FISHERIES DYNAMICS

HARVEST MANAGEMENT & SAMPLING

Phillip R. Mundy · Terrance J. Quinn II · Richard B. Deriso

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Fisheries Dynamics

Harvest Management and Sampling

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Part I.

HARVEST CONTROL SYSTEMS FOR COMMERCIAL MARINE FISHERIES MANAGEMENT; THEORY AND PRACTICE

THEORY—A PROVISIONAL DEFINITION OF HARVEST CONTROL

Phillip R. Mundy

When discussing harvest control systems the first step is to define our terms. The first lecture, and perhaps some of the second, will be devoted to a provisional definition of "harvest control." The definition is designed for a general audience, since it has been developed through my interaction with administrators, attorneys, and harvest control biologists in state and federal agencies over the past seven years. The term *provisional* is an appropriate modifier because harvest control is an active area of research in which new concepts are continually being tested.

The second logical division of the lectures is a provisional definition of the system for harvest control. Perhaps there is a single conceptual framework within which we can understand fisheries as diverse as the adult salmon fisheries of Alaska and Puget Sound and the shrimp fisheries of North Carolina. Again the intention is to develop the provisional definition in language comprehensible to a general audience.

In the third lecture the application of the concepts of harvest control and a system to deliver the objectives of harvest control to a living resource will be illustrated by work from the Yukon River, Alaska. The gillnet fishery for chinook salmon in the waters of the river delta has been studied by my research group since 1980, and it will demonstrate the pitfalls involved in translating theory into practice.

Before entering the first lecture a word of caution is necessary. Students frequently find my concept of harvest control depressing on first hearing because it seems to deny the basic, literal interpretation of conservation of natural resources to which most biologically educated people subscribe. Of course I believe that conservation is the primary objective of a harvest control system. The misunderstanding occurs because I must emphasize, over and over again, that the political state, not the biologist, has the prerogative to determine the exact meaning of the term *conservation*.

Ultimately the message of these lectures is one of hope, not despair. For if the harvest control biologist is frequently frustrated by inability to achieve conservation of the resource, then the path around frustration lies in understanding how the system can be manipulated to a purpose. Such understanding may be found in the precise, yet readily generalizable, definition of harvest control and of the system which delivers the objectives of harvest control.

Preliminaries

Three references offer material supplementary to the definition of harvest control. Wright (1981), Neilsen (1976), and Royce (1983). Sam Wright is a former head of harvest management for the Washington Department of Game. His article is a serious effort to translate his experience into a coherent body of knowledge. I do not necessarily agree with the opinions of Wright, however he has certainly chosen the correct topics for discussion, and the value of his experience cannot be ignored.

The philosophical basis for harvest control spans many years of thought, and the quick, concise presentation of Nielsen (1976) provides a painless entry to the literature. The motivation for the development of harvest control within the fisheries profession and its academic environs is discussed by Royce (1983).

Harvest Control

In April 1976 I took my first job in commercial marine fisheries management of Puget Sound. In the seven years since then I have observed and participated in harvest control operations for salmon in many parts of Alaska, in both marine and freshwater areas. During the past three years I have directed research on harvest control methods for brown shrimp (***Penaeus aztecus***) in North Carolina, and for the past year harvest control methods for the blue crab (***Callinectes sapidus***) have consumed part of my research time. With the ample opportunity for observation during the past seven years, I have come to understand that the term ***fisheries management*** does not have a specific meaning but is all things to all biologists. Indeed it is not clear whether anyone can offer a definition of fisheries management which could be relevant for the majority of commercial marine fisheries, or even for the majority of fisheries on adult Pacific salmon. Fisheries management is a general term akin to the terms medicine and law, within which can be defined a myriad of specialties. Unfortunately there is a pronounced tendency among fisheries scientists to use this term as if it had a specific meaning.

In Alaskan salmon fisheries, the specialty of harvest control is most often referred to as fisheries management, and in commercial marine fisheries it is my experience that harvest control is usually referred to as fisheries management. The term, "Real-Time Salmon Management," is synonymous with "harvest control of salmon." My current research is directed toward the definition of harvest control as a fisheries management specialty.

The search for a fisheries management specialty which is essential to most commercial marine fisheries has led me back time and again to the need to direct the operation of fishing gear to achieve some specified harvest objective: harvest control. Harvest control is a fundamental requirement for any fishery which is said to be managed. If there is a single concept which can unite the fisheries management of Pacific salmon, brown shrimp, and blue crabs, I believe it would be the design of a rational system of harvest control. Indeed the need to establish overall principles of harvest control with respect to the numerous species exploited is very important to the development of fisheries as a profession. During my employment on the east coast of the United States, I have frequently been introduced as a "salmon biologist," or, worse yet, as a "salmon person," by well meaning colleagues. The same colleagues wonder why a salmon person would be interested, or even qualified, to study brown shrimp or blue crabs. It is obviously essential to demonstrate that sound principles of harvest control do not respect phylogenetic barriers.

Harvest control is a set of procedures, an algorithm, for the interpretation of information used in directing a commercial fishing operation toward some objective. The objective varies but the central challenge in the conduct of any commercial marine fishery is the proper division of the relevant biological population into two categories: dead and alive. The categories go by various names, catch and escapement, or yield and stock, but the partition is always into two sets. Within the course of a year or a season, harvest control consists of a series of decisions to harvest or not to harvest, and no decision can be recalled since fish do not rise from the dead (except in federal court). Harvest control is the rate-limiting step among all the activities called "fisheries management," and all the efforts focused to determine the proper level of harvest count for nothing if the fishing operation cannot be directed to achieve that specified level.

Thus two compelling reasons for the study of harvest control have been reached. Research on the design and implementation of methods capable of achieving any specified level of harvest is essential (1) to cut across the primarily artificial phylogenetic barriers which divide the conduct of commercial marine fisheries and (2) as the rate limiting step of fisheries management.

A third reason is touched by Royce (1983) in his inquiry into the status of fisheries science. The regulatory process is the interface between the fisheries profession and the general public. If the harvest control process is inept, then the profession appears to be inept. If the regulations have little or no rational basis, then the profession is perceived to be irrational. Obviously appearances are important, because fisheries science hardly exists outside of federal, tribal, and state agencies and the consulting firms which depend upon these governmental entities for sustenance. As most of us are now acutely aware, the funding to these agencies depends on how the public perceives the need for fisheries science, which in turn depends on how the public perceives fisheries scientists.

A Provisional Definition—The Objectives

Harvest control may be defined in terms of its objectives and the information necessary to achieve those objectives. One objective has been frequently mentioned already: the specified level of harvest. Such a level has been variously called the maximum sustainable yield (MSY), the optimum sustainable yield (OSY), the guideline harvest level, the total allowable catch (TAC) or as the complement of some catch level, an escapement goal. The general term for the primary objective of harvest control is *conservation*. However, be immediately warned that conservation should never be accorded its literal, or popular, meaning in the context of harvest control. Perhaps the most difficult lesson for a new harvest control biologist is the meaning of the conservation objective. The harvest level—the embodiment of conservation in a practical, tangible sense, is not necessarily set by fisheries biologists, but by the agent of the proprietor, or owner, of the resource, the political state. It comes as a great shock to some biologists to find that they do not own the resource.

