganak or Chefornak herring fishing areas for 1986 and 1987.

Harvest Levels. Herring harvest data from Nunivak Island and Kuskokwim Bay communities have been collected, intermittently, between 1976 and 1987 by various entities using differing methodologies (Alaska Department of Fish and Game, 1986; Hemming *et al.*, 1978; Pete *et al.*, 1987; Stickney, 1982). Table 4 shows subsistence-herring harvest data from these reports. Only for 1985 were harvest data collected from all five communities; the total estimated harvest was 31.1 short tons. The 1985 harvest the largest recorded to date for Mekoryuk and Kongiganak. Larger harvests have been documented for Chefornak, Kipnuk, and Kwigillingok prior to and since 1985 (Table 4).

TABLE 4. ESTIMATED NUNIVAK ISLAND AND KUSKOKWIM BAY COMMUNITIES SUBSISTENCE-HERRING HARVEST LEVELS (IN SHORT TONS), 1976-87

Community	'76	'77	'78[a]	'79	'80	'81[b]	'82	'83[b]	'84[b]	'85	'86	'87[c]
Mekoryuk		0.6[a]	0.6				0.3[d]			0.7	0.2	
Chefornak			3.1							13.0		14.0
Kipnuk			6.1							9.4[e]		14.4[e]
Kwigillingok	11	1.0		7.9	13.2		13.2			4.6		
Kongiganak		.3								3.4	2.0	
Harvest totals (short tons)	11	1.9	9.8	7.9	13.2		13.5			31.1	2.2	28.4
Communities represented	1	3	3	1	1	0	2	0	0	5	2	2

SOURCE: Unless otherwise noted, harvest levels are from Alaska Department of Fish and Game, 1987.

[a] Hemming *et al.*, 1978.

[b] No surveys conducted; blank spaces reflect lack of data rather than no harvest for individual communities.

[c] K. Schultz, pers. comm. 1987.

[d] Stickney, 1982.

[e] Pete *et al.*, 1987.

Total Subsistence-herring Harvests

Subsistence-herring harvest information from 1976 to 1988 from all nine communities discussed in this report is compiled in Table 5. The figures do not reflect complete harvests for all fishing families for Mekoryuk or Kuskokwim Bay communities. However, the total upper-range harvest estimate for all these communities was 212.5 short tons. This is twice the previously assumed typical subsistence harvest for all communities along the eastern Bering Sea coast (Hemming *et al.*, 1978). Furthermore, the harvest estimates for the years depicted in Table 5 were reported by local residents to approach normal subsistence production from healthy herring stocks. Not until 1984 were herring returns considered "recovered" by elderly residents of the Nelson Island region. Herring were considered "good-sized" and abundant in areas traditionally fished with customary gear, and necessary harvest levels were attainable in reasonable timespans. Thus, harvest estimates for years prior to the late 1970s portrayed less productive times, and possibly, reduced effort.

On an average, Nelson Island communities accounted for approximately 70 percent of the total subsistence-herring harvests for the nine communities. Kuskokwim Bay communities have harvested the remaining 30 percent of the total harvest. Mekoryuk harvests were the lowest, averaging one-half ton (Table 5). However, information on Mekoryuk subsistence-herring harvests was the most incomplete of all communities, because fishing families that camp on the south side of the island have never been contacted. Although, historical sources report less dependence on herring than the Nelson Island communities (Lantis, 1946), no complete or current data exist to confirm the level of use for Mekoryuk or Nunivak Island.

TABLE 5. TOTAL SUBSISTENCE-HERRING HARVESTS (IN SHORT TONS), NELSON ISLAND AND NUNIVAK ISLAND DISTRICTS AND KUSKOKWIM BAY

Community	Average harvest	Range of harvest	Years with data
Nelson Island District			
Newtok	11.6	10.0-12.6	86, 87, 88
Tununak	53.2	48.0-63.3	86, 87, 88
Toksook Bay	59.3	51.0-69.5	86, 87, 88
Nightmute	17.4	15.0-21.4	86, 87, 88
Subtotals	141.6	124.0-166.8	
Nunivak Island and Kuskokwim Bay			
Mekoryuk[a]	0.5	0.2-0.7	77, 78, 82, 85, 86
Chefornak[a]	10.0	3.1-14.0	78, 85, 87
Kwigillingok[a]	8.5	1.0-13.2	76, 77, 79, 80, 82, 85
Kongiganak[a]	1.9	0.3-3.4	77, 85, 86
Kipnuk	10.2	6.7-14.4	78, 85, 87
Subtotals	9.1	?-45.7	
Totals	150.7	?-212.5	

[a] Data represent minimal harvest estimates; not all fishing households were contacted.

Effects of Reduced Herring Stocks on Subsistence Fishing, *ca.* 1960-80

Beginning in the early 1960s, changes in the herring runs returning to Nelson Island were observed. Numbers fluctuated from year to year, herring sizes decreased, and productivity changed in fishing areas. During this time, Nelson Island residents reported finding more glass floats and pieces of monofilament herring gill net webbing on the beach around Nelson Island. In 1968 and 1969, local residents saw large, foreign fishing boats north of Nunivak Island, and in Etolin Strait, while seal hunting in spring (early May). In 1973, one person found an extremely long section of webbing, over several thousand feet long. Locally made nets, ranging from 20 to 60 feet in length, with multifilament cotton or nylon twine, were the predominant gear for subsistence-herring fishing.

From the late 1960s through the mid-1970s, subsistence-herring fishing was generally unpredictable and often not productive for many fishermen. Herring were small; they passed through set gill nets previously used. Fishermen began using smelt and capelin dipnets or pieced together webbing with mesh sizes of 1 to 1-1/2 inch. They often drifted for herring with these short nets. Nets were set for weeks rather than days. A few fishermen salvaged and hung the monofilament webbing they found on beaches. Although herring were more likely to get caught in those nets, because of the smaller mesh size, the nylon dug into the flesh of the herring, complicating processing and sometimes making them unusable for food.

Consistently productive fishing areas, such as waters off Chinit Point and Cape Vancouver became erratic, and were heavily fished by residents of all communities when herring occurred in appreciable numbers. Because roe was sparse, local residents felt that whatever spawn was deposited should be allowed to produce herring, and roe-on-kelp collecting ceased. Subsistence-herring harvests declined; several families noted for catching up to two tons of herring estimated that they got no more than 100 to 200 pounds -- "a pilot-cracker-box full."

Because of the unpredictable nature of herring fishing and unreliability of success, many families ceased subsistence-herring fishing and concentrated on other species. This was especially true for the residents of Newtok and Nightmute. These two communities, located near productive fresh water fishing areas, reportedly increased production of pike, whitefish, burbot, and blackfish for food to sustain them through the winter. Tununak and Toksook Bay residents also targeted other species as well. Halibut, sculpin, "needlefish" (stickleback), flounder, saffron cod, Dolly Varden, all species of salmon, smelt, and capelin harvests increased. Late-summer and fall berry picking trips made by residents of all four communities to the east side of Nelson Island and the adjacent mainland were prolonged in order to set nets for pike, whitefish, and burbot. These substitutes increased gasoline and time expenditures during both harvesting and processing.

By 1972, local residents began appealing for help from agencies and organizations, such as Nunam Kitlutsisti in Bethel. A few elders remember emergency food drops (government cheese, macaroni, dried milk) (Lenz, 1980). Either the Department of Military and Veterans Affairs, Alaska Division of Emergency Services, or the Alaska Air National Guard were credited with the food drops. However, a few younger people have attributed the food drops to other circumstances, which may have coincided with the reduced number of herring.

It is not difficult to understand the local view that offshore foreign fishing in the 1960s and 1970s was directly responsible for herring depletions in the Nelson Island area. After their experience, area residents became vocal about their opposition to any commercialization (Hemming *et al.*, 1978) and have played an active role in the regulatory process pertaining to all herring fishing affecting subsistence uses.

SUMMARY

The subsistence-herring fishery in Nelson Island was a significant aspect of the economy of the communities in the area, demonstrated by total harvests, per capita and family harvests, and with available data, by the proportionate contribution of herring to total wild resource outputs. The proposal to establish a commercial herring sac-roe fishery in the Nelson Island district and its subsequent authorization have underscored the importance of herring in the subsistence economy.

Subsistence-herring use occurred in five other communities in the Nunivak Island and Kuskokwim Bay areas. Although not of the same magnitude of use as that in Nelson Island villages, the total contribution of subsistence-herring use to the economy is unknown because data have not been collected for the Kuskokwim Bay communities.

Of the communities outside the Nelson Island region, Kipnuk was the only community for which harvests by all fishing families were documented in 1985 and 1987. Participation in the subsistence fishery was considerable; up to 60 percent of all households were involved in subsistence-herring production in 1987 (Pete *et al.*, 1987).

Table 5 summarized available subsistence-herring harvest information for all the communities in the Nelson Island, Nunivak Island, and Kuskokwim Bay area. The community for which there exists the least amount of subsistence-herring harvest information is Mekoryuk where households fish for herring in the Nunivak Island district. The 1990 projected returns of herring for the Nunivak Island district are one-fifth of the total biomass necessary to allow a commercial harvest; 320 short tons are expected to return and the minimum biomass estimate to allow commercial harvest is 1,500 short tons.

Depleted herring stocks within the past several decades resulted in hardships for fishing families in the Nelson Island area. Procuring herring became very time-consuming and expensive. Other resources were harvested to substitute for the decrease in stores of herring. In 1984, when local representatives of the Alaska Department of Fish and Game, Division of Commercial Fisheries, explained the inevitability of commercial utilization of herring surpluses, local residents reluctantly supported commercialization of Nelson Island herring stocks. The commercial fishery has provided important local options for securing monetary income. With declines in projected herring returns, local residents have expressed the most concern over the opportunity for continued and sustained levels of subsistence use.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

On the Danger of Incidental Fishing Mortality in Herring Purse Seining

A.K. Beltestad and O.A. Misund
Institute of Fishery Technology Research
Bergen, Norway

ABSTRACT

Incidental fishing mortality may occur when purse seining on large, dense schools and during storing of herring in net pens. To indicate the potential for net bursts, the availability of herring concentrations for Norwegian purse seining is illustrated. On the basis of unofficial purse seine fishery statistics, we calculate a figure of unaccounted fishing mortality in the order of 10^4-10^5 tons. This estimate is based on questionable assumptions, however, especially that every fish involved in a net burst suffers either long term or instant mortality. We therefore argue for further research to quantify the incidental mortality during purse seining and live storing of herring.

INTRODUCTION

The purse seine gear is undoubtedly the most sophisticated and effective fishing gear for schooling species developed by man. In combination with acoustic school detection equipment and hydraulic gear handling devices, the purse seine has been the major tool for fishing down large clupeoid resources, as the Hokkaido-Sakhalin herring, the Downs herring, the Pacific sardine, the Japanese sardine, the South African sardine, and the Peruvian Anchovy, causing a total loss of fish production in the order of 10 million tons (Murphy 1980). As the life history parameters of these species can indicate a critical stock recruitment depensation (Ulltang 1980), the danger exists that these stocks may go extinct when fished down to very low levels. Bjørndal & Conrad (1987) showed that the closure of the North Sea herring fishery at the end of the 1977 season probably saved the stock from possible extinction.

However, purse seining is a high quality product, low cost fishing method that, when optimally regulated and closely monitored, fulfills the goals of modern conservation oriented fishing. The aim of this paper is therefore to illustrate both the advantages and dangeres with the purse seine method, examplified by the Norwegian herring fisheries. We will also draw attention to the incidental mortality problem, that for the period 1985-1987 was estimated at 150 000 tons in the Norwegian spring-spawning herring fishery (Anon. 1989).

It is claimed that one of the reasons for such unaccounted mortality is net bursts, which occurs when a purse seine is torn due to the amount of fish. Before the 1989-season, the Norwegian authorities closed daytime purse seining on Norwegian spring-spawning herring as a result of several net bursts on large and dense spawning schools. Incidental mortality may also occur during transfer and storing of live herring in net pens.

AVAILABILITY

In the last years, the fishery for Norwegian spring-spawning herring has taken place at the spawning grounds outside Western Norway in winter, and at the hibernating areas in the fjords of Northern and Western Norway in autumn/early winter. The Norwegian fleet catches herring also in the eastern, sentral, and northern North Sea, and west of the Shetland Islands. During 1987-1989, we have participated in six cruises in the actual areas, and among other objectives quantified the schooling behaviour of the herring, according to Misund & Øvredal (1988). The North Sea and Møre 1988 cruises were run by R/V "Eldjarn" (1043 GRT), the others by R/V "Fjordfangst" (20 GRT).

Average school biomass, calculated from the sonar, echo sounder, and echo integrator data of the recorded schools, was significantly different among the different areas and seasons (Table 1). Rather small schools were most abundant (Fig. 1), and schools larger than 200 tons were recorded at Møre in 1988 and in Gratangen in 1989 only. This indicates that relative few potential net burst schools were recorded on the actual fishing grounds. It should be noted, however, that the nine 200 tons-schools in Gratangen 1989 sum up to a total biomass three times larger than the 60 other schools, which averages about 10 tons.