That the proprietor's agent is often a biologist causes confusion, not satisfaction. Fisheries biologists may contribute information relevant to the appropriate harvest level, a fisheries professional may even write the regulations, but the harvest level is ultimately set by the political process. Certain enlightened political entities, such as the State of Alaska, permit fisheries biologists broad privileges in interpreting and implementing salmon harvest levels. However, a Fisheries Board of concerned citizens and the Commissioner of Fish and Game are ultimately responsible to the public for the actions of the biologists. Other political entities, such as the Commonwealth of Virginia, determine the harvest levels in the marine fisheries by default, allowing the traditions and inefficiencies of 350 years of history, and contemporary market conditions, to set the harvest level for blue crabs and most fin fishes.

Thus the primary objective of a harvest control operation is not set by biologic or economic factors as evaluated by fisheries biologists or economists; they are set by the owner of the resource, the political state. This is a bitter pill for many fisheries biologists to swallow, but it may cool the fever of their frustration in trying to carry out the objectives of conservation. These frustrations are nothing new. Among the most accurate forecasts of catch by species ever made for any commercial fishery were those given to the International Whaling Commission by its scientific committee for the Antarctic whale fishery (see McVay 1966). The names of the committee members are internationally known in fisheries circles: Douglas Chapman, Kay Allen, Sidney Holt, and, later, John Gulland. Even after the committee's understanding of the population dynamics of the fishery was confirmed by subsequent catches, the political process prohibited implementation of the harvest goals by species as recommended by the committee. The quotas by species were set higher than conservation demanded until the fishery collapsed. It is a classic pattern: conservation measures are implemented only after the demise of the fishery even in the face of compelling scientific evidence. The Antarctic whale fishery offers a chilling example of the inability of resource management professionals to influence the outcome of a harvest control operation even when armed with adequate information and astute analysis of both the dynamics of the populations and the behavior of the fleet. The history of the IWC is knowledge basic to anyone who would be a resource management professional.

Unfortunately, adequate data are rare in commercial marine fisheries, and astute analysis of the existing data is even less common. The lack of consensus among fisheries scientists which results from inaccurate and incomplete data is another circumstance which may preclude a harvest objective consistent with conservation of the resource and fishery. In the face of disagreement among the experts, the political system is ready and waiting to impose its own solution which will be consistent with legal and social concerns, if not with conservation requirements.

In any event it should not be the responsibility of the harvest control biologist to dispute any particular harvest objective at the level of professional responsibility. The professional requirement is to deliver the harvest objective as accurately as available data permit. Therefore in a professional harvest control sense, conservation is a number, total allowable catch (TAC), total allowable foreign fishing (TALFF), or even maximum or optimum sustainable yield (MSY or OSY). On occasion a harvest rate may be specified as a percentage of the individuals available for harvest. If the harvest level is repugnant, the biologist can work through the political system as an informed citizen to effect change.

The concept of conservation in harvest control must also be understood to contain a responsibility to the harvester. In some heavily politicized fisheries, harvest control biologists may tend to favor harvesters over fish (see Wright 1981). The opposite favoritism has occurred in Alaska, where conservative harvest control procedures have at times generated smaller salmon catches than dictated by the escapement objectives in order to be absolutely sure that adequate escapement was obtained. Relying on counting towers located well up the rivers from the harvest areas to ascertain the escapement, the control agents often found a surplus escapement between fishing districts and the counting towers by the time the fisheries were opened.

For the harvest control specialist the responsibility to both resource and harvester precludes having either as a "client." The resource is not the client and neither is the harvester; the reponsibility is to obtain the specified harvest level and thereby to serve both resource and harvester. If either is abused by the harvest objective, then let the agents of resource or harvester take what remedy is available from the political system.

The term "conservation" is still appropriate to the primary objective of harvest control, since federal, tribal, and state laws in most cases require that conservation be served before harvest can occur. Fisheries professionals in all specialties must necessarily defend literal conservation and the laws which to some extent protect the right of a species to exist. The only U.S. law which specified the right of a species (other than human) to exist, the Rare and Endangered Species Act (federal), has been neutralized through the efforts of Tennessee Senator Howard Baker and the Tennessee Congressional delegation. The law once read approximately, "Thou shalt not destroy a species," but it now reads approximately, "Thou shalt not destroy a species unless thou hast a good reason." The persistence of the law in its original form could have made life much easier for harvest control biologists caught in a conflict between harvest objectives and conscience.

The two remaining objectives of harvest control are relatively obscure in fisheries education, but they are important nonetheless. ***Public safety*** is the second objective of harvest control, in order of priority. Public safety requires that fishing regulations are written with concern for the physical well being of the harvesters. Fishing areas should not contain militarily restricted areas, such as naval torpedo ranges, or other avoidable hazards. Even if such restricted areas and hazards are clearly indicated on charts, the public may interpret the fishing regulation to mean that permission is granted to transit the restricted area for the purpose of fishing. Scheduling openings during severe weather conditions should be avoided if possible. Such a precaution is particularly applicable in short-term intensive operations such as adult salmon fisheries. A harvester may have only a half dozen, or fewer, opportunities to make a year's income, so to open the fishery during hazardous weather conditions is to tempt him to risk his life.

The final objective is also of primary concern in short-term intensive fisheries: ***product quality***. In herring roe and salmon fisheries, for example, the unit price of the product is a function of time. Inappropriate scheduling of fishing periods can lead to the loss of millions of dollars of product, or to the delivery to the consumer of less than a premium quality product. In adult salmon fisheries an optimistic sign for product quality considerations is the provision of escapement goals as a function of time, not just as a single numerical value for the year. The sockeye salmon fishery of the Copper River delta, Alaska, is regulated to meet an escapement goal by time interval, and excesses, or deficits, of escapement in one time interval are not credited to, or subtracted from, escapements in any other time interval. Such a premeditated system of achieving a more equitable distribution of catch (and escapement) through time is highly desirable (see Mundy 1982b).

In summary, harvest control regulations must properly divide the stock into catch and escapement, must not threaten the physical well being of the harvesters, and must consider the welfare of the processing sector. Since those three objectives of conservation, public safety, and product quality may be mutually exclusive, priorities must be established before the fishing season starts and even before the regulations are written.

Information Requirements—The Provisional Definition Continued

The minimum information necessary to achieve the objectives of harvest control can be divided into the categories of spatial distribution, temporal distribution, and abundance. The information requirements are best remembered as the answers to the questions, "Where, when, and how many?," with respect to each identifiable stock of fish, and fishing gear type, under the jurisdiction of the harvest control authority.

At this point in the definition of harvest control it is not necessary to talk about the sampling problems involved in obtaining those answers. Sampling considerations for a commercial marine fishery are addressed by Terry Quinn in another paper in this series. Regardless, however, of *how* the answers to "Where, when, and how many?" can be obtained, the possession of that minimum information is a valid test of whether a fisheries management agency is actually performing its legislatively mandated function. Assume this agency is charged with achieving some objective, such as conservation, which is defined in the enabling legislation of the agency. One could look merely at annual yields, escapement levels, the status of critical habitat, and at any other category of data which might describe the status of the fish stocks under the jurisdiction of the agency. If the stocks are in good shape, as judged by the legal definition of conservation, then the agency might be said to be in performance of its duties, while if the stocks are below conservation levels, the agency might be charged with dereliction of duty.

Such arguments would, of course, be superficial. The status of the stocks could well be independent of any actions taken by the agency. Indeed, the activities of other agencies and of the public at large might be the primary determinants of stock status in the management area. How can one tell if the stock status is due to the activities of the agency?

While it may not be possible to determine if the stock status is the direct result of agency efforts, it is relatively easy to tell if the agency has the capability to fulfill its mission. If the agency cannot produce the minimum information necessary for harvest control, then it cannot possibly be exerting any rational influence on the operation of the fishery. Thus endless arguments about the status of the stocks, the appropriateness of escapement goals, the condition of critical habitat, and other difficult issues are avoided. If the agency does not command the answers to "Where, when, and how many?" for each identifiable stock and gear type in its areas, then harvest control is void. In plain language, it is possible to determine whether the agency is managing, or just keeping score.

The extent to which the agency can define the abundance of stocks and gear types by area and time interval determines the ability of the agency to direct the fishing operation to achieve any given objective. A perfect command of such information will rarely, if ever, be found within any single agency. But if such knowledge is entirely lacking, if the budget of the agency contains no provision for mastering such information, then clearly the agency cannot control the harvest. The lack in itself can identify an agency which is incapable of managing its resource for the public trust.

On the basis of the preceding criteria, one might question the harvest control capabilities of most resource management agencies. Given the realities of budgetary constraints within most agencies the application of such absolute criteria might not be considered "fair." The purpose here is not to be fair, but to forge in general terms an objective definition of the information required to manage a fisheries resource. It is intended to pave the way for a general theory of harvest control which can unite the principles on which the regulations of commercial marine fisheries are based.

THEORY AND PRACTICE— SHRIMPING IN NORTH CAROLINA

Phillip R. Mundy

Recapitulation

Recall that "real-time salmon management" has been termed "harvest control of salmon" and a definition of the objectives of harvest control has been offered. It has also been argued that the management of commercial marine fisheries is all things to all people, but usually it refers to harvest control. In general terms harvest control is directing the operation of the fishery to achieve some catch level set by the proprietor of the resource. Unfortunately life is never so simple, and harvest control has many dimensions, including not a few facets which lie on the dark side of human nature. The following quote of a former administrator of fisheries in Washington State of over 60 years ago is a vivid illustration of the source of most complexity in harvest control operations.

> At the end of eight years, I realize what a thankless task it is to try to preserve a great natural resource for a country. To him who tries to stand between the greed of those to whose private interest it is to destroy a great natural resource and the state which owns that resource, there is reserved a most umpleasant portion. In the Senate Chamber in 1919, at a public hearing on the fisheries code, which I prepared and which would have curtailed the fishing for both mature and immature salmon, one of the spokesmen for one of the fishermen's organizations declared that any person who would put forward a proposal for curtailing fishing should be beheaded. (Darwin 1921 *in* Wright 1981, p.29)

Advances in technologies change the appearance of human societies fairly rapidly, but behind the technological facade human nature never changes.

The elementary formal definition of harvest control is departed when one says that the control is undertaken to achieve the three objectives of conservation, public safety, and product quality. To achieve these objectives it is necessary to answer the questions of "Where? when? and how many?" for each identifiable stock and gear type in the fisheries.

Preliminaries

Three references provide supplementary information and an entry point to the literature: Holling (1978), Mundy and Mathisen (1981), and Mundy (1982b). Two other sources, Babcock and Mundy, and Matylewich and Mundy have been accepted for publication in 1985 by the North American Journal of Fisheries Management.

A Provisional Definition—The Harvest Control System

Harvest control systems have been specified in rigorous form by a number of authors (see Peterman in Holling 1978), however I believe that harvest control systems are constrained to be no more complex than is justified by the educational backgrounds of the people who must operate the system. This is not to say that the best available data and analytic tools are not to be applied to the development of the systems but, rather, that the system will fail if the results of the system cannot be interpreted to the public and its elected representatives.

In the Alaska adult salmon fisheries, decisions on the disposal of tens of millions of dollars of product are made every twelve hours over a period of several weeks, and under enormous pressure. The system must be trusted to function under such conditions, and to be trusted it must be understood. In some areas of Alaska harvest control biologists are accustomed to spending the summers managing the fishery and the winters in court answering suits filed by processors and harvesters. Only trusted, well-tested methods will be used by people who are subject to such intense public and legal scrutiny.

The elements which I include in a harvest control system are a performance curve and a set of rules for the use of the performance curve in setting harvest regulations. The performance curve specifies the cumulative proportion of the catch, catch per unit effort (CPUE), or total abundance which will occur within a fixed geographic reference frame. The term *performance curve* is a synonym for "cumulative time density' which I have used in past publications and which was derived by analogy to a probability density function in the time domain. But the term "performance curve' has intuitive appeal and it is highly descriptive of the use to which such constructs are put.

Very simply, the performance curve is an image of the cumulative percentage points of the fishery in a specific locality. When the locality is a small, well-defined area through which a single life history stage of the target stock migrates, the performance curves are likely to vary little from year to year, as reflected by the catches from a well-established fishery. If the area is geographically very broad (e.g. the North Pacific), and if the catch is not divisible by life history stage, then the performance curves will probably vary a great deal from year to year. Obviously the cases amenable to the type of harvest control system discussed here are those in which the annual performance curves are quantitatively similar for each application.

The time series of catch in a fishery is the result of the distribution of the stocks and gear in time and space. The performance curve is an attempt to wrest simplicity from a complex situation by fixing the spatial domain, while allowing time to vary. Since the balance of the lectures will be concerned with variation in the cumulative proportion of catch as a function of time, let me note in passing that a performance curve can be written as the cumulative proportion of catch (or CPUE) as a function of space on a time interval. For example, if harvest control needs to track a migration along a body of water such as a river, or inlet, the cumulative proportion of CPUE (or its first derivative) on each time interval can be used to track the "center of mass" of the migration. The spatial domain is composed of the various statistical areas aligned along the axis parallel to the path of the migration from the point of entry to the destination of the migration.

Performance curves in the time domain have broad application in harvest control of well-established fisheries with long-standing statistical reporting areas. But other methods which rely on the concept that catch is proportional to total abundance (in the vein of Baranov) may also be applicable to these situations. When only a limited number of years of data, or no data at all, are available, the performance curve may be the only rational basis for harvest control.