Table 1. Schooling behaviour of the Norwegian spring-spawning and North Sea herring recorded in various areas and seasons. Average values with maximum recording in brackets are given. (L: fish length, IM: immature, M: maturing, PS: pre-spawning, SF: surface distribution, N: no. of recorded schools, S: $p < 0.05$)

Area	Season	L (cm)	Stage of maturity	School size (tons)	Swimming depth Day (m)	Swimming depth Night (m)	Fish density Day (n/m^3)	Fish density Night (n/m^3)	N
Møre	Sept -87	28.1	M	17 (131)	29 (53)	SF	4.6 (15.7)	-	41
Møre	March -88	30.0	PS	26 (224)	55 (89)	-	1.9 (8.1)	-	22
Lofoten	Sept -88	32.3	M	6 (40)	31 (57)	0-40	1.2 (9.0)	0.03 (0.17)	57
Gratangen	Oct -88	33.0	M	40 (278)	37 (72)	20-70	1.5 (7.8)	0.02 (0.04)	69
North Sea	July -88	>20	IM-PS	4 (40)	33 (127)	-	3.2 (11.7)	-	66
North Sea	July -89	>20	IM-PS	8 (43)	40 (118)	-	3.4 (18.5)	-	60
Kruskal Wallis-test				S	S		S		

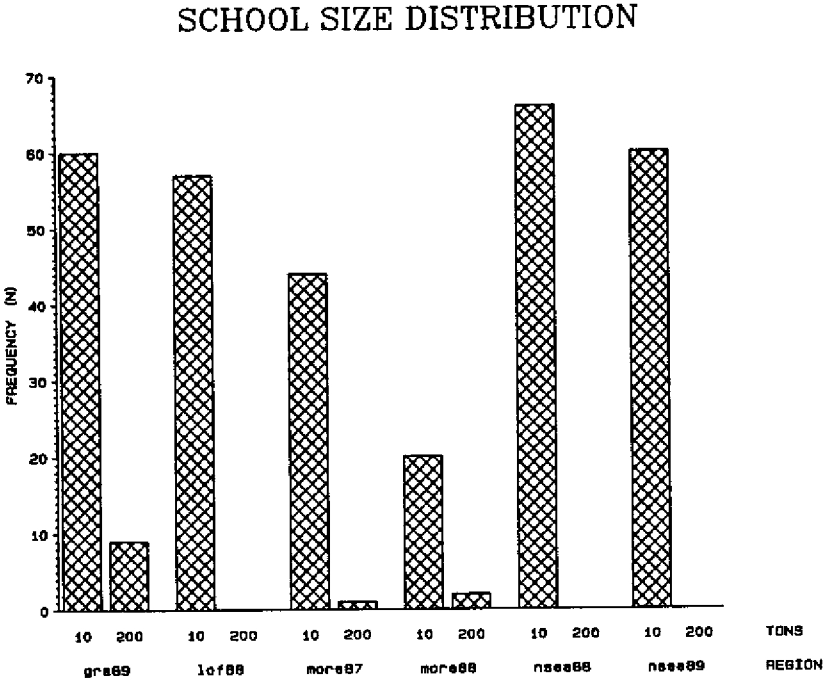


Figure 1. School size distribution in actual regions for Norwegian herring purse seining (gra89: Gratangen 1989, lof88: Lofoten 1988, more87: Møre 1987, more88: Møre 1988, nsea88: North Sea 1988, nsea89: North Sea 1989).

Similarly, the average swimming depth of the schools varied significantly among the areas (Table 1), but most schools were swimming shallower than 60 m (Fig. 2). Even if there was a significant, overall tendency for the largest schools to swim at greater depths ($r_s = 0.31$, $p < 0.05$), none of the sonar recorded schools larger than 200 tons were swimming deeper than 90 m. Thus, they were all available by conventional Norwegian herring purse seines, which can catch schools down to about 100 m depth. However, both at Møre in 1988, and in Lofoten and Gratangen, there were also echo sounder recordings of herring schools swimming at depths down to 200 m. At night, the herring migrated closer to the surface, the schools disperced, and the fish density dropped from about 2 herring/m^3 to 0.02 herring/m^3 in average (Table 1).

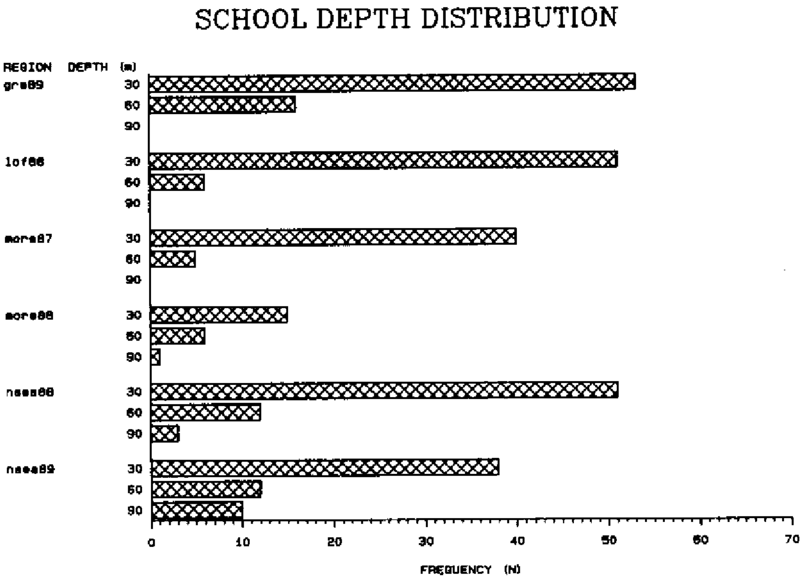


Figure 2. School depth distribution in actual regions.

PURSE SEINE FISHING STATISTICS

Official, quantitative information on unaccounted fishing mortality, or the frequency of net bursts in the Norwegian purse seine fisheries, is scarce. We have collected some catch data directly from the log books of several purse seiners during the fishing seasons 1985 and 1986. A fishery organization recorded the net burst frequency during the herring fishery in winter 1989. Data about the mortality caused by net burst do not exist, but our purse seine statistics can be used to estimate *worst case* figures of incidental fishing mortality.

Figure 3 shows the frequency distribution of catch size and time of catch for the Norwegian spring-spawning herring, North Sea herring, and mackerel fisheries. The Norwegian spring-spawning herring were mainly caught during winter night-time, along the northwest coast of Norway, while the North Sea herring were fished during the daylight and dusk hours in May-July and July-October, respectively. The catch size in these fisheries varied from 5 to 500 tons, but most catches were less than 100 tons. Average catch size was significantly different in these fisheries ($p <$ 0.05, Man-Whitneys test), and the biggest average and maximum catch size were obtained during the Norwegian spring-spawning herring fishery (Table 2, Fig. 3).

Table 2. Catch size in Norwegian purse seine fisheries for herring. (N = no. of catches)

	CATCH SIZE		
	Average (tons)	St.dev. (tons)	N
Norwegian spring-spawning herring	73.1	95.9	88
North Sea herring	57.9	49.9	192

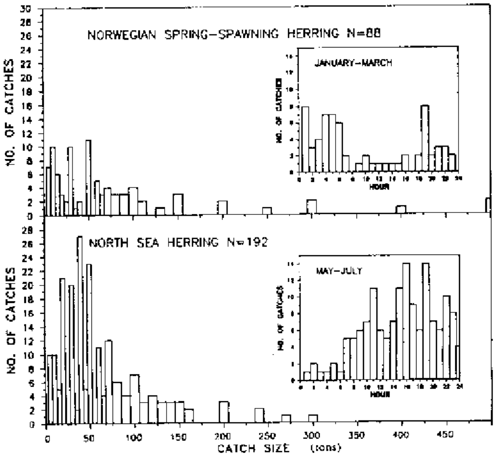


Figure 3. Distribution of catch size and time of catch for the Norwegian purse seine fisheries for herring, 1985-1986.

The distribution of catch size related to time of day for these fisheries is given in Figure 4. There is a tendency to larger catches during daylight hours in the Norwegian spring-spawning herring fishery, but one 500 tons catch was also obtained at night. One net-burst (in an evening trial) was reported in this material from the Norwegian spring-spawning herring fishery.

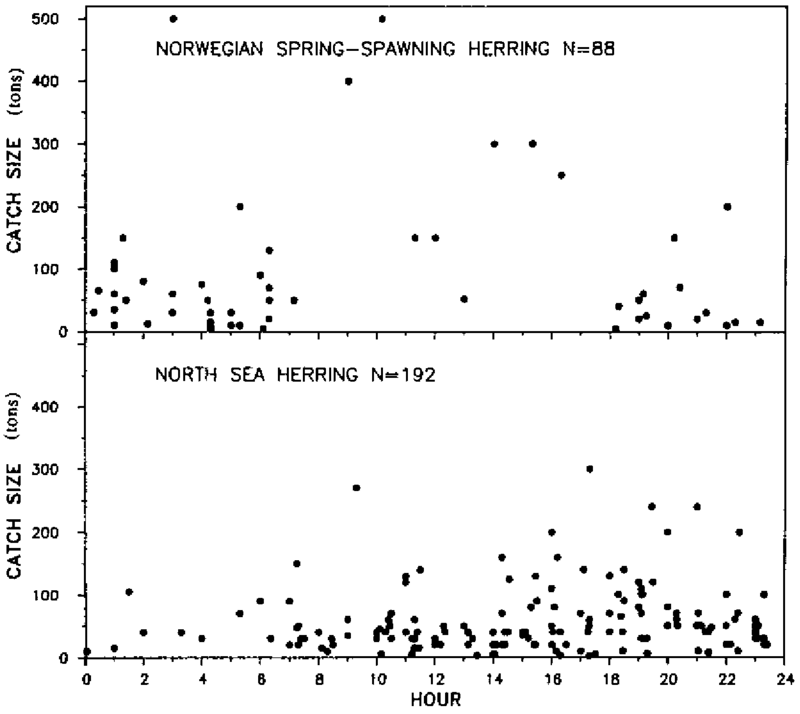


Figure 4. Distribution of catch size to time of day for the Norwegian purse seine fisheries for herring, 1985-1986.

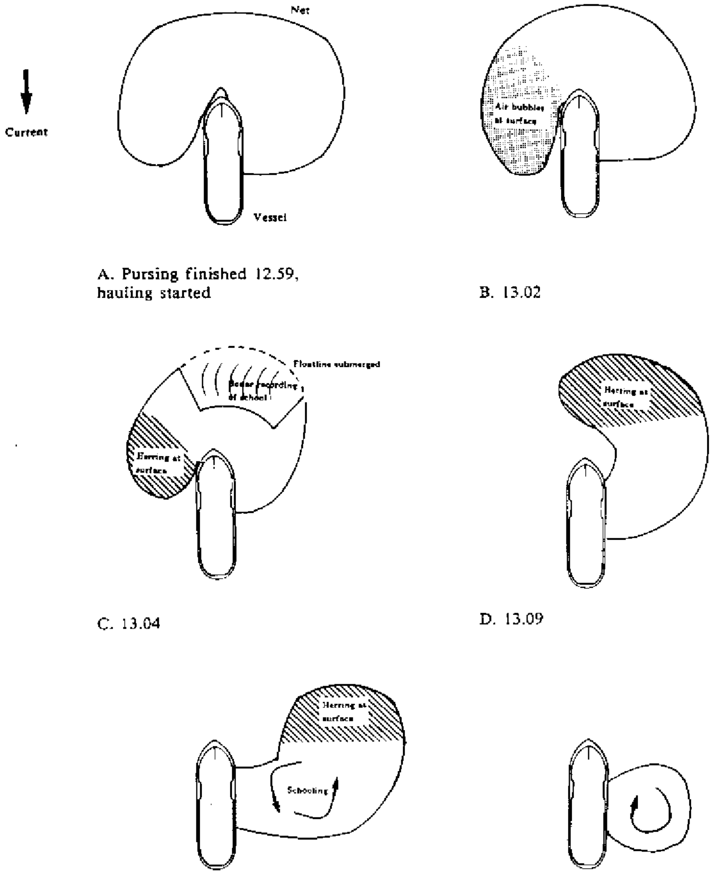
Number of net bursts for parts of the 1989 fishing season on the traditional spawning grounds for Norwegian spring-spawning herring off the northwest coast of Norway, as recorded by a fishery organization, is given in Table 3. As mentioned in the introduction, daytime fishing was closed during this season (week no. 9). Prior to the closing of the daytime fishing, net bursts (and loss of catch) occured in about half of the daytime sets (6 net bursts in a total of 14 daytime sets). During evening and nighttime, the number of net bursts was 1 out of 35 sets. These data clearly demonstrate that net burst occur mostly during daytime, but the data contain no information of the school size or mortality caused by the net bursts.

Table 3. Weekly numbers of net bursts in the 1989 fishing season for Norwegian spring-spawning herring.
(E = net burst during the early phase of the net hauling, L = net burst during the late phase of the net hauling, * daytime fishing closed, total number of sets in brackets)

	6	7	8	Σ 6-8	9*
Daytime	1E + 2L (5)	2L (5)	1E (4)	2E + 4L (14)	-
Evening	(3)	1E (4)	(3)	1E (10)	5
Night	(2)	(2)	(21)	(25)	10

It is tempting to calculate a figure for the unaccounted fishing mortality during the Norwegian spring-spawning herring fishery on the basis of the described purse seine statistics. The total quota for the period 1985-1987 was about 180,000 tons for the purse seine fleet. Given an average catch size of 73 tons (Table 2), the total quota has been fished by 2465 sets. Only one evening net burst, as recorded in the log-book data, is probably an underestimate when compared to the Table 3 data, which clearly show that net bursts mainly occur during daytime fishing. Assuming that the data in Figure 3 are representative, the frequency of daytime sets is 8/88, and the average daytime catch size 262.5 tons (SD = 136 tons, n = 8). This indicates that about 60 000 tons have been fished during daytime. Further, assuming that the frequencies of daytime sets causing accounted and unaccounted fishing mortality are given by the Table 3 data (8/14 and 6/14 respectively). Then there have been 168 daytime sets causing unaccounted fishing mortality for the period 1985-1987. Assuming that a net burst causes either instant or long term mortality to every fish involved, this shows that the total unaccounted fishing mortality is bigger than the total daytime fishing mortality for the actual period, if the school size causing net bursts was bigger than about 360 tons in average. Net bursts occur seldom in the summertime North Sea herring fishery.

We have no exact information of mortality and school behaviour during and after a net burst. During cruises on board commercial fishing vessels to study and quantify the swimming behaviour of herring and mackerel schools during purse seining (Misund 1989), we never observed net bursts, but two incidental observations are relevant. One was made during daytime in a shallow fjord. A 150 tons school of Norwegian spring-spawning herring performed a behaviour which could have caused a net burst (Fig. 5), but the net was strong enough to resist the pressure by the fish. This behaviour did not seem to have caused any instant mortality or damage to the herring, as the herring were visually observed to school around in the net until it was concentrated in the bunt, and no damaged fish were recorded during pumping. Figure 6 shows the Simrad SM 600 sonar recorded swimming behaviour of a 150 tons school of Norwegian spring-spawning herring during circling of the vessel and shooting of the net. Half an hour earlier, the very same school caused a net burst by another vessel. In the recorded situation the school was caught, and there was no sign of damage on the herring. These two observations clearly indicate that at least not all fish involved in a net burst suffer instant fishing mortality.