The claim that a performance curve can serve harvest control in the absence of any historical data needs to be explained. In 1977 while working for the Point No Point Treaty Council at Kingston, Washington, I was faced with the need to write fishing regulations for a set gillnet fishery for coho salmon (*O. kisutch*) on the Elwha River, just west of Port Angeles. The Elwha was dammed only a few river miles from its entrance into the Strait of Juan de Fuca about 1912, consequently no native coho salmon populations existed in the river in 1977. But in that year a harvestable surplus of coho salmon returning to the Elwha River was anticipated due to the release of smolts from a rearing channel on the river operated by the Washington Department of Fisheries (WDF). A gillnet fishery at the mouth of the river was justified to take any surplus, but how could the level of surplus be determined and the desired level of escapement be achieved with no historical performance data to guide the formulation of regulations? Waiting for the fish to accumulate in the river would have meant a substantial loss in the value of the harvest due to the decline in quality of maturing fish, and there was no sure method to enumerate the fish even after they had accumulated in the river. In the end the success of the operation would be judged when WDF personnel attempted to recover brood stock from the river.

The smolts which had been released from the Elwha River had originated at the WDF hatchery on the nearby Dungeness River, and catch records from a gill net fishery at the mouth of that river were available. A performance curve based on Dungeness catch was used to set harvest regulations on the Elwha River under the assumption that the timing of the transplanted salmon would not change. A further assumption was a 100 percent exploitation rate, and the cumulative percentage points of the performance curve were used to give a very conservative estimate of the total return of coho for the year; the cumulative catch of a date was then divided by the expected cumulative proportion specified by the performance curve on that date. The appropriate harvest level for the season is continually updated by subtracting the escapement goal of WDF from the estimated total return on each time interval. In 1977 and 1978 the WDF channel operation received its escapement requirement with not more than a 20 percent surplus of spawners, and the gill net harvesters received top dollar for river caught fish. The fishery ended after 1978 because WDF had ceased releases of coho, since the fishery was operated by a treaty Indian tribe, the Lower Elwha Klallam.

To illustrate the application of performance curves to a specific fishery, I have chosen some work from North Carolina (Babcock and Mundy, in press, and Matylewich and Mundy, in press). Catch and nominal effort data have been available for this trawl shrimp (*Penaeus* spp.) fishery on a weekly basis only since 1978, however monthly catch data extend back to 1966. Prior to the declaration of the exclusive economic zone, EEZ, by Mexico about 1976, the penaeid shrimp fisheries had the highest dollar value to United States fishermen of all commercial fisheries. Even now that landings are primarily limited to catches from U.S. waters, the shrimp fisheries are leaders in economic value in U.S. fisheries. The brown

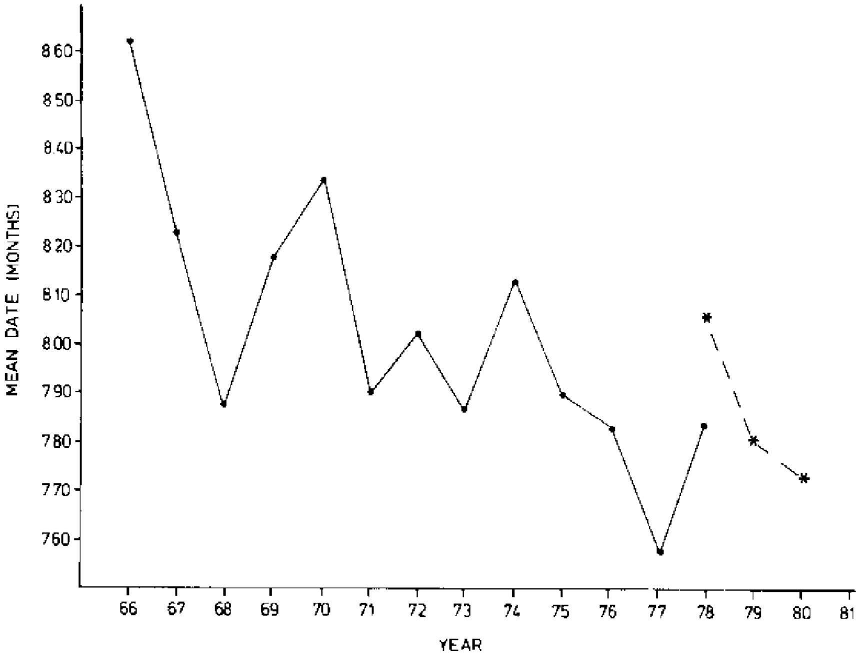

Figure 1. Mean date of brown shrimp catch based on monthly landings from all of North Carolina (o), 1966–1978, and the same statistic based on weekly landings from Pamlico Sound, Core Sound and Neuse River (*), 1978–1980.

shrimp (*P. aztecus*) is usually the most valuable commercial species in North Carolina, although blue crab (*Callinectes sapidus*) landings have occasionally eclipsed those of the brown shrimp in recent years. Landings of brown shrimp from a single area, Pamlico Sound, usually account for the majority of the state's brown shrimp landings.

To determine the similarity of the annual performance curves over all years of record we examined the mean of the time series of percentage catch (the first derivative of the performance curve—the time density; see Mundy 1982b). While the variances of the annual time series of percentage catch would not be comparable between monthly and weekly data, the means are comparable. The mean date of the North Carolina brown shrimp catch (1966–1980) has fluctuated over a range of about one month, with the center of the range falling at the end of July or beginning of August (Fig. 1). Based on past experience with salmon fisheries, I felt the results looked promising. Using the weekly data and the catch for only a single major statistical area (Pamlico Sound, 6354), performance curves of weekly catch data of 1978–1981 were constructed (Fig. 2). The close similarity of the annual performance curves of catch, and the even more striking resemblance of the performance curves for catch per boat hour (Fig. 3) for the same years, demonstrate the applicability of performance curves to harvest control. If the best available approach to answering the questions of temporal and spatial distribution and abundance is to say that the proportionate time series of catch, or CPUE, or total abundance (combined catch and time lagged escapement) by statistical area in the current year will resemble that time series of past years, then performance

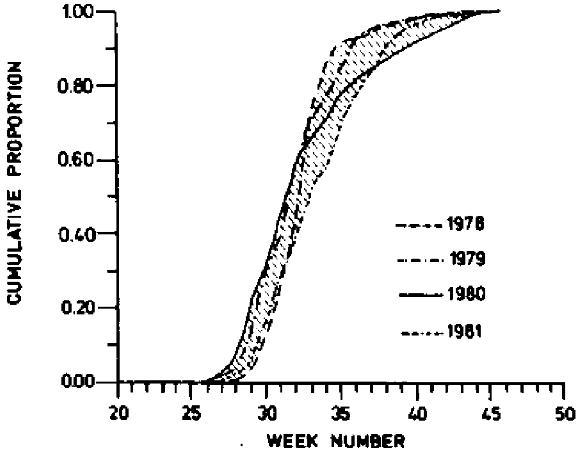

Figure 2. Cumulative proportion of commercial brown shrimp catch by week (Jan. 1-7 is week 1) from Pamlico Sound, North Carolina, 1978–1981.

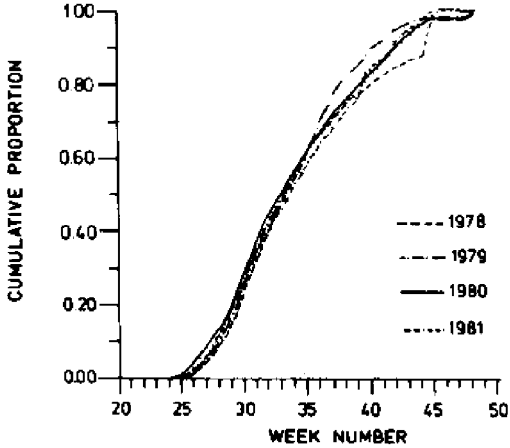

Figure 3. Cumulative proportion of commercial brown shrimp CPUE (lbs heads-off per boat hour) from Pamlico Sound, North Carolina, 1978 1981.

curves provide a means of displaying those arguments in a quantitative fashion. The estimation of total annual yield for the brown shrimp fishery is accomplished on each time interval by dividing the cumulative catch of the time interval, R(t), by the expected cumulative proportion of catch (or CPUE), P(t); w(t) = R(t)/P(t). An estimate of the variance of this estimator is given by Walters and Buckingham (1975);

$$\sigma^2_{w_t} = \frac{R_t^2 \sigma^2_{P_t}}{P_t^4}\left\{1 + 2\ 2\sigma^2_{P_t} / P_t^2\right\}$$

The important points to note about the variance of this estimator are (1) it approaches zero as the percentage of catch approaches 100, and (2) it is directly proportional to the variance of the cumulative proportion of total catch (CPUE) on the time interval. As one would expect, once the season is over, it is possible to estimate the yield with almost perfect accuracy, but as may not be obvious, the variance of cumulative proportion increases from zero at the beginning of the season to a maximum near the mean of the time density, and then it decreases to zero at the end of the season.

Using a system of estimation in which the average performance curve of three years is used to estimate the total CPUE of the fourth year, the error of estimation quickly settled down to the plus or minus 20 percent range (Fig. 4) for brown shrimp in Pamlico Sound. The expected cumulative proportion of CPUE can be used to estimate either the total catch or the total CPUE for the season, depending on which is of interest. To judge how soon the information will be available to management during the course of the season, note from Figure 3 that by week 30 about 30 percent of the total annual CPUE has been expended, so that by the 30 percent point in the season, the harvest control biologist could be in a position to estimate the total catch per unit effort for the season within 20 percent.

Of course more years of data will probably add more variability to the estimator, and the methods employed here can be considered only as a simulation of the real world. But the

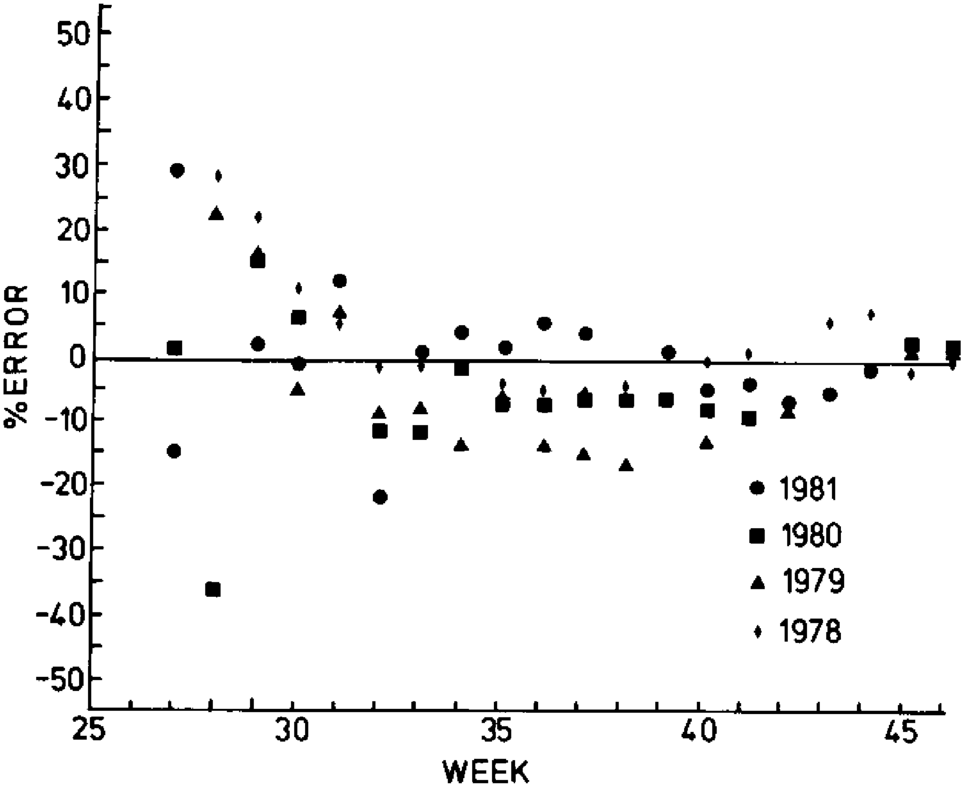

Figure 4. Percent error in estimates of total annual brown shrimp CPUE for Pamlico Sound, 1978–1981.

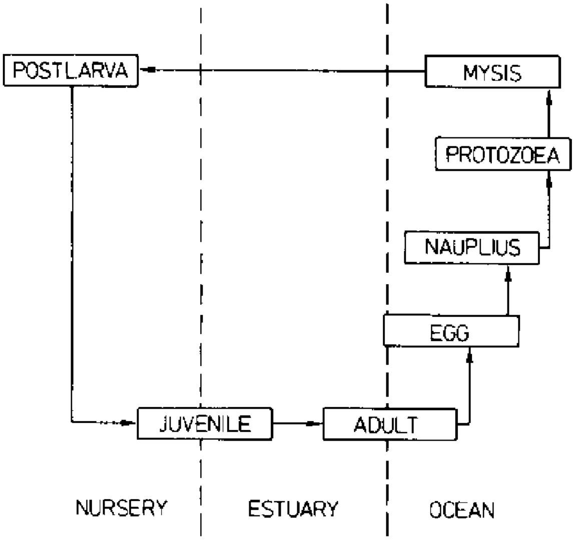

Figure 5. Life history and route of migration of the brown shrimp.

accuracy of the estimator in simulation, the similarity of the annual performance curves of catch and CPUE (1978–1981), combined with the stability of the mean date of catch (Fig. 1), are sufficient to make the point that a performance curve harvest control system would be appropriate for regulating the harvest of brown shrimp in Pamlico Sound.