A. Pursing finished 12.59, hauling started

B. 13.02

C. 13.04

D. 13.09

E. 13.15

F. 13.25
Brailing started 13.30

Figure 5. Visual observations and sonar recording of a 150 tons Norwegian spring-spawning herring school during purse seining in Solemsundet, Northwest Norway, January 14, 1985.

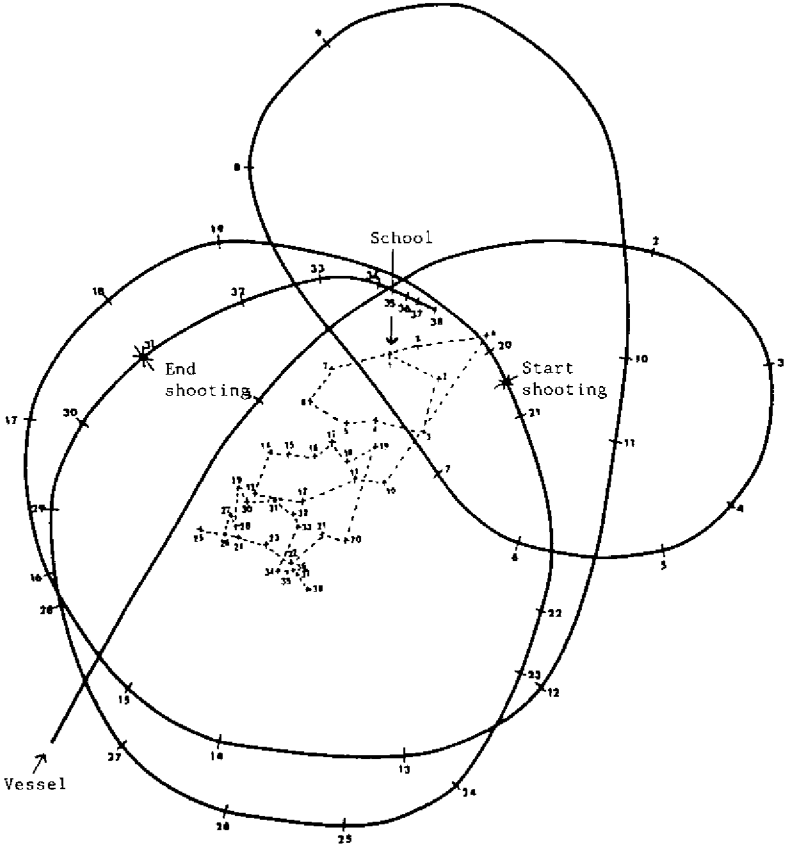


Figure 6. Simrad SM 600 sonar recording of a 150 tons school of Norwegian spring-spawning herring in Freifjorden, Northwest Norway, January 18, 1985 (observation interval: 30 sec.).

STORING IN NET PENS

The smaller coastal purse seiners transfer captured herring to net pens where it is stored up to several weeks before it is sold. In many occations, large quantities of herring have died in the net pens, causing not only unaccounted mortality but also local pollution. The reason for such mortality has not been determined, but possible explanations may be lack of oxygen due to high densities and large fish quantities, loss of scales that causes osmoregulation difficulties and easier exposure to infectional diseases, and lethal concentrations of metabolithes due to high swimming activity (Blaxter 1969). The extent of the mortality in herring net pens is not known.

In the North Sea herring fishery, the larger purse seiners often wait uptil 24 hours before brailing. Meanwhile the herring are kept schooling around in a fraction of the closed purse seine to excrete the gut content. Catches up to several hundred tons can be handled by this method, and unaccounted mortality occurs seldom.

DISCUSSION

The probability of a net burst is dependent of school size, the schooling behaviour, and the strength of the purse seine. In the Norwegian herring fisheries, it is commonly recognized that net bursts may occur for school biomasses larger than 2-300 tons. As shown by the availability analysis, such big schools may be absent or constitute only a rather small fraction of the total number of schools in the actual fishing areas. Most schools available are rather small, but average catch size in the Norwegian purse seine fisheries for herring exceeds 50 tons due to precapture size selection of target schools.

Based on the unofficial purse seine fishing statistics, a figure of unaccounted mortality in the Norwegian spring-spawning herring fishery for the actual period in the order of 10^4-10^5 tons is suggested. Even if smaller than the 150 000 tons estimated by Anon (1989), unaccounted mortality in this order of magnitude is unacceptably high. Our estimate is, however, calculated on questionable assumptions leading to the high number of sets with net bursts, and especially that every herring in a school causing net bursts suffer either long term or instant mortality. In the Gulf of Riga pelagic trawl fishery, Treschev et. al (1975) estimated an average mortality of 3 % of herring that escaped through the cod end meshes. Efanov (1981) showed that such mortality, being up to 35 %, was dependent on the mesh size, while Borisov & Efanov (1981) found that the juvenile herring suffered 100 % mortality, and that the mortality of the larger herring was lowest for the size classes that were less affected by the meshes. Prior to a purse seine net bursts, large number of herring must be pushing against the net wall in a similar manner as when struggling through the cod end meshes of a trawl. This may indicate that the mortality caused by a net burst is far from total, but, as some of the front individuals may be squeezed against the net wall, the net burst mortality may be higher than for herring escaping through cod end meshes. Similarly, the complains about high mortality when storing herring in net pens are not in accordance with Kreiberg & Solmie (1987), who found survival from 75 to 97 % for herring in net enclosures. Therefore, to quantify the unaccounted mortality in the Norwegian spring-spawning herring fishery, further research is needed, both with regard to net bursts and storing in net pens.

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Herring Spawning Grounds in the Northeastern Baltic: Recent Changes and Present Situation

T. Raid
Baltic Fisheries Research Institute
Tallinn, Estonia

ABSTRACT

The most important spawning grounds of herring in the Northeastern Baltic are situated in the Gulf of Finland, the Gulf of Riga and the Western-Estonian archipelago. During the last 10-20 years certain changes in the conditions for embryonal development of herring on the spawning grounds, more affected by human infuence can be observed (mudding, disappearance of bottom vegetation or changes in its composition etc.). That has resulted in an increase of embryonal mortality. Changes in zooplankton composition observed in some coastal regions may begin to affect the feeding conditions of herring larvae in the future.

MATERIAL AND METHODS

The condition of herring spawning grounds and spawn was studied by SCUBA- divers near the southwestern coast of the Hiiumaa Island in 1982-1983 and in the Pärnu Bay in 1987-1989 (Fig. 1). Still, in general, the location of spawning areas was estimated indirectly based on the long-time mean distribution pattern of herring larvae. The latter also allows to compare the paticular importance of different spawning grounds in the total reproduction. The ichthyoplankton surveys were performed in the Gulf of Finland in 1976-1989, in the Western-Estonian archipelago in 1987-1989 and in the Pärnu Bay in 1960-1989.

The zooplankton data used in present work were kindly provided by A. Lumberg and L. Svistunova.

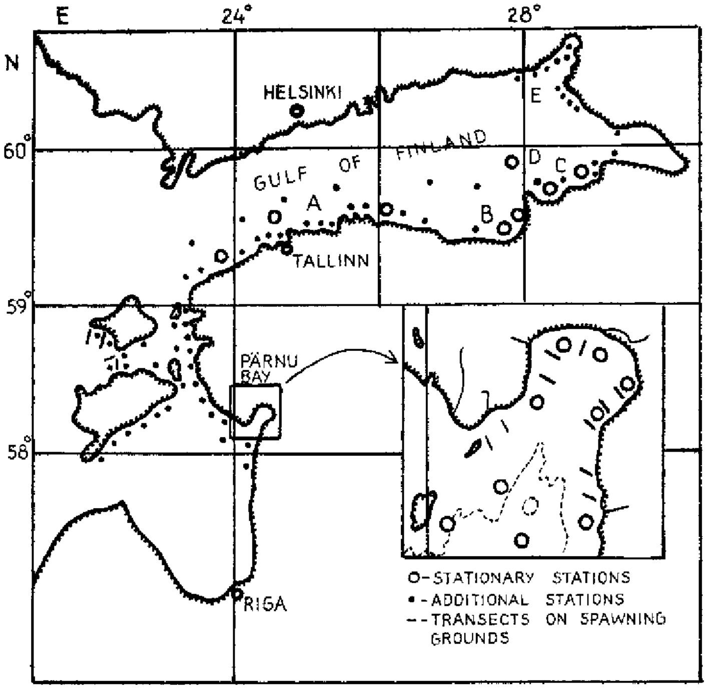

Figure 1. Location of sampling stations and transects.

RESULTS AND DISCUSSION

Location of Herring Spawning Areas in the Northeastern Baltic

At present, the five major herring spawning areas can be distinguished in the southern and eastern parts of the Gulf of Finland(Fig. 1, see also Raid, 1985): A- southwestern coast; B- banks in the Narva Bay; C- the Luga and Koporye Bays; D- eastern archipelago; E- northeastern coast.

The main spawning areas in the Western-Estonian archipelago are situated in the outer zone of the Matsalu Bay, in the Kassari Bay and around the Muhu Island. The spawning grounds of special importance are also located near the southern coast of Saaremaa Island and in the Pärnu Bay (Fig. 2).

A comparison of our results with the historical data from the 1940s and 1950s (Rannak, 1959). shows that no

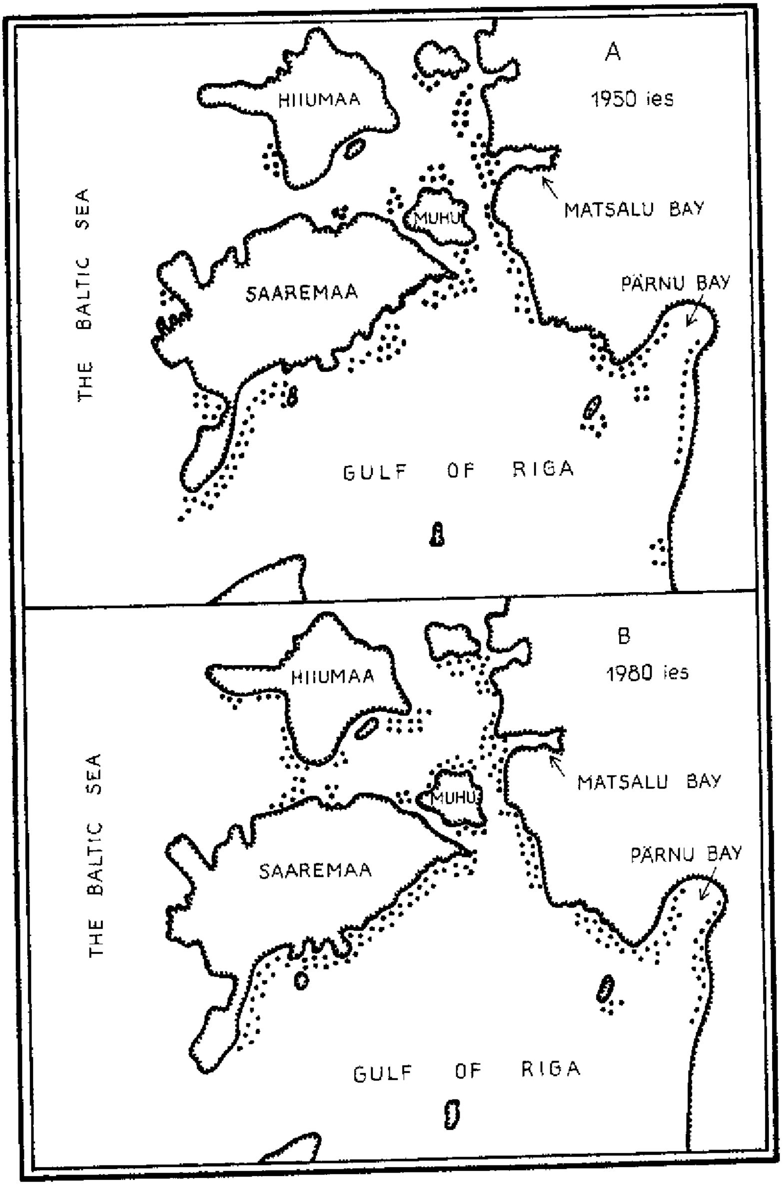

Figure 2. Location of herring spawning grounds in the Western-Estonian archipelago in the early 1950s (after Rannak, 1959), and in 1980s.

remarkable changes has occurred in the location of the main spawning areas in the Western-Estonian archipelago in last 30-40 years (Fig. 2). Unfortunately the respective historical data for the Gulf of Finland are scarce.

Spawning Depth

Near the SW- coast of the Hiiumaa Island the herring spawn was found in the depth range of 4.5 - 8.5 m whereas the bulk of the eggs was deposited at the depths from 5.5 - 8.0 m.

In the Pärnu Bay the main spawn was observed at the depths of 3.0 - 6.0 m. Despite of careful search no eggs were found at the depths less than 2 m. Still, the local fishermen have reported about herring spawning also at the depths of 1.5 - 2.0 m.

Consequently, the Baltic herring spawns in the areas investigated at the depths similar to these observed in the northern part of the Gulf of Finand (0.2 - 6.5 m; Oulasvirta et al., 1985), in the SW Finland Archipelago (0 - 8 m; Kääriä et al., 1988) and near the east coast of Sweden (0 - 11 m; Aneer and Nellbring, 1982).

Spawning Substrates

The red algae Furcellaria, Ceramium and Polysiphonia are the common spawning substrates for herring near the SW-coast of the Hiiumaa Island. Despite of wide distribution of brown algae Fucus in the area investigated, the herring seemed to avoid that species. Also, no spawn was found on bottom sediments and rocks.

In the Pärnu Bay herring prefers to spawn on the red algae Furcellaria and the Polysiphonia. In addition, the brown algae Pilayella and Sphacelaria were exploited. In the areas where Furcellaria occurred the preference of the latter to the loose-lying algae could be stated. In the areas without any vegetation, the spawn was found also on bottom sediments (sand and gravel).