The extension of methods developed in the salmon fisheries of Alaska and British Columbia to brown shrimp harvest in North Carolina was relatively easy because the life cycle of the brown shrimp is a mirror image of the life cycle of the salmon (Fig. 5). The adults spawn in the Atlantic Ocean, and the young develop through several stages to become the mysis, which is returned to the nursery areas in the mouths of rivers by Ekman transport and other physical processes which are exploited by the behavior of the mysis and postlarva. As the postlarvae grow into juveniles, they start the movement back into the estuary where the transition to adult starts. The fishery acts on the maturing shrimp in the estuary as they return to the ocean. Once the maturing shrimp reach the ocean they are not targeted by a fishery. The geography of the North Carolina situation (Fig. 6) completes the analogy. Juvenile shrimp from the Neuse and Pamlico rivers, and other nursery areas, migrate into Pamlico Sound where a fishery is directed on them. As they begin to mature, the shrimp migrate through the passes between the barrier islands into the Atlantic Ocean. Once in the ocean the shrimp are free of the fishery.

The Control of the Fishing Operation

The basic concept of harvest control and the performance curve being understood, there remains a question which has been answered only implicitly so far. It is essential to ask, "What means are available to achieve the objectives of harvest control, assuming adequate

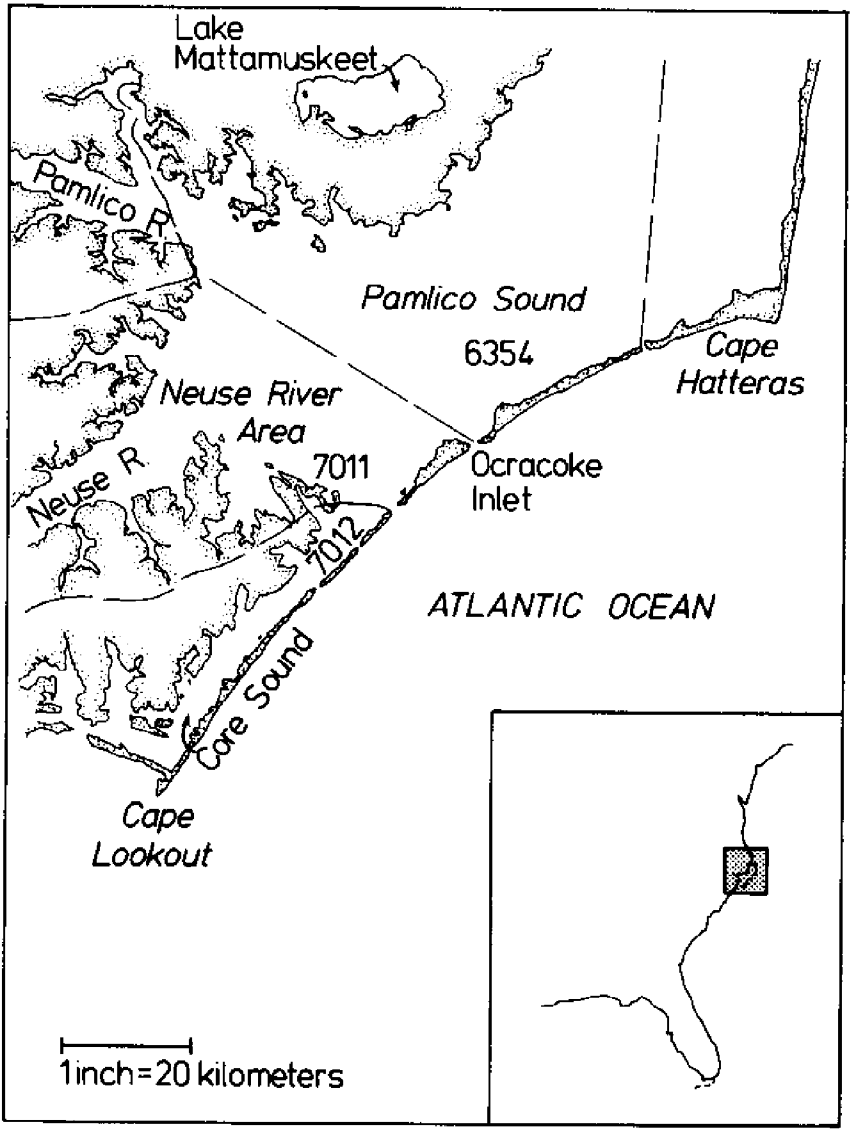

Figure 6. Coastal North Carolina and the statistical reporting areas for the brown shrimp harvest.

information is available?" Harvest control is normally achieved through enforcement of legal restrictions on the time of fishing, the area of fishing, and the gear for taking fish—abbreviated as time, area, gear (TAG) restrictions.

For harvest control operations which are directed on a daily basis (i.e. real-time salmon management) the means of control most frequently available is the time restriction. Area control is frequently available, however it is never as flexible as the time control. Fishing areas have to be defined in legal terms before the start of fishing, and if the area cannot be readily defined by geographic landmarks and visual navigational aids such as channel markers and lighthouses, then the management agency will have to provide the markers. Purchasing and deploying area markers can entail tens of thousands of dollars in expenses to the harvest control program. Once statistical reporting areas are long established, there are compelling economic, legal, and mathematical reasons for leaving them undisturbed. The least flexible means of controlling the fishing operation is by gear restriction. Typically inefficiencies are legislated into fishing gear by prohibiting the application of emerging innovations in marine architecture. Once a standard vessel has been defined, and once large numbers of people have invested in the standard vessel, changes are difficult to effect. The amount of fishing gear; the length, depth, and mesh of nets; and the total number of hooks, pots, or other appliances can be altered, but enforcement problems are directly proportional to the number of vessels and appliances in the fishery and the area over which the fleet is dispersed. The volume of fishing activity can be ascertained rapidly, from the air for example, but the amount of gear actually being fished usually must be determined by on-board inspections. Furthermore, changes in vessels or fishing gear can thwart attempts to define a standard unit of gear for the purpose of estimating abundance from arguments of the proportionality of catch to effort and abundance (e.g. Baranov; Leslie, and others).

Consequently the most effective, and common, means of directing the fishing operation is by opening and closing a fixed area to fishing by a predictable number of units of effort. It is precisely for this type of situation of control that the performance curve is appropriate. If the primary means of achieving the objectives of harvest control is the time regulation, then the primary criterion for determining the status of the binary switch—fishing/no fishing—in a given area will be the current performance as interpreted within the context of the historical performance of the fishery in that area. My argument is that the record of historical performance of choice is the cumulative proportion of catch, CPUE, or total abundance as a function of time, the performance curve.

Summary and Conclusion

In harvest control the operation of a commercial fishery is directed to achieve the objectives of conservation, public safety, and product quality, where the precise meanings of the objectives are determined by the proprietor of the resource, the political state. The objectives cannot be achieved, except possibly by chance, without information on the distribution and abundance of the resource, and gear, in time and space. A convenient summary of the necessary information is the performance curve, the cumulative proportion of catch or CPUE as a function of time in a fixed locality. When annual performance curves are similar, the performance curve forms the rational basis for opening and closing the fishery within its reference frame by serving to scale current performance by historical performance. If the annual performance curves differ radically, it is not likely that any system of harvest control is appropriate to the fishery. This is true because the time series behavior of the performance curve of the fishery is unstable and there is consequently no basis to evaluate the relation of the catch on a given time interval to a specified seasonal management goal such as a quota (i.e., TAC or TALFF) or annual spawning escapement goal. In a fishery with an unstable performance curve, for example, it would not be surprising for the seasonal catch quota to be exceeded in a single harvest period due to unpredictable behaviors of the target species and the harvesters. In a salmon fishery where the time series behavior of the performance curve is unstable, escapement goals will be routinely missed by substantial margins. The key concept is that the level of uncertainty about the behavior of the fishery is directly proportional to the magnitude of the variability associated with its performance curve.