Despite of the fact that eggs of the Baltic herring can be found on the bottom and benthic organisms (Oulasvirta et al., 1985), red and brown algae seem to be its preferred spawning substrates in all coastal regions of the Baltic (Ojaveer, 1981 and others). The remarkable coincidence of the location of herring spawning grounds with the distribution pattern of certain algae (Pilayella, Sphacelaria, Ceramium, Furcellaria) was revealed in the southern part of the Gulf of Finland (Raid, 1985). That forces to pay attention to changes in bottom vegetation, observed in some areas. In 1940s and 1950s the red algae Furcellaria, Ceramium and Polysiphonia were the common spawning substrates for herring in the Gulf of Riga. The deposition of spawn on the bottom sediments was rare (Rannak, 1959). From the 1970s onwards changes in the coverage of bottom vegetation and/or in its composition

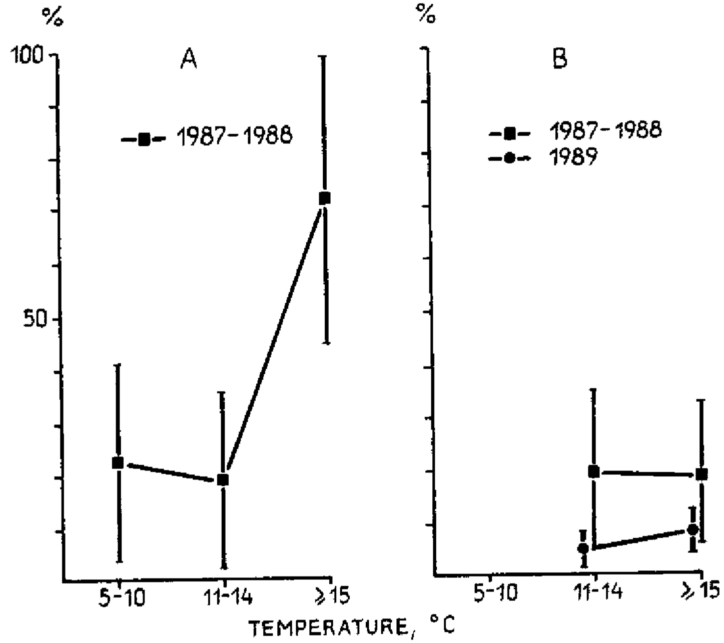

Figure 3. Mean percent of dead eggs on sand (A) and bottom vegetation (B) with 95% confidence limits at different temperatures.

have been observed in this area, particularly in the inner zone of the Pärnu Bay. The share of red and brown algae has diminished and that of green algae (Gladophora) expanded (Trei, 1986).

Egg Abundance and Mortality

When spawned on bottom vegetation, eggs usually lay sparsely, forming aggregations up to 100 eggs. In such aggregations eggs were deposited in 1-3 layers. The mean abundance of eggs varied from 860 to 10640 eggs per m^2.

In case of spawning on bottom sediments, found in the Pärnu Bay, the mean egg abundance appeared to be higher extending from 18000 to 350000 eggs per m^2. The spawn was deposited in thick aggregations of up to 10 layers.

The share of unfertilized eggs was low on all studied spawning grounds and varied from 1.2 to 4.6 %. In 1987-1988 the mean percent of dead eggs at 1...5 stages of development (after Klinkhardt, 1988) was 19.6 in the case of algal substrates at the temperature 11-14° C, and 18.7 % when temperature exceeded 15°C. In 1989 the corresponding values were 4.0 and 7.5 % (Fig. 3).

When spawned directly on the bottom, the mean percent of dead eggs varied from 19.6 to 22.5 at the temperatures 5-14° C. At the temperatures over 15° C the mean mortality rise to 71.6 %, reaching in some samples 100 %.

The deposition of the Baltic herring eggs on substrates is generally described as sparse that has been considered to keep its embryonic mortality low (Ojaveer, 1981a and others). In the 1940s and 1950s the mean embryonic mortality of herring was 2-7 % in the Gulf of Riga, reaching 15 % while the temperature exceeded 15° C (Rannak, 1959). In 1977 the mean mortality of herring eggs in the same area varied from 0.2 % shortly after spawning to 25 % at hatcing (at the temperature range 7.8-8.5 C. Next year the mortality at hatching stage varied from 4.3 % to 31.0 %. The latter level occurred at an unfavourable temperature for herring development (Ojaveer, 1981a).

A comparison of historical and our data allows to conclude that herring mortality during its embryonic development has the tendency to increase, particularly during last one or two decades. That is especially evident in the temperature conditions exceeding the optimum level for Baltic herring development, 5-17° C (Ojaveer and Simm, 1975) and if the spawn is deposited directly on the bottom. The higher mortality of eggs spawned in thick patches on sand can be explained with worse aeration conditions and uneffective removal of metabolic vastes.

In several recent publications it has been concluded that the composition of bottom vegetation may play certain role in the mortality of herring eggs. In this connection the assumption by G. Aneer (1987) that exudates of Pilayella may affect herring eggs is worth of special attention since that species has become a common substrate for herring spawn. Nevertheless, the direct lethal effect of algae on herring eggs is likely not the main mortality factor since the duration of embryonic development of Baltic herring lasts only about 2000 degree - hours (Herra, 1986). However, the effect of possible local oxygen shortage as a result of algal decay should be studied as a probable reason of egg mortality.

Herring Reproduction and Condition of Ecosystem

Extinction of bottom vegetation, observed in some areas of the Northeastern Baltic should be treated in complex with other alterations in the sea ecosystem, particularly with eutrophication of the coastal zone. The results of Secchi disk observations in the Pärnu Bay presented in Figure 4 show that the water transparency in the inner part of the Bay has remarkably diminished in last 30 years. That phenomenon could be one of the direct reasons for

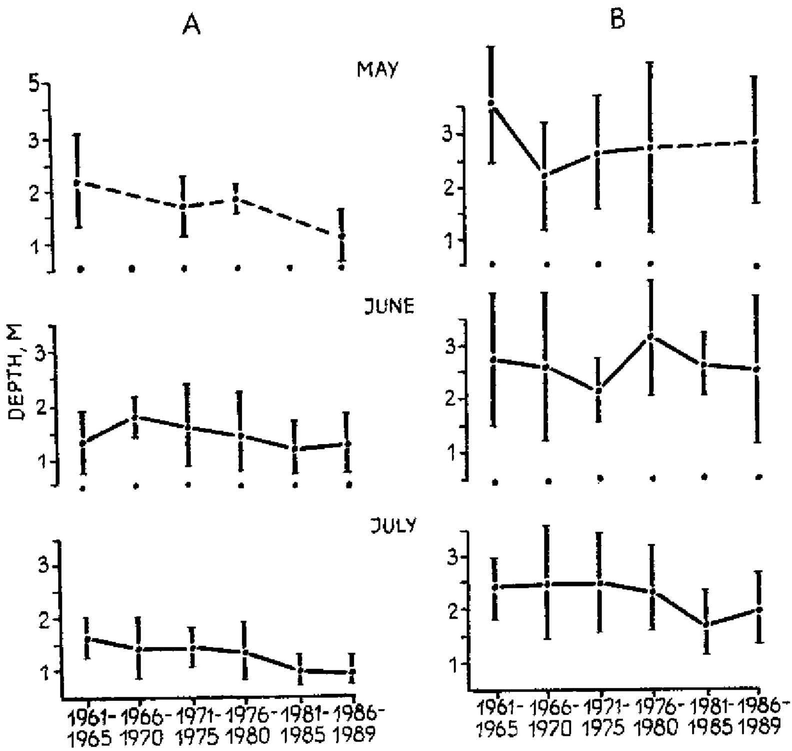

Figure 4. Mean transparency of water (Secchi depth) with 95% confidence limits in the Pärnu Bay: A- inner bay, B- outermost area.

changes in bottom vegetation in the Pärnu Bay and in other coastal areas of the Baltic Sea. Simultaneously other indications of eutrophication can be observed in the Pärnu Bay. So the share of cladocerans and rotifers has remarkably increased in zooplankton while that of copepods has diminished during last decades (Raid, 1990). Notable is the decrease in the mean abundance of copepod nauplii- the main prey for herring larvae- about 5 times, compared with the 1961-1970 level (Table 1).

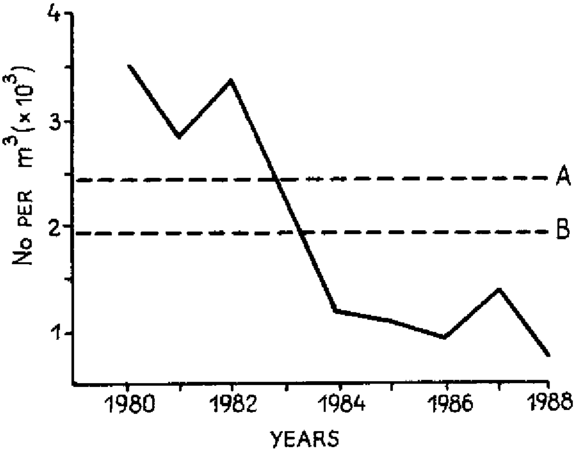

Figure 5. Mean abundance of copepods in May at sampling stations in the Gulf of Finland in 1980s: A- mean for 1967-1987, B- mean for 1980-1988.

Table 1. Mean abundance of copepod nauplii at the stationary stations in the Pärnu Bay (thousands per m^3)

Month	Years 1961-1970	 1971-1980	 1981-1987	 1988	 1989
May	37,5	14,8	4,5	5,1	4,4
June	46,7	35,1	8,8	6,8	10,4
July	33,8	26,2	9,4	12,6	15,6

The analogous situation was found in the Gulf of Finland where the mean abunance of copepods has also sharply decreased (Fig. 5).

The long - term dynamics of the mean abundance of herring larvae on the spawning grounds in the Pärnu Bay (Raid, 1990) and the state of herring stocks in the Northeastern Baltic (Anon., 1989) show that the degradation of the conditions for herring early development has not yet seriously affected the reproduction of the stocks. In spite of that, the continuous worsening of environmental conditions may begin to reflect on stock condition already in the nearest future. Increase in egg mortality due to disappearance of natural spawning substrates and the food shortage due to the changes in zooplankton communities are the main risk factors. Analogous trends, observed on herring spawning grounds in the SW Archipelago of Finland have already caused substantial effect on herring fishery in that region (Kääriä et al., 1988).

The populations of Baltic herring have adapted for spawning at specific temperatures to provide the better survival conditions for larvae (Ojaveer and Simm, 1975). Consequently, a steady increase in the embryonic and/or postembryonic mortality of some stocks may finally result in changes in the Baltic herring population structure.

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Stock Discreteness

Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Workshop on Member/Vagrant Hypothesis and Stock Discreteness

J. Collie, Moderator

[Editor's Note: The transcription of this workshop was edited and condensed by Vidar Wespestad, Jeremy Collie, and Elizabeth Collie.]

COLLIE: The 1988 book by Michael Sinclair, *Marine Populations, An Essay on Population Regulation and Speciation,* presents a view of population regulation that differs from the traditional perspective. The member/vagrant hypothesis explains many aspects of population regulation, but some things about the hypothesis are unanswered in my mind.

What are the advantages to members? For larval herring, what are the advantages of being retained? Sinclair down plays the traditional trophodynamic explanations of larval survival and implies that imprinting is important. We need to determine what's so great about a retention area. The converse question is, what's the fate of the vagrants? The idea in Sinclair's book is that vagrants don't contribute reproductively to the population. Jacques Gagné gave a counter example in which there may actually be advantages of vagrancy.

Is the member/vagrant hypothesis useful for directing or stimulating future research? Are there additional hypotheses we should consider? While the original Iles and Sinclair retention hypothesis was testable, as it has evolved into the member/vagrant hypothesis, it has become so general that it may be irrefutable. We should go through the key points in the member/vagrant hypothesis and decide which are supported by the evidence and which aren't. Jacques Gagné suggested this workshop and I think he's prepared to give an epitaph for the member/vagrant hypothesis today, and would like to lay it to rest.

GAGNÉ: Jeremy and I went through Mike's book and tried to come up with definitions of the key components or terms of the hypothesis. We feel the following are definitions proposed by Mike Sinclair.

Stock:
This we didn't find defined anywhere in the book, so we are proposing the following definition: A stock is mainly a fisheries-management unit that includes individuals of a species in a given area. A stock could be only a fraction of a population, with population defined as a self-sustaining component of a particular species, or a stock could be several populations all managed as a unit. A member is an individual in the right place at the right time to contribute to the reproduction of a population. A vagrant is an individual separated from its population at any stage of the life cycle. So it's not only during the larval stage that vagrancy occurs, it could be as a juvenile or as an adult. Separation could come either from spatial or energetic processes.

Retention:
I found two definitions that add to each other. First was persistence of an aggregated distribution in spite of the diffusive state of the physical environment, or in other words, a distribution that is not dispersed to the degree predicted from passive transport by currents. The second is homing, stressing the point that homing doesn't simply mean returning to the same spawning location year after year; it has to be the place of birth.

HAY: Is there anything in those definitions that implies a genetic basis to any unit?

GAGNÉ: The self-sustaining phrase would imply that. The populations, then, must have a genetic basis.

HAY: I didn't think you wanted to pursue this yet, but I note that you're defining a population as genetic. I don't think that's necessarily the case. The systematic literature recognizes geographic separation as one criterion for identifying subspecies. If populations are components of a species and they're not geographically isolated, then you have to have a mechanism to maintain genetic distinction between them. In that sense, geographic distinctness of populations is consistent with fishery literature but at odds with general biological literature as represented by the classics of such people as Mayr and Dobzhansky.

STEPHENSON: I think the essence of the modern stock structure debate is the definition of a population. That's what we're arguing about: Are stocks in fact populations? The definition I think is nice to put up there for population implies genetic discreteness, geographical separation, and so on. That is the idealized case. The question then becomes, how far are stocks towards that ideal. I think it's a useful definition, useful for comparison.

COLLIE: Yes. What we recognize as stocks aren't completely genetically isolated, and the definition of population does imply some degree of reproductive isolation and a lack of mixing at some scale.

FOGARTY: We must clarify the genetic basis of this, because Mike's book develops an evolutionary argument that entails specific evolutionary mechanisms. It's more than just ecological issues. Keep the genetic basis of these issues firmly in mind, because it's critical to evaluating his hypothesis. So far we've mostly talked about things you'd see in an ecology book, but it's also an evolutionary argument.

COLLIE: Lew Haldorson agreed to review the basic tenets of the member/vagrant hypothesis and what it purports to explain.

HALDORSON: I'm just going talk about the things that may apply to herring. The hypothesis Sinclair formulated, as pointed out, is fairly far reaching. This is a summary in three statements of the implications of the member/vagrant hypothesis in relation to herring stocks. Jeremy's first question was something like "what does it purport to explain?" Thinking about it, it seems to purport to explain almost everything about population structure. The hypothesis states that population richness [richness meaning number of populations], geographic pattern, and distribution of these populations are functions of the number and location of hydrographic features which promote retention of planktonic early life history stages. Throughout his book, Sinclair focuses on early life history and the importance of his hypothesis to explain the kind of population structure we see in animals with planktonic early life history stages. That seems to be where the emphasis lies.

Second, the abundance of individual populations—the average population size over time—is determined by the size and cohesiveness of the geographic-hydrographic features that promote retention. We've explained how many populations there are, and that their size and location are functions of the hydrographic structure of the marine areas. The temporal variability in year-class abundance (the number of recruits that result from a given year's reproduction) is a function of interannual variation in the rate of loss from retention areas. The hypothesis also explains the variance around the average population size. We've gone a long way to explaining population dynamics if it's all true.

A couple of figures from the book demonstrate how spatial pattern and richness depend on the size of retention areas. They show that retention areas can overlap, be separate, or of various separate sizes. For herring we might contrast the hydrography of the Bering Sea or the North Sea (large areas) to, for instance, Sitka Sound in southeastern Alaska (the area I'm more familiar with), which is fairly small. The average population sizes therein are determined by the sizes of the geographic or hydrographic features. A population associated with a small hydrographic feature is small, with a certain amount of variance. A large hydrographic feature enables a large population and a corresponding variance. These, I think, are the major features of population structure supposedly determined by the member/vagrant hypothesis.

Sinclair talks about the importance of losses from a retention area—the vagrants that disappear—and abundance variability. Differences in retention might cause variability, but I don't think he claims retention as an exclusive kind of mechanism. Other things we know of affect year-class strength: prey availability, temperatures that affect growth rates, etc. So, variability due to differences in hydrographic retention is mixed up with variability due to these other things. Trying to separate out the variability from different causes would be a serious problem.

HAY: Does that argument apply only to herring? I think the answer is no.

HALDORSON: The book goes on to say that this applies to zooplankton and all sorts of things. So it's an inclusive hypothesis and requires these planktonic life stages.

HAY: Then how can it be that you don't have exactly the same stock structure for different species in the same area? How can you have multiple stocks of one species and single stocks of another if they're all subject to the same requirements?

STEPHENSON: I guess they're not subject to the same requirements. They're different beasts with different life history strategies or parameters, different requirements. I don't know why you would say that they would.

HAY: Well, presumably two species spawning at the same time in the same depth would be subjected to the same hydrographic conditions.

STEPHENSON: Perhaps at that stage in their life history, but I think we're talking here about the entire life history.

HALDORSON: I think the crux of his argument is that it's pelagic larvae. Of course, pelagic larvae are doing a lot of things besides drifting around. For instance, larvae doing different sorts of vertical migrations could go different directions or perhaps have different abilities to stay within certain oceanographic features. I've done vertical migration studies on fish larvae within a certain area. While some species are going to the surface, others are going down. All the fish larvae aren't doing the same thing at the same time. Pelagic fish larvae exhibit a whole suite of life history strategies. Even if they occur at the same time of year, they may do different things. And of course they don't always occur at the same time, there's usually a whole range of times when they would occur.

FOGARTY: I think that what happens to the vagrants is an important element of this hypothesis. Mike takes the tack that the principal benefit of sexual reproduction is to repair damaged DNA (rather than the more usual view of recombination). The more similar the genomes of mating individuals, the higher the probability of repair of any errors in transcriptions—a view quite controversial in evolutionary circles! And therefore, an individual that is a vagrant is effectively dead to that population, and in a sense has reduced fitness because if that individual does make it to another population its role in repair of errors in DNA transcription won't be as effective as if it had stuck with its original population. This DNA repair hypothesis is counter to the conventional evolutionary argument that there is an advantage for some members of the population to stray and take advantage of new areas that may open up for colonization so the population can increase. This bears some close consideration.

COLLIE: Well, Mike [Fogarty], turn that argument around. If you dispute the DNA repair explanation of benefits of sexual reproduction, and consider the more conventional idea of benefits of recombination and outcrossing, then would the whole basis of the member/vagrant hypothesis fall apart?

FOGARTY: Not necessarily, but this genetic argument has strong implications for the relative levels of vagrancy that may be adaptive under the alternative explanation of recombination. One difficulty with the repair hypothesis is that it would lead to more genetic homogeneity and presumably less adaptability to changing environmental conditions. You could construct a counter argument, promoting recombination as the principal benefit of sexual reproduction. Of course, Mike does make the good case that you have to find a mate of your own species, a disadvantage for a vagrant though the probability is still not zero.

STEPHENSON: I thought we were getting to the point of whether a vagrant can become a member of another group, and I guess that's relevant to this debate, isn't it? I don't believe that's dealt with in the book as a specific topic. But under the normal way of looking at things, what Mike has termed vagrants would become members of another group.

FOGARTY: Yes, but if you accept Bernstein's repair hypothesis, on which Mike relies heavily, it is not advantageous to join another group, because your ability to contribute to DNA repair is compromised. With a more conventional view, with assortive mating, you've increased genetic diversity and that's, presumably, beneficial.

STEVENSON: This seems like a good time to bring up something that's been bothering me—before we get off onto an evolutionary discussion of what becomes of vagrants. It still bothers me that larvae may be lost from a retention area, become vagrants, then return to that same area as adults, spawn, and therefore contribute reproductively to that stock. Does that describe a vagrant or a member of the population?

GAGNÉ: It seems to me that all the larvae that are evacuated away from their retention area are by definition vagrants. They're not supposed to come back to reproduce on those same grounds.

STEVENSON: Some must, though. Rob Stephenson and some of the people at our laboratory wrote a paper in which they argue that some larvae persist in a spawning area, while other larvae "leak" out. These would be the vagrants. However, we have found that, as they mature, these fish make an eastward migration back toward their spawning ground.

GAGNÉ: I thought Townsend said that all the larvae evacuated away from the retention area of Grand Manan, I believe, toward the coastal estuaries would not survive the winter. Only those larvae retained close to the spawning grounds (wintering in Gulf of Maine) would form the recruits.

STEPHENSON: We didn't mean to imply in that paper that the larvae were being removed from the retention area. In fact, it's a continuous body of water of uniform mixing—an ideal retention area—bounded on one side by a stratification, on the other by the shore. It's all one retention area or one larval distribution area, if you want to call it that. There was movement of larvae within that area, but it was a continuum—they weren't separate patches.

STEVENSON: Then what becomes a vagrant?

STEPHENSON: I think vagrants, in that situation, as I understand Sinclair, would be those that get outside into the mid-Gulf of Maine where we know that larvae do not persist.

STEVENSON: Well, I'll sit down and shut up now, but that seems to be one of the fuzzy areas of the hypothesis, or maybe those of us trying to apply it don't understand it. But what is the scale of these retention areas? It needs to be more strictly defined.

FOGARTY: The critical issue is whether an individual comes back to mate with its larval group. To fit Sinclair's hypothesis, an individual must return to mate with an individual of similar genotype.

STEVENSON: Is the entire coast of the Gulf of Maine a single retention area? I'm not sure it's a very useful concept.

HAY: The hypothesis is long on theory and short on evidence. I don't think there's been any demonstration of retention areas for planktonic fish, except for some of the papers here. We're a long way from showing genetic change in any population, given the work that has gone on with mitochondrial DNA and electrophoresis. I grant you a lot of meristic work shows differences, but the paper that I think is crucial is one by Smith and Jamieson, which said that there's no demonstrable genetic change among herring populations over wide spaces. I've heard denigrating comments about that paper, but the onus is upon people to show it to be false. One study showing clear genetic difference among populations would falsify their hypothesis.

STEPHENSON: Yes, there is some evidence. We've done some mitochondrial DNA work, which indeed does not show the kinds of differences we're looking for. But lack of demonstrable genetic differentiation does not prove uniformity. Smith and Jamieson argued this erroneously in their paper. It just tells you that you're not looking at the right part of the genome or at the right elements to be able to differentiate them.

GAGNÉ: If I may make one comment on what Doug [Hay] just said. I don't agree that there is no evidence of retention. If we use the definition from Mike's book, and if you look at the evolution of distributions of herring larvae almost anywhere, you'll see that the aggregations don't just disperse passively. The larvae remain aggregated, usually close to spawning grounds, for periods of weeks, and in certain cases for months. This is quite convincingly demonstrated, in this book and in the papers that led to the book. Also other evidence published recently is supportive.

COLLIE: I want to return to this list of what the member/vagrant hypothesis purports to explain. Jacques tried to test the hypothesis, and from what he's said, I think he would support the first contention that population richness is determined by the number and location of retention areas. It seems the second contention, that the absolute size of the population depends on the size of the retention area, wasn't supported. Neither the prediction about temporal variability in abundance nor the predicted spawning times were supported in Jacque's study. In summary, the member/vagrant hypothesis explains more about biogeography than about temporal patterns in spawning or abundance.

Lew brought up a good point about whether temporal variability is a function of the size and/or cohesiveness of the retention area. It's an appealing hypothesis, but he said it's very hard to sort out the proportion of variability associated with the physical retention from the variability due to other causes. I know Fritz Funk struggled with how to test the hypothesis, formally, instead of just being opportunists and trying to interpret our data in the light of this hypothesis without going out a priori to test it.

FUNK: This is a brief aside about determining whether a hypothesis is testable. Imagine the ideal experimental environment for testing hypotheses. We can talk for a long time about the member/vagrant hypothesis, but producing a testable hypothesis will be difficult. We've tended to look in our own back yards at systems we find convenient to sample, which might not be the best way to test Sinclair's hypothesis. Specifically, estuaries may not be the best sites for testing hypotheses about larval retention. There are so many strong geographic features in estuaries that could obscure and complicate matters; a better place to look might be a less complex coastline where we can isolate one specific mechanism.

Perhaps thinking of the ideal experimental system—although we'll never find it—might help us determine those parts of the hypothesis that are indeed testable. I also want to put in a plug for testing this in the Bering Sea. The Bering Sea coastline is a bit less convoluted, particularly in Norton Sound.

FOGARTY: Another idea is to take advantage of comparative studies. As Doug [Hay] said you should see similar patterns of stock number (or population richness as Mike [Sinclair] calls it), because species spawn at the same time. They could use similar retention mechanisms and apparently don't. That has bothered me in the book. It should be possible, through comparison of life histories, to see whether these species have similar levels of population richness. An experimental approach would be the strongest, but because of the spatial and temporal scales under which most populations operate, it would be difficult. So the next best thing would be comparative analyses. Fritz [Funk] is right—experiment where possible. But the comparative approach is also open to us, though not fully explored in the book.

HAY: My feeling on this member/vagrant hypothesis is that you're providing answers before the questions and before the observations are established. I don't disagree; retention areas might enhance population richness. But the only thing that's rich about herring populations on the East Coast is the terminology describing them.

I'd like to step back and just observe something from a different point of view. This area of the West Coast was glaciated; 10,000 years ago it was covered in ice, so every species here is in a sense a vagrant. We're not seeing incipient speciation over that time; we're seeing colonization and development of stocks.

On the coast of British Columbia, and I think it's true for Alaska, there are 200 to 400 marine species. Some of them are very old. The *Clupeas* have been around for millions, hundreds of millions of years, and there are only about 300 *Clupeas* worldwide. They're not as species rich a genus as others. There are 2,000 species of Cyprinids in the Amazon River alone. So looking at herring as a species, it's quite plastic; it adapts. As for the rockfishes on this coast, there are over 50 of them in British Columbia, and I think hundreds in California. They adapt somewhat differently—less plastic, perhaps.

Pacific salmon stocks in British Columbia number in the thousands. Clearly they're stocks, because they run up rivers and become genetically differentiated. But they became stocks before they became genetically differentiated, right? If a bunch of rivers suddenly become accessible, the salmon run up there; then they become genetically differentiated, though they're not species (they're all reproductively homogeneous). They are genetically different. I think it's irrelevant. They're adapted to their circumstances, of course that's relevant. If you're going to have a member/vagrant hypothesis, you have to have homing. In the literature, Blaxter states that herring larvae cannot home because they're small. A herring larva when first hatched weighs about two to three milligrams. They're not much besides eyeballs and guts. As juveniles, they have more substance. They're up to the two and three gram range. That's a thousand times bigger. They have big olfactory rosettes—all the morphology they need to imprint. When Pacific salmon imprint they are in the range of a couple of grams, and they're imprinting to materials in the water. Imprinting, therefore, is probably not at the young larval stages but at the old larval stages. However, if anyone could demonstrate imprinting in larvae, then that's just great.

My feeling is that the member/vagrant hypothesis is very interesting—and esoteric. It's not very useful. There may be a host of genetic groups along the coast. As people who provide advice, we must provide the most sensible advice, using the best science available. The member/vagrant hypothesis does suggest a potential for genetic differences among very small units. This has yet to be demonstrated, but I believe we should protect these stocks considering there may be genetic differences. As a strategy, we should look at the smallest possible units practical to fish. In British Columbia we recognize five to seven units that we fish on. That's not consistent with retention areas, but we should be conservative. We should manage for the smallest units and we should be splitters working to lumpers, and we should lump when the evidence warrants it. The argument that we're not seeing genetic differences because we haven't looked for them yet, I accept, but you need a point of no return. When people have looked in the salmonids and other species, they have found differences.

So when are you going to stop looking? Jake Schweigert in our lab is looking at nuclear DNA, and if he finds differences in nuclear DNA between herring, that will be a major impact. But I don't hold my breath. The Kornfield study on mitochondrial DNA says there's no demonstrable difference. Nevertheless, we should recognize these as potential stocks. Smith and Jamieson put together a fairly nice picture that maybe there are no genetic differences. However, we should recognize stock differences, even if there are no genetic differences. So fishery management, I think, should recognize little stocks that may or may not have a genetic base.

COLLIE: Doug, you say you don't buy imprinting at the larval stage, or the contention that the population is defined at the larval stage, but you might be willing to consider the juvenile stage. At what age and how dispersed are the stocks in British Columbia by that stage? What spatial scale would you be willing to believe defines the stock?