Practice—Salmon Fishing in Alaska

Phillip R. Mundy

Preliminaries

In tracing the literature on the development and use of performance curves in the salmon fisheries of Alaska, I have found two distinct lines, one of which is rather short. The short line is the Bureau of Commercial Fisheries research in southeastern Alaska which culminated in the work of Elizabeth Vaughan (1954). Vaughan characterized the migration of pink salmon by a generalized probability density function which could assume various forms depending on the parameter values. The analogy between migration in a fixed reference frame and a probability density function in the time domain was an important conceptual achievement, since in one stroke it removed the variability of fluctuations in abundance and established the relevance of a body of literature in mathematical statistics to the study of migration. I used the same approach in my dissertation work (Mundy 1979), however I was ignorant of Vaughan's work until it was pointed out to me by M. Alexandersdottir in 1980.

The longer line of research is the work of members of the Fisheries Research Institute, FRI, University of Washington, which is exemplified by W.F. Thompson's observations on the shift in timing of Columbia River chinook salmon *(O. tshawytscha)* catches from May and June toward July and August with a concomitant loss in productivity from the entire system. Thompson attributed the decline in catches to differing reproductive potentials of the various timing segments of the migration and the differential exploitation of the timing segments by the fishery. Thompson's influence is seen in the work of the International Pacific Salmon Fisheries Commission, IPSFC, which he directed for many years (Thompson 1940; see also Schaefer 1951; Killick 1955; Gilhousen 1960; Henry 1961) and in the work of faculty and students of FRI: Bevan 1962; Sheridan 1962; Royce 1965; Narver 1966; Dahlberg 1968; Mathisen and Berg 1968; Roberson and Fridgen 1974; Mundy 1979; Mundy and Mathisen 1981; Hornberger and Mathisen 1982; Brannian 1982; Alexandersdottir and Mathisen 1982.

Both lines of research have merged in the current dissertation work of Alexandersdottir; the work is focused on the extension of concepts outlined by Vaughan for pink salmon of southeastern Alaska, and it is being directed by Mathisen, a student of Thompson. Performance curves are now in use, or under development, for harvest control of adult salmon fisheries on Puget Sound and in Alaska from Dixon Entrance to Kotzebue, and in every case such work is logically descended from the concepts of W.F. Thompson. The texts for this lecture are Mundy (1982a and 1982b).

The Chinook Fishery of the Lower Yukon River

In June of 1980 I first visited the Alaska Department of Fish and Game, ADF&G, facility at Emmonak on the Yukon delta (Fig. 1). The Yukon is a vast drainage basin of 330,000 square miles, about two-thirds of which are in the United States. Some chinook travel over 2100 river miles to spawn in Canadian areas which lie only a few hundred miles east of Juneau, Alaska. Chinook are harvested at various points along the river, but the majority are taken by the subsistence and commercial fisheries of the lower river.

The fishery is small by Alaskan standards, taking annually about 100,000 chinook from set and drift gill nets, including those catches from two statistical areas above the delta to Old Paradise Village which lies about 300 river miles from the mouth. The majority of the catches of the lower river come from the delta area. Initially the research project examined catch and effort records from all of the lower river (Mundy 1982a), but my remarks will be confined to an analysis of the records from only the first 63 river miles, the delta proper which ends at the Anuk River.

The harvest control objective is to deliver a guideline harvest level set by the Board of Fisheries. The harvest level for the lower river is an approximate historical average of catch, and I interpret it to be that level of catch which, on average, will do no harm to the stock since populations have borne that exploitation over a long period of time without being perceptibly diminished. Considerations of stock and recruitment are difficult to include in setting the harvest controls because data are lacking; no quantifiable estimates are available for escapement to the many spawning areas to which stocks caught in the Yukon delta are bound. Harvest controls are implemented by the opening and closing of fishing periods and by restricting the mesh size of gillnets in the chum salmon fishery which follows the chinook salmon migration.

The proportion of the available stock removed by a unit of effort in a unit of time (boat/hour) has probably changed upward during the past ten to twelve years. During the first ten years of ADF&G control over the fishery (1960–1969), commercial fishing operations and equipment were relatively unsophisticated, as were the processors who bought the fish. The prices paid for chinook were quite low, $4.60/fish in 1969, and no one was seriously interested in buying the chum salmon which could be caught during and after the chinook season. In the following decade the rapid rise in prices paid to harvesters ($20.32/fish in 1977), a development of interest in chum salmon eggs, and increased competition among processors, brought about substantial changes in the fishery. Investment of increased income by the harvesters and processors has most probably increased the rate at which the unit of effort takes chinook due to (1) decreased delivery time, (2) increased tender capacity, (3) increased vessel capacity, and (4) improved communications among harvesters with respect ot fish location. A fifth factor of interest is the increased incidental harvest of chinook in July due to the increased effort on chum.

It is no surprise that the time open to chinook fishing has been steadily reduced in an attempt to counter the perceived increase in the efficiency of a unit of gear. In 1965, chinook fishing was authorized for 24 days while in 1980 only 12 days were open. Such reductions in fishing time are common in the evolution of commercial fisheries, and these reductions are of

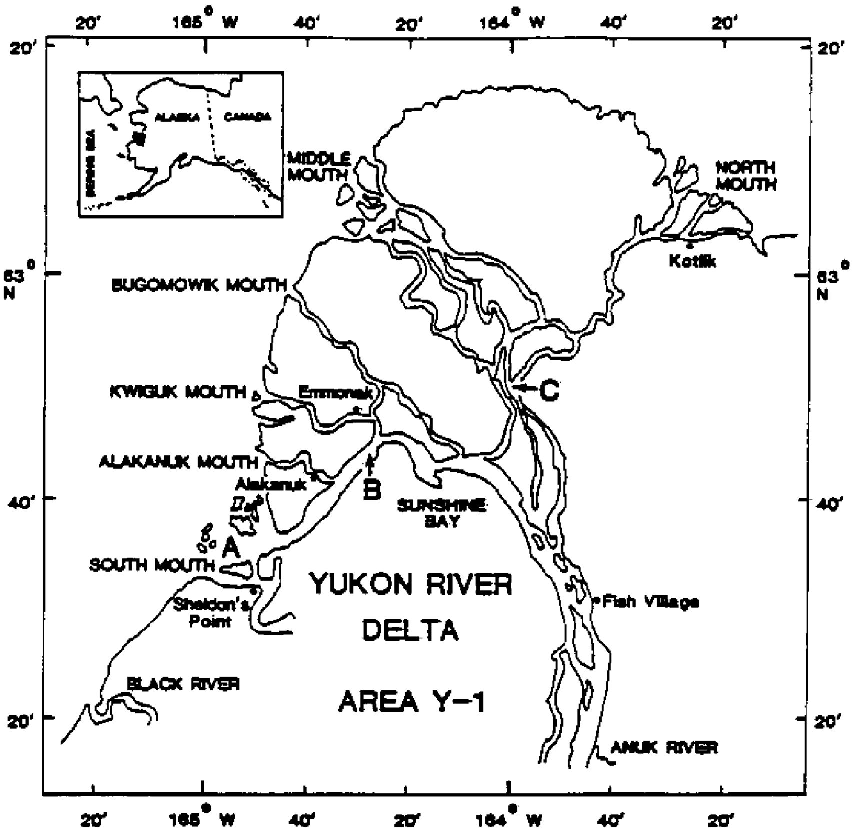

Figure 1. Yukon River delta, Alaska; fisheries statistical area Y-1.