HAY: In British Columbia larvae are distributed over a small area and juveniles are distributed over a much broader area. The adults are distributed over a much larger area still. Some areas don't have continuous spawn year after year. There are a few areas in British Columbia where we see, especially following El Niño, an injection of fish, and a persistence of spawning for somewhere between one and 15 years. Then it stops, consistent with the vagrant idea. But for herring, the point where they really move out is the juvenile stage. At that stage they are spread quite widely on the coast. We find juvenile herring everywhere but inshore. If juvenile herring could imprint to one of these areas, then we would have the basis for some sort of imprinting back to a unique area on the coast. But we don't know anything about what they might be imprinting to. It's not the same as a river system, although many of the big spawning areas are associated with some fresh water.

STEPHENSON: I just wanted to say to Doug that you've correctly distilled this argument down to one of stock discreteness, but there's a flaw in your logic. If there are no differences among B.C. Pacific herring, why propose to manage them separately? This is the basis of all our management.

HAY: Not to preserve genetic integrity, but to preserve the stability of the stocks over time. If we had one stock in British Columbia, we could take, presumably, all the fish from the north in one year, all the fish from the south in the next year. Or to take the extreme example, if we have one stock on the Pacific coast, why don't we take all the fish in one year from California? Would you expect, then, that next year there would be any fish left in California? Surely not. Consider the spatial scale of fisheries—the distance fish can recolonize. Our purpose is not to retain genetic integrity. Although why not? That's also done if you manage your fisheries conservatively.

STEPHENSON: I'd like to present a short review of the arguments for and against discreteness in Atlantic herring. This issue has come up many times at this meeting. It's elicited some interest and even emotion. Few topics stir up so much emotion in herring biologists! We should resolve this because stock discreteness underlies assessments and management. Substructure of some sort exists within Atlantic herring. In fact, an old quote from 1865 shows that fishmongers in the United Kingdom recognized differences among herring stocks. However, there is disagreement about the degree of that substructure. We do know that adults return to previous spawning areas. We need further work to determine whether this is, indeed, homing. There's a wealth of stock-specific population dynamic information: The age structure of herring stocks indicates that you're dealing with the same group of fish year after year. That's pretty good evidence of discreteness. At least on the east coast of Canada and the United States, there are discrete larval distributions. There's no doubt about that. On the other hand, we have evidence for changed spawning groups (groups that switched from the spring to the fall). I think evidence is weak, but it is a point against discrete populations. Also relevant are new populations. Georges Bank was dry land not long ago geologically, and there's a population there.

There are many moot points. Spawning continua—bunches of small populations along the coast—some have said that's loads of small stocks, others have said it's one. Same thing with clines and spawning time. We have seen some radical changes in behavior and migrations. A few instances have been cited of great groups of herring disappearing from one area and appearing in another area. Also there's the lack of consistent meristic or biochemical differences. Smith and Jamieson suggest that shows it's one population. I and others have argued that doesn't really show anything.

The life history of Atlantic herring, as follows, shows what we need to study to establish discreteness. (1) Larval distribution; (2) juvenile distribution; (3) prespawning aggregation; (4) spawning group (starting at age three or four); (5) overwintering; (6) aggregating to prespawning and (7) spawning again. And the thing repeats itself. A more complicated situation is common, in which a population has discrete spawning areas within it, but the larvae (the products of those spawning areas) are together in larval areas, they mix with others in nursery areas as juveniles, then mix in prespawning aggregations, separate out again to spawn, and so on. The only place, then, that there could be separation—imprinting or whatever—is at the larval stage, and that's where we have to look. If these things are discrete stocks, we should be able to show fidelity to natal spawning grounds. Also, we must find the mechanism for separation between units, and some way of rationalizing new populations evolving. And that brings me to my quote from a famous herring biologist, Doug Hay, "At this meeting obviously none of us know what we're talking about."

FOGARTY: Rob, could I ask for a couple of clarifications? Among items for discrete populations, you listed discrete population dynamics. Environmental influences could control growth, maturation rates, age compositions, even dominant year-classes over broad geographic ranges. So which elements of population dynamics do you feel argue for discrete populations and why can't they be explained by environmental factors?

STEPHENSON: First, spawning. Timing and precise location are regular within stocks, or populations as I like to call them, but are extremely varied between. Second are the population parameters themselves: consistency in age structure and growth parameters within populations, with differences between. Third is the predictable behavior and so on of stock units. I'm thinking here of Georges Bank versus southwest Nova Scotia, two groups in close proximity. One of them disappeared completely, and the other is very large.

Under mixing conditions one would not have expected that to occur. I agree that the evidence is confounded by parallelism in year-class strength. You see it not just in the western Atlantic but also in the eastern Atlantic and elsewhere.

MOSER: My question is to Doug Hay. You and others have brought herring into cages and let them spawn. If these cages or enclosures are put in nontraditional spawning areas, and if herring began to home back to those areas, wouldn't that be evidence of imprinting?

HAY: We tried to inoculate an area, like you would a salmon hatchery, and have a return. We moved a couple billion live eggs—which isn't that much, the equivalent of a couple of tons of herring—from one area to another. We did it for two years in a row. The eggs hatched into larvae, which moved out. After two years, there was no evidence that any juveniles came to be, and there was no spawning in that area (Blind Bay on Nelson Island). They were about 20 or 30 kilometers removed.

Most of what Rob [Stephenson] said could have been explained without genetics. One wonders why after 10,000 years there is no clearly established genetic difference between stocks. Why do we have only one clear morphological type of herring? Pacific salmon in some areas display genetic differences within a few generations. So I think everything you said could have been explained without genetics, and I also think that if you had used a fresh water example of salmon there, you could have been correct in your larval retention areas, your juvenile areas, winter areas, summer areas, and clearly you would have had stocks, but not a genetic basis to them.

STEPHENSON: I'm not a geneticist, but my feeling is that a small part of the genome is responsible for the separation of these things into units. Most of the genome, I gather, is to keep them going as fish. We simply haven't hit on the piece that explains differentiation. Also, I gather that these herring populations are large (relative to salmon populations). For small populations under odd conditions, such as those associated with anadromy, the pressure for change is greater than for herring. That would be my feeble way out of that one.

HALDORSON: I would be very surprised if there were genetic variation among these stocks, but I still think they're isolated, perhaps, to a large degree. The amount of leakage you need between groups of reproductively isolated fishes, per generation, is relatively low to maintain fairly uniform genetic composition over fairly long geographic distances. So virtually all of the studies I've seen or tried to do find geographic uniformity over quite long ranges. There may be modest barriers to gene flow, but it doesn't take much gene flow to swamp out isolating factors.

STEPHENSON: The east and west Atlantic don't look different in the tests we've used so far, and we know they can't be mixing.

HAY: Grant found clear cut electrophoretic differences between Bering Sea and more southern Pacific stocks. So differences do exist over broad ranges.

FOGARTY: I would like to take a different tack by showing a case study of a system that might be useful for testing some of these ideas. It has to do with the collapse and subsequent recovery of the Georges Bank herring population. In the early 1960s a very large multi-national fishery developed for herring on Georges Bank. At its heyday nearly 400,000 metric tons a year were removed from the population. Virtual population analyses show that the stock collapsed by the mid- to late 1970s. (Beyond 1977 we weren't able to do further virtual population analyses because the fishery had collapsed.) We have had continuous research vessel surveys. The data show a precipitous decline to very low levels through the mid-1970s and early 1980s, and now what appears to be a recovery in the population.

What is the system like on Georges Bank? Basically, it's a "leaky" clockwise gyre. The mean retention time for a particle of water during the period of stratification is about two months. It is an extremely productive area with primary productivity of almost 400 kcal per square meter per year. It's shallow and there's constant mixing on the central part of the bank with regeneration of nutrients and so on. Stratification is very well defined during the warm months of the year. Iles and Sinclair identified the Georges Bank region as demarcated by a stratification zone, clearly an important retention area. Another important retention area they identified is Nantucket Shoals. Larval sampling programs have been undertaken at various times on Georges Bank. A systematic sampling pattern under the ICNAF larval herring program was in place from 1971 to 1977. MARMAP surveys, instituted in 1977, ran through the last couple of years. More recently, the recovery of the local herring population has been examined. The distributions of larvae of different size classes from the ICNAF larval herring surveys show little dispersal or drift. Two foci of abundance are apparent, one on the northeast peak of Georges Bank, the other in the Nantucket Shoals. As the larvae age the centers are maintained but spread out. From 1977 to 1982, when the population had collapsed, some residual spawning was evident along the northern edge of Georges Bank and in Nantucket Shoals, but levels of larval production were much lower. From 1983 through 1987 there was renewed intense spawning, mostly in the Nantucket Shoals region and into the Gulf of Maine. The densest areas remained centered in the Nantucket Shoals region, but with more dispersion of some part of the larval population. So they have been dispersing to some degree. We found no clear evidence of spawning on Georges Bank proper (although some may have taken place that we missed).

In 1988 we saw some evidence of early stage larvae on Georges Bank, but the most intense spawning activity remained in the Nantucket Shoals region. This suggests that the recovery on Georges Bank has been fueled by a contribution from the Nantucket Shoals region, which had been identified as a separate retention area. I think it is a separate retention area, because an important concentration of larvae remain there. Nonetheless there is dispersal, sufficient to start or at least supplement the recovery on Georges. But according to the Iles and Sinclair hypothesis, these two areas should have been completely distinct. The pattern of recovery of this population might help us understand something about the role of the putative retention areas. Retention is important, but spillage may have helped refuel the recovery of the decimated population on Georges.

COLLIE: Re Doug's question of why don't we see the same patterns in other species: on Georges Bank we do, in other groundfish such as yellowtail flounder. Their spawning areas are slightly different, but there is evidence of discrete spawning areas on Georges Bank and Nantucket Shoals, and there must be some degree of retention. The fate of a vagrant from Georges Bank is basically to be transported downstream (that is, down the coast). To maintain populations on Georges Bank there has to be some return. Without retention, there would have to be an against-the-current return (homing), otherwise vagrants would be lost from the population. I'm saying there are common patterns on Georges Bank.

FOGARTY: Well, many of the populations on Georges Bank do appear to be separate or distinct. Some Georges Bank groundfish are distinct from those of Browns Bank or the Scotian shelf. But a fairer test of the retention hypothesis would be like this: that separate populations exist not only on Georges Bank but within the Gulf of Maine. For example, there's a stratification area around Grand Manan Island, yet we've not identified stocks of groundfish unique to Grand Manan, though we have for herring, and so on.

I think you're right, Jeremy. Georges Bank seems like a retentive system with an important role in stock discreteness of many species. On closer examination—in finer spatial resolution in other areas—it tends to break down a bit. Maybe we haven't looked in the right places for groundfish. In the book there's a bit of a backing away from retention as a specific mechanism, as proposed in the *Science* paper.

STEPHENSON: The book is more general, and there was the thought that retention is the operative thing in Atlantic herring on our side of the Atlantic, but there might be other mechanisms in other beasts. We've returned a couple of times to the observation that Pacific and Atlantic herring differ in their strategies and that Atlantic herring may be different west and east.

MUNK: The recovery of the North Sea herring stock has some resemblance to what you've showed us for Georges Bank. The northern parts remained during the very low levels of the herring stock during the same period, in the late 1970s. Recovery was seen as an outbreak of spawning in the more southern areas of the former spawning grounds. There could be something occurring similar to what has been described as a leaking from spawning grounds. The early life of one of the stocks occurs in a separate ecological unit from the other stock. How much do physical parameters mix these two, at what stage, and to what extent? Part of one group may then go to another group.

HAY: Based on the work you and your colleagues have done in the North Sea, how do you feel about the potential for herring larvae to home?

MUNK: I think there must be homing as there must be imprinting of the larvae. That could be smell. It could incorporate all the senses or it could be something else. It could be physical environment such as prey types, temperature, or it could be a combination.

HAY: Dr. Dragesund mentioned that larvae in Norway are transported 800 nautical miles from one place to the next. Given they are moved that far, do they have the potential to home back to where they started?

MOKSNESS: We have concluded that there is some kind of homing in cod. We have reared cod in the western part of Norway to a size of 15 to 20 cm. These were taken to the southern part of Norway and released. If you have imprinting during the larval or juvenile stage, these cod should have gone back to western Norway for spawning. Around 95% of the cod stayed in the area of release, and dispersed in equal directions from the center of release for about 50 km. This is a very good example that imprinting may not occur during early life stages.

STEPHENSON: Then how do you have herring returning to an area to spawn? How do you have spawning areas persisting in time when those fish are not around the rest of the year? In fact once the larvae leave an area they're not back there for three years. How do those stocks persist unless you have some form of homing?

MOKSNESS: In Norwegian spring-spawning herring, there have been great shifts in spawning over time. In recent years spawning has ranged from Bergen, at about 60°N, to Karmoy, at about 58°N.

FOGARTY: In the early 1960s, a paper by Saul Saila and one of his colleagues showed mathematically that salmon homing could be explained by random search patterns with guiding reflecting barriers. For example, temperature barriers that a returning animal wouldn't cross, or perhaps a topographic feature—something of that nature. It is possible the mechanisms of homing could be fairly coarse, and the key is to get back to an area with the appropriate substrate.

STEPHENSON: Georges Bank shouldn't have taken eight years, then, should it? There were plenty of fish around under that scenario.

FOGARTY: We don't know what fraction of a population gets back to spawn or what fraction is needed to maintain the population. If it gets below a critical level maybe the numbers that do find their way back can't replenish the population. Or maybe they're swamped by predators when they get down to such a threshold.

PEARSON: About the behavioral mechanisms behind homing: Somewhat contrary to what you said, I doubt the behavioral mechanisms behind homing are elaborate. In work with salmon, Hassler and Johnson have shown a simple reotactic response (orient to current) in the release of the stimulus. If swimming upstream I smell the home stream water, I swim against the current; if I don't smell it, I turn around and go downstream. Modeling based on those two simple rules, and behavioral studies using experimental interventions, give a good deal of evidence for that. Taking that analogy into the ocean, Johnson and Deving found that salmon migrating into Norwegian fjords zigzagged along discrete structures in the hydrographic regime and that you could find single neurons with which they could distinguish different water masses. I see no reason why, once imprinted, a herring couldn't show a similar sort of capability with very simple rules.

FOGARTY: I thought the neurological evidence suggested that early stage larvae weren't capable of that sort of imprinting.

PEARSON: Well, all right, I'm talking about the adult returning. At what point do salmon imprint? During smoltification (the process of metamorphosis). I submit to Dr. Hay this question: If herring imprinted at metamorphosis rather than at hatching or the first days of larval development, would they be able to home to their spawning ground?

HAY: Metamorphosis in Pacific herring may be different from Atlantic herring. We are uncertain about where Pacific herring are when they metamorphose. I think if they are attaining some kind of benthic or semi-benthic existence, it's a good time to imprint, if they are in one area long enough. If they're pelagic, they could be moving a number of nautical miles per day. Tidal fluctuations could move them over a 10-mile range back and forth each day. If they are pelagic, what would they imprint on? Blaxter said, a number of years ago, that young larvae don't have the ability to home. They're pretty small to imprint at that point. But, I expect I would be surprised by the truth if we knew it.

SUMMARY

CORTON: It's difficult to summarize the whole discussion of this afternoon. I'll pick out a few items that I have understood. I'm not an expert on stock discreteness, I'm more interested in management, and I tend to lump stocks together as much as possible. The first thing I learned this afternoon was that we shouldn't talk about stock discreteness because stock is not a very well-defined concept. We should talk about population discreteness. There are three questions: Are there differences between populations? How do they arise? How do we deal with them?

The question of whether discreteness exists among populations is a simple one. We know from experience that we have discrete populations of herring. We see that from the spawning grounds, and we see that from age compositions. I think that is something we can take for granted. The next question is, how do these differences arise? And there we come up with this member/vagrant hypothesis, which tries to find the basis of different populations in physical processes of the sea.

The hypothesis is that what determines the number of populations is the number of retention areas. The number of retention areas and their sizes determines both the number of populations (richness) and their sizes. This heuristic hypothesis has evoked quite a lot of thought and discussion, and a lot of questions. One of the questions is how to define retention areas. Sometimes larvae stray outside particular gyres. Should we consider the retention area as a rather small unit or should we extend it over a rather wide unit?

The concept of a retention area needs refinement. One essential element of the member/vagrant hypothesis is that the larvae contained in a certain retention area are going to come back to spawn. Homing is necessary to support the hypothesis. Much of this afternoon's discussion has concerned evidence for homing. I think it's nearly impossible to prove whether there is homing or not. Some participants feel that early larvae are too small to become imprinted. Doug Hay has said you cannot expect a larva of a few millimeters to learn where it is well enough to remember three years later when it comes back to spawn. He suggests imprinting might occur at a later stage, at metamorphosis or in the juvenile stage. The problem then arises that quite often the herring, when they are metamorphosing or when they become juveniles, are no longer in the immediate vicinity of the spawning ground. I wouldn't like to see herring in the North Sea become imprinted as juveniles because then they are along the Danish coast and they would go back there to spawn, and that would be a disaster.

There was a suggestion I liked very much, that imprinting may occur even later, when the herring are adults and spawning for the first time. To me, that seems the most plausible idea. Homing is critical to the member/vagrant hypothesis. We have talked about testing the hypothesis, which would be difficult because we cannot do laboratory experiments or find nice places of coastline where we could do such experiments. Apparently the best approach is to look at similar stocks that spawn in the same area and are subject to the same environmental and hydrographic conditions, and see whether they produce the same number and diversity of populations. This would require comparative analysis of similar stocks.

We had quite a bit of discussion on genetic differences among populations. The member/vagrant hypothesis requires populations to be genetically distinct. Thus far, however, laboratory experiments—work on DNA, etc.—have not been able to demonstrate genetic differences between populations. So that fact doesn't support the member/vagrant hypothesis. There have been other experiments in transplanting eggs from one area to another by Doug Hay in British Columbia. These showed that if you transplant eggs to another area, the larvae do not show up later as spawning fish, which also is contrary to the theory of homing.

The results of larval surveys in the Georges Bank vicinity show that the recovery of the Georges Bank population may be due to relocation by larvae from the Nantucket Shoals. So it seems that larvae from other areas can recolonize new areas, and in that case there is no homing.

We must draw the same conclusion from the experience with releases of cod in Norway where the juvenile cod were released far away from the place where they were born, and again they didn't show any intention of going back to their place of birth. So I think most of the evidence that we have does not support the theory that fish are homing toward the place where they were born. In conclusion we must say there is no strong evidence for homing. There are no strong indications for genetic differences among populations, yet we do have these populations. As managers, we have to treat populations separately as far as possible, even if they are not known to be genetically distinct.

I want to conclude with my personal opinion. I always compare herring with people. That's something you get from working with herring for 20 years. I think of a herring population as the people living in my village, which could be considered as a sort of self-contained spawning stock. There is another village 10 miles down the road, and that is also a self-contained spawning stock. I think the inhabitants of the two villages are genetically almost equal, that there are no great differences. Still, the two populations are separate spawning stocks, there may be some vagrants, I don't know, but I think from a management point of view it would be wise to treat them as separate units. This, then, is the conclusion I would like to draw for herring stocks: Although there may not be genetic differences, and although there may be some vagrancy between stocks, it would be wise to regard them as separate. Thank you.

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Proc. Int. Herring Symposium
Oct. 1990, Anchorage, Alaska

Stock Discreteness in Atlantic Herring: A Review of Arguments For and Against

R.L. Stephenson
Department of Fisheries and Oceans
St. Andrews, New Brunswick, Canada

ABSTRACT

Although the issue of population structure in Atlantic herring has been studied for over a century, there remains a debate concerning the integrity, fidelity and discrete nature of herring spawning units. Regularity of spawning (both geographic and temporal), tag evidence for homing, differential population dynamics of neighbouring groups and larval retention all indicate that herring spawning units are distinct populations. On the other hand, the lack of demonstrable differences in genetic (particularly isozyme) characteristics and weak results from traditional stock identification methods have been interpreted as indicating significant gene flow among neighbouring spawning aggregations of a larger population.

This paper addresses the issue of stock discreteness in order to define critical questions in this debate. A summary of arguments for and against discrete populations reaffirms that, while much of the evidence is inferential, it favours the discrete population concept. Demonstration of fidelity to natal spawning grounds and of mechanisms which may allow stock separation are critical to resolution of the discrete population debate.

INTRODUCTION

> "A Lochfyne fish differs in appearance from a herring taken off the coast of Caithness while the latter again differs from those taken by the Dundee boats of the Isle of May. Experienced fishmongers know the different localities of the same kinds of fish...they can tell at a glance a Lochfyne matie [herring] from a Firth of Forth one."
>
> J. G. Bertram 1865; p. 234.

The issue of stock or population structure in fish has been debated for over a century, and throughout this debate, attention has focussed on Atlantic herring. Sinclair and Solemdal (1987), in their review of the development of "Population Thinking" in Fisheries Biology, point to the pivotal role of Atlantic herring of the northeastern Atlantic in the early debate concerning the existence of self-sustaining populations within species.

Swedish research into reasons for the collapse of the Bohuslan herring fishery in the early 1800's concluded that the species *Clupea harengus* L. was comprised of a large number of geographically restricted, self-sustaining populations (Nilsson, 1832, cited by Sinclair and Solemdal, 1987). But this thinking contradicted the prevailing typological view developed during the 18th century that assumed a single, highly migratory population eminating from Arctic waters and migrating annually to northeastern (and even northwestern) Atlantic coastal waters.

It was not until after Darwin's theory of evolution (1859) undermined the typological species concept and focussed attention on patterns of intraspecific variability that the groundwork was set for the studies of Heincke, Schmidt and Hjort which have shaped present concepts of fish populations. Sinclair and Solemdal have concluded that these early studies (by Heincke specifically) on herring populations, "as well as having a major impact on subsequent development in fisheries biology and management (in essence the definition of management units based on geographic populations or population complexes), also had an important impact on the biometritions... and the development of the evolutionary synthesis" (Sinclair and Solemdal, 1987, p. 1).

In spite of the early attention to herring, its economic importance and relative wealth of scientific study, major questions of stock structure have not been resolved. Today, while no one would dispute the existence of subspecific structure in herring, there is debate as to the discreteness of herring stocks or populations. Recent papers point to a dilema. Regularity of spawning (both geographic and temporal) (Sinclair and Tremblay, 1984), tag evidence for homing (Harden-Jones, 1968; Wheeler and Winters, 1984), persistent site-specific population characters but differential population dynamics of neighbouring groups (Sinclair and Iles, 1985; Stephenson and Kornfield, 1990), and distinct predictable areas of spawning and larval retention (Iles and Sinclair, 1982) have all been interpreted as suggesting that herring spawning units are distinct populations. On the other hand, the lack of demonstrable differences in genetic (particularly isozyme) characteristics (Kornfield et al., 1982; Grant, 1984) and weak results from traditional stock identification methods have been interpreted as indicating significant gene flow among neighbouring spawning aggregations, and it has been suggested that herring populations are artificial subdivisions of a larger gene pool and are of no evolutionary or taxonomic significance (Smith and Jamieson, 1986).

In this paper, I have attempted to define critical unresolved issues of herring stock structure. By way of example, I present overviews of two studies aimed at testing aspects of stock definition in Gulf of Maine herring. And finally, through a review of evidence in favor of and against discreteness, I have attempted to define essential questions or hypotheses and logical tests that may help resolve the issue.

TESTS OF STOCK DEFINITION IN GULF OF MAINE HERRING

Two current studies on herring of the Bay of Fundy and Gulf of Maine illustrate issues and the present state of knowledge with respect to stock definition.

The first, a stock identification study (Stephenson and Gordon, this volume), is a modification of the traditional approach of comparing phenotypic traits of hypothesized populations. Samples have been taken from 13 spawning areas, most within the Bay of Fundy and Gulf of Maine (of relevance to stock assessment) but some from as far away as Newfoundland (for comparison) of both males and females and, in most cases, covering two successive years. Approximately 2900 individual fish have been analyzed for an extensive list of attributes, including morphometric and meristic characters and parasite loads, and a limited number as well for some biochemical traits.

The study differs from most previous studies of this type in that it contains only documented spawners ("ripe and running" fish) collected from spawning grounds. The rationale has been that discrete spawning samples would overcome the potential problem caused by stock mixing in many previous studies (where samples were taken from commercial fisheries on fish other than at spawning time). Further, the study involves a multivariate approach (including some new or modified variables) in a field which has traditionally considered single or groups of related attributes.

This stock identification project grew out of a need to partition juvenile herring from mixed aggregations to stock units for assessment. First, however, it was necessary to test for the ability to discriminate the stocks of origin. It hypothesizes phenotypic differences among neighbouring spawning groups, and implicitly assumes discrete population status of each spawning group.

Predictably, preliminary results confirm the limited usefulness of several traditional identification techniques (including several meristic characters), but show that some differentiation is possible based upon parasites, occasional meristic characters and particularly combinations of characters.

A second study (Stephenson and Kornfield, 1990) considered the recent reappearance of a Georges Bank herring stock. This stock, which had been the largest in the northwest Atlantic (once estimated at 1.14 million t), collapsed in 1977 after a classic "boom and bust" fishery of approximately 2.7 million t over 15 years. For several years, there was virtually no sign of either adults or larvae but, since 1986, there has been evidence of successful spawning.

The reappearance of spawning herring on Georges Bank is of considerable interest in that it represents a critical test of hypotheses concerning stock structure. Was reappearance the result of resurgence of a remnant of a discrete Georges Bank population, or recolonization by members of a neighbouring spawning group? Stephenson and Kornfield (1990) argue on the basis of biochemical characteristics (differences in electromorph frequencies of phosphoglucose-isomerase-2 (PGI-2)), age composition (reappearance by a single year-class rather than an age distribution representative of a neighbouring group) and timing of the reappearance (later than might have been expected of replacement by a related neighbouring unit) that it has been resurgence rather than recolonization or replacement, and that this supports the discrete population concept.

HOW DISCRETE ARE STOCKS?

The modern stock structure debate reduces to the question of whether herring stocks are in fact populations in the self-sustaining, geographically and genetically discrete sense. If defined in this way, the assumptions are: 1) of fidelity with respect to population of origin (i.e. complete homing); and 2) isolation from neighbouring populations. I have attempted to compile a list of arguments of relevance to this debate.

Arguments for discrete populations

1. Herring tag evidence for homing (Harden-Jones, 1968; Wheeler and Winters, 1984) offers direct evidence that fish return to areas in which they have spawned previously. Due to the inability to tag young fish, however, there is a lack of information on the question of fidelity to natal spawning location.

2. Stock-specific population dynamics - Herring show considerable within-stock consistency but between-stock difference in many aspects, including:

    i) spawning - regularity of timing and precise location within stocks but extreme variation in timing, substrate, depth, etc. between stocks (e.g. Sinclair and Tremblay, 1984).

    ii) population parameters - consistency of age structure, growth parameters within, but differences between stocks (e.g. assessment reports such as Anon., 1988; Stephenson and Power, 1988).

    iii) population dynamics - predictable behavior of stock size within stock units, compared to the differences between neighbouring groups (e.g. the differences in patterns between neighbouring southwest Nova Scotia and Georges Bank herring stocks; Stephenson and Kornfield, 1990).

3. Discrete larval distributions - Persistence or retention of larvae which is linked to particular geographical or hydrographic areas and separate from neighbouring groups (Iles and Sinclair, 1982; Sinclair, 1988; Chenoweth et al., 1989) provides a mechanism for separation of stocks and imprinting.

Arguments against discrete populations

1. Evidence for changed spawning time - Some have inferred switching of spawning groups on the basis of inappropriate otolith type; for example, a "spring" otolith in an autumn spawning adult (e.g. Otterlind, 1987). Winters et al. (1986) claim changes in growth rate of juveniles of large enough magnitude to facilitate switching.

2. New populations - Several present spawning areas (for example, Georges Bank) were only recently (on a geological time scale) submerged. There must be a mechanism for establishment of new populations.

Moot points

Several points can be argued for or against discrete populations:

1. Spawning continua - Several areas of coastline support a series of spawning locations. These are considered in some cases localized small populations - but arguably may form a continuum of spawning locations and times.

2. Clines in spawning time - While peak spawning in a particular area is typically predictable and of short duration, there are also cases of protracted spawning (e.g. Chenoweth et al., 1989) and there is evidence of waves or pulses of spawning. Such clines in spawning could be argued to be potential mechanisms for temporal separation of populations or, alternatively, for reducing separation.

3. Changes in behavior - While there are general patterns of movements of juvenile and adult herring which are characteristic of a particular stock (e.g. present Chedabucto Bay overwintering of 4WX herring), there are occasional dramatic changes to these general patterns (e.g. changes in proportion of juvenile North Sea herring in the Skagerrak/Kattegat (Anon., 1988), change in overwintering location in Chedabucto Bay about a decade ago). These may be argued to be unimportant to stock structure or a potential for mixing.

4. Lack of distinguishing physical and biochemical features - Inability of traditional stock identification studies to differentiate herring from different spawning groups has been taken as evidence for mixing (Smith and Jamieson, 1986). However, lack of demonstrable difference is not proof of affinity.

DISCUSSION

Much of the evidence is inferential, but there is a considerable amount consistent with, and little sound evidence against, the discrete population concept of herring.

While there must be potential for departure from a discrete population model in order to be able to explain colonization, it is important to separate ecological and evolutionary time scales. On an ecological time scale, populations must be discrete or there would not be such common differences in population dynamics and other traits among neighbouring groups.

Similarly, on an ecological time scale, genetic mixing among populations must be small in order to account for the observed stock differences. On the other hand, it would take only a small amount of genetic mixing to account for a lack of difference between populations in genetic studies.

An essential consideration in the discussion of stock structure is of the size of populations and scale of separation. There appear to be both populations with single, discrete spawning areas (local spring spawning populations such as Bras d'Or Lakes) and those with a complex of spawning units (for example, the southwest Nova Scotia) (Stephenson and Power, 1988). I have attempted to summarize this schematically in Fig. 1. In this example, three groups are separate at spawning (this could be spatial and/or temporal separation) but overlap to different degrees at other life-history stages. Mixing between A and B occurs only at the juvenile and adult stages, whereas the two B groups overlap also at the larval stage. It is suggested that the two spawning groups marked B would comprise a single population, separate from A. Separation at the larval stage seems to be a critical factor in maintaining population discreteness (Iles and Sinclair, 1982; Sinclair 1988). This conclusion is important in stock assessment and management for it is on the basis of a B-type model that spawning groups have been aggregated into single assessment

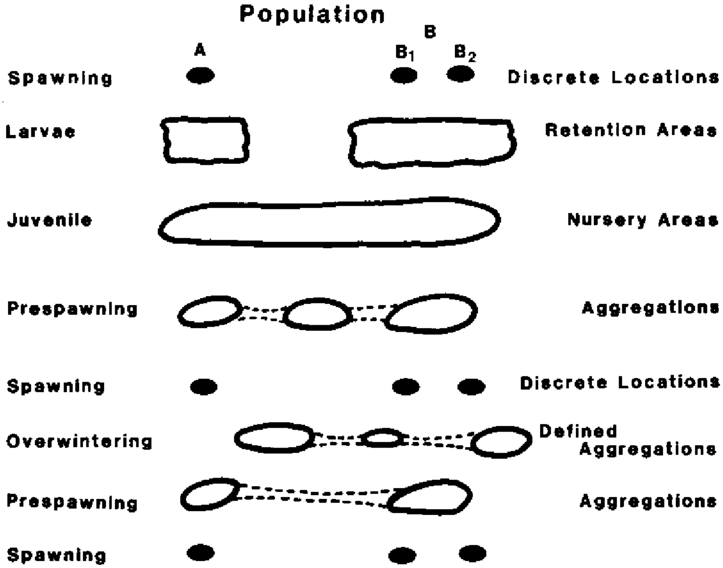

Fig. 1. Conceptual model of the potential for mixing at life-history stages of Atlantic herring populations.

units (e.g. 4WX herring - Stephenson and Power, 1988, North Sea - Anon, 1988). But individual spawning units within such complexes have suffered disproportional effort and in some cases collapsed, indicating that an A-type model may be more appropriate, and further supporting the discrete population concept.

The question of population discreteness in herring will continue to be debated. Critical tests of:

1) fidelity to natal spawning grounds and definition of mechanisms involved, and
2) the degree of, and mechanisms for, separation between neighbouring groups

are essential to resolution of this debate.

ACKNOWLEDGMENTS

This topic is a favourite with most of the herring fraternity and I am grateful to discussions and debates with many colleagues including T. D. Iles, M. Sinclair, I. Kornfield, members of the ICES herring assessment working groups, the CAFSAC pelagic subcommittee, US National Marine Fisheries Service, Maine Department of Marine Resources (Boothbay Harbor, Maine) and Biological Station, St. Andrews. I acknowledge too the input of members of the Canadian and US herring fisheries of the Bay of Fundy and Gulf of Maine who continue to emphasize the importance of this topic.

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This paper is based on one presented at the FSBI Symposium on Fish Population Biology, University of Aberdeen, 12–21 July 1989. This paper was not presented at the International Herring Symposium.

Participants

Cindy Anderson
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518-1599

Robert Armstrong
Department of Fisheries & Oceans
3225 Stephenson Pt. Rd.
Nanaimo BC V9T 1K3
CANADA

Timothy Baker
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518-1599

Don Beeson
Icicle Seafoods, Inc.
3838 W. 50th Avenue
Anchorage AK 99502

Arvid Beltestad
Institute of Fisheries
Technology Research
P.O. Box 1964, Nordnes
N-5024 Bergen
NORWAY

Evelyn Biggs
Alaska Dept. of Fish and Game
P.O. Box 669
Cordova AK 99574

Chuck Blaney
Alaska Dept. of Fish and Game
Box 689
Kotzebue AK 99752

Linda Brannian
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518-1599

Kevin Brennan
Alaska Dept. of Fish and Game
211 Mission Road
Kodiak AK 99615

Jeff Bromaghin
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518

Tom Brookover
Alaska Dept. of Fish and Game
P.O. Box 230
Dillingham AK 99576

Fred Bue
Alaska Dept. of Fish and Game
Box 1148
Nome AK 99762

Lawrence Buklis
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518

Charles Burkey, Jr.
Alaska Dept. of Fish and Game
P.O. Box 90
Bethel AK 99559

Steven Burton
Washington Dept. of Fisheries
Building 4, Room 2129
7600 Sand Point Way, NE
Seattle WA 98115

Mark Carls
NMFS Auke Bay Laboratory
P.O. Box 210155
Auke Bay AK 99821

Dennis Chalmers
Department of Fisheries & Oceans
3225 Stephenson Pt. Rd.
Nanaimo BC V9T 1K3
CANADA

Jeremy Collie
UAF JCFOS
11120 Glacier Highway
Juneau AK 99801

A. Corten
Netherlands Institute for
Fishery Investigations
Postbus 68
Ymuiden 1970 AB
THE NETHERLANDS

Doug Coughenower
University of Alaska
Marine Advisory Program
4014 Lake Street
Homer AK 99603

Didrik Danielssen
Flodevigen Biological Station
4817 His
NORWAY

Dwane Day
Washington Dept. of Fisheries
7600 Sand Point Way NE
BIN C15700 Bldg 4 Room 2129
Seattle WA 98115

Olav Dragesund
Department of Fisheries Biology
University of Bergen
Pb. 1839
5024 Bergen
NORWAY

Page Else
Univerity of Alaska
Marine Advisory Program
329 Harbor Drive, Room 213
Sitka AK 99835

Ellie Evans
University of Alaska
Marine Advisory Program
2221 Northern Lights Blvd., #110
Anchorage AK 99508

Michael Fogarty
National Marine Fisheries Serv.
Northeast Fisheries Center
Woods Hole MA 02543

Petter Fossum
Institute of Marine Research
P.O. Box 1892
N-5024 Bergen
NORWAY

R. Kim Francisco
Alaska Dept. of Fish and Game
P.O. Box 90
Bethel AK 99559

Fritz Funk
Alaska Dept. of Fish and Game
P.O. Box 3-2000
Juneau AK 99811-2000

J.A. Gagné
Min. des Pêches et des Oceans
Inst. Maurice-Lamontagne
Mont-Joli Québec G5H 3Z4
CANADA

Dolly Garza
College of Marine Studies
University of Delaware
Robinson Hall
Newark DE 19716

Hal Geiger
Alaska Dept. of Fish and Game
P.O. Box 3-2000
Juneau AK 99802

Larry Gilbertson
Genesis Technical Services
P.O. Box 221284
Anchorage AK 99522

Dennis Haanpaa
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518

Carl Haegele
Department of Fisheries & Oceans
Pacific Biological Station
Nanaimo BC V9R 5K6
CANADA

Olle Hagstrom
Havsfiskelaboratoriet
Box 4
Lysekil S-453 00
SWEDEN

Vivian Haist
Department of Fisheries & Oceans
Pacific Biological Station
Nanaimo BC V9R 5K6
CANADA

Lew Haldorson
UAF JCFOS
11120 Glacier Highway
Juneau AK 99801

Helen Hamner
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518

D.E. Hay
Department of Fisheries & Oceans
Pacific Biological Station
Nanaimo BC V9R 5K6
CANADA

Per Hognestad
Flodevigen Biological Station
N-4817 His
NORWAY

Gail Irvine
Minerals Management Service
949 E. 36th Ave, Room 110
Anchorage AK 99508-4302

Kurt Iverson
Commercial Fisheries Entry
Commission
8800-109 Glacier Highway
Juneau AK 99811

Laurie Jarvela
NOAA/OAD Alaska Office
Anchorage Fed. Bldg. #56
222 W. 7th St.
Anchorage AK 99513

Arne Johannessen
Inst. for Fiskeribiologi
University of Bergen
Pb. 1839
5024 Bergen
NORWAY

George Kautsky
Washington Dept. of Fisheries
Building 4, Room 2129
7600 Sand Point Way, NE
Seattle WA 98115

Wolfgang Konkel
Exxon Co. USA
7501 Middlewood
Houston TX 77063

E. Krixunov
Moscow State University
Department of Ichthyology
Moscow 119899
USSR

Gordon Kruse
Alaska Dept. of Fish and Game
P.O. Box 3-2000
Juneau AK 99802

Bob Larson
Alaska Dept. of Fish and Game
P.O. Box 667
Petersburg AK 99833

Charlie Lean
Alaska Dept. of Fish and Game
Box 1148
Nome AK 99762

Dennis Lodge
Alaska Voc/Tech Center
Box 889
Seward AK 99664

Deborah Lyons
State of Alaska
Board of Fisheries
Box 296
Petersburg AK 99833

Pat McAllister
Washington Dept. of Fisheries
7600 Sand Point Way NE
BIN C15700, Bldg. 4, Room 2129
Seattle WA 98115

Jim McCullough
Alaska Dept. of Fish and Game
211 Mission Road
Kodiak AK 99615

Michael McGurk
Triton Environmental Consulting
120-13511 Commerce Parkway
Richmond BC V6V 2L1
CANADA

Charles Meacham
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518

Brenda Melteff
University of Alaska
Sea Grant College Program
138 Irving II
Fairbanks AK 99775-5040

Robert Meyer
Minerals Management Service
949 E. 36th Avenue, Room 110
Anchorage AK 99508-4302

Erlend Moksness
Fldevigen Biological Station
Arendal N-4800
NORWAY

John Moores
Department of Fisheries & Oceans
P.O. Box 5667
St. John's NFLD A1C 5X1
CANADA

Mike Moser
UC Santa Cruz
Long Marine Lab
100 Shaffer Road
Santa Cruz CA 95060

Peter Munk
Danish Institute for Fisheries
and Marine Research
Charlottenlund Castle
Charlottenlund DK-2920
DENMARK

Ben Muse
Commercial Fisheries Entry
Commission
8800-109 Glacier Highway
Juneau AK 99801

Dave Musgrave
University of Alaska
Institute of Marine Science
114 O'Neill
Fairbanks AK 99775-1080

David Negus
UAF JCFOS
11120 Glacier Highway
Juneau AK 99801

Mark O'Toole
Washington Dept. of Fisheries
7600 Sand Point Way NE
BIN C15700, Bldg. 4, Room 2129
Seattle WA 98115

Raimo Parmanne
Finnish Game and Fisheries
Research Institute
P.O. Box 202
Helsinki SF-00151
FINLAND

A.J. Paul
University of Alaska
Seward Marine Center
P.O. Box 730
Seward AK 99664

Walter Pearson
Battelle Northwest
439 West Sequim Bay Road
Sequim WA 98382

Mary Pete
Alaska Dept. of Fish and Game
P.O. Box 1788
Bethel AK 99559-1788

Richard Radtke
Hawaii Institute of Geophysics
University of Hawaii
Honolulu HI 96822

Jeff Regnart
Alaska Dept. of Fish and Game
Box 37
King Salmon AK 99613-0037

Kathy Rowell
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518-1599

Kurt Schelle
Commercial Fisheries Entry
Commission
8800-109 Glacier Highway
Juneau AK 99801

J.F. Schweigert
Department of Fisheries & Oceans
Pacific Biological Station
Nanaimo BC V9R 5K6
CANADA

Jeff Skrade
Alaska Dept. of Fish and Game
P.O. Box 230
Dillingham AK 99576

Harold Sparck
Nunam Kitlutsisti
Box 267
Bethel AK 99559

Robert Stephenson
Department of Fisheries & Oceans
St. Andrews NB E0G 2X0
CANADA

David Stevenson
Maine Dept. of Marine Resources
W. Boothbay Harbor ME 04575

Kurt Stick
Washington Dept. of Fisheries
7600 Sand Piint Way NE
BIN C15700, Bldg. 4, Room 2129
Seattle WA 98115

Denis Tremblay
Department of Fisheries & Oceans
901 Cap Diamant
P.O. Box 15,500
Quebec Quebec G1K 7Y7
CANADA

Lauri Urho
Finnish Game and Fisheries
Research Institute
P.O. Box 202, SF-00151
Helsinki 15
FINLAND

Kenneth Vogt
University of Alaska Anchorage
Department of Biology
3211 Providence Drive
Anchorage AK 99508

Hal Weeks
North Pacific Fishery Management
Council
P.O. Box 103136
Anchorage AK 99510

Vidar Wespestad
NMFS Alaska Fisheries Center
7600 Sand Point Way, NE
Bin C-15700, Bldg 4
Seattle WA 98115

J.P. Wheeler
Department of Fisheries & Oceans
Science Branch
P.O. Box 5667
St. John's NF A1C 5X1
CANADA

John Wilcock
Alaska Dept. of Fish and Game
P.O. Box 669
Cordova AK 99574

Henry Yuen
Alaska Dept. of Fish and Game
333 Raspberry Road
Anchorage AK 99518-1599

Abdelkrim Zebdi
UAF JCFOS
11120 Glacier Highway
Juneau AK 99801