vital concern in the formulation of performance curves from commercial catch data.

The tendency toward reduced fishing time with increasing age in a fishery means that the catch and effort data become a more and more censored series of samples with respect to the time distribution of abundance of the target stock. For example, the commercial fishery on the Yukon once provided a sample of the chinook stocks in the delta area for five days out of every seven, however by 1982 the sampling frequency had dropped to one day (two twelve-hour periods) out of seven. It is probable that commercial catch data no longer provide an adequate sample upon which to base the performance curve. As the fishery evolves, the catch data become an increasingly truncated image of the time distribution of abundance of the target stocks, and test fisheries become an invaluable source of performance curve data.

Test fisheries have been operated in the delta area since 1963. Until 1978 set gillnets comparable to commercial chum and chinook gear were operated at Flat Island (Site A, Fig. 1). Flat Island was originally chosen, in part, because most of the chinook were thought to enter by way of the southern most entrance to the delta, but subsequent experience showed that in some years substantial proportions of the migration entered through other passes. In 1979 test fishing operations were moved to sites B and C (Fig. 1), although logistical problems precluded a full season of data from both test sites until 1980.

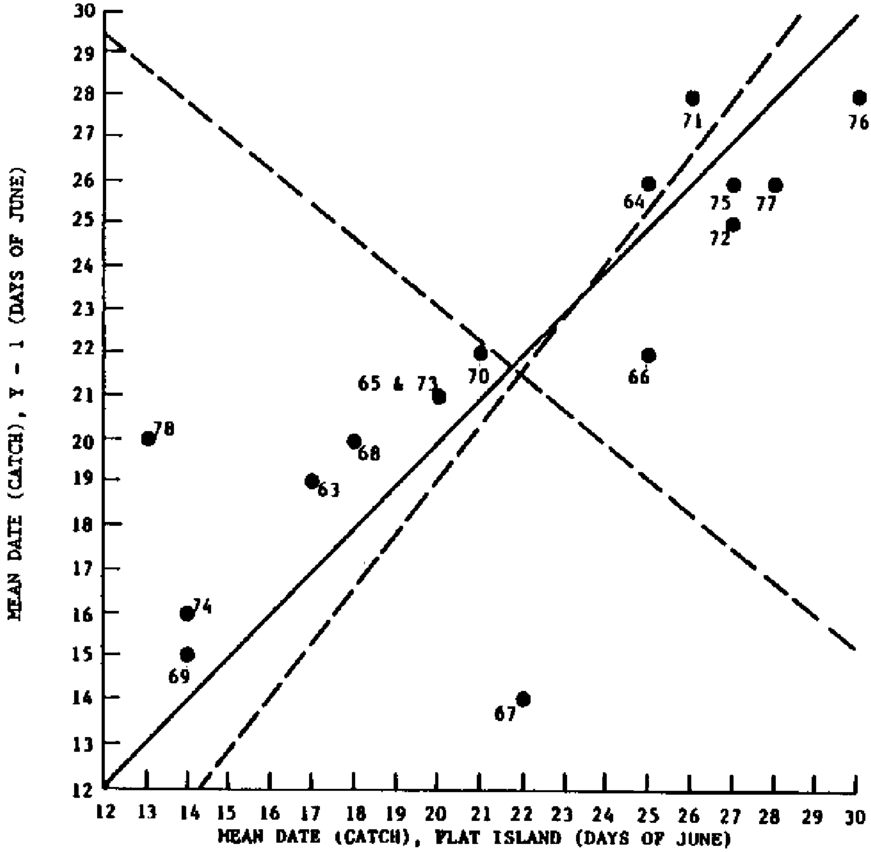

Figure 2. Mean date of commercial chinook catch in area Y-1 versus the mean date of test catch at Flat Island (site A, Fig. 7), 1963–1978. Solid line has slope of one, and dashed lines are major and minor axes.

Even though the number of days fished each year had been steadily declining, the catch data could provide an accurate estimate of the timing as measured by the mean date of the time distribution of catch. (Other moments of the distribution such as the variance are extremely sensitive to the rate of sampling, while the mean might be accurately estimated from the catch of a single day, although this would be unlikely.) By comparing the estimate of the mean date of catch from the test fishery at Flat Island to the mean date of commercial catch some understanding of the potential problems of censorship might be gained (Fig. 2). The test fishery operates every day throughout the entire duration of the migration, so that censorship and truncation are not a factor. A paired comparisons t-test did not show any significant difference between the mean dates of the test and the commercial catches, as one might suspect from the plot of the data. Of the two outliers (1978 and 1967) one was early in the series of years examined, 1963–1978, and the other was late, so that no time trend in misidentification of timing by the commercial catch was evident. The slope of the major axis

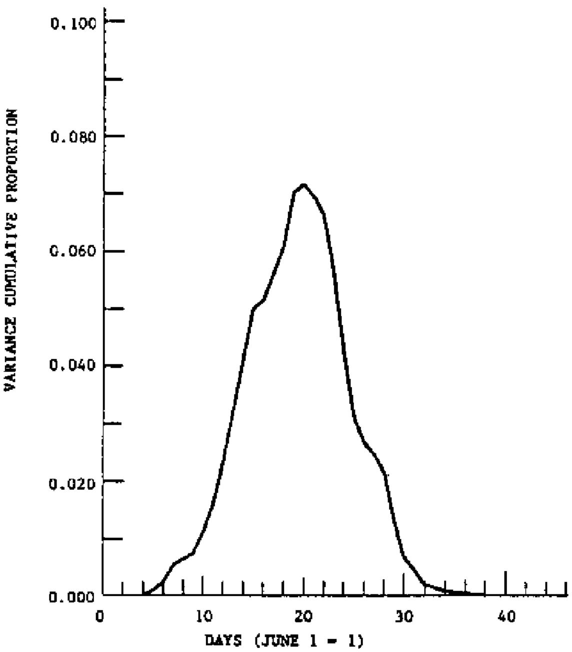

Figure 3. Variance of cumulative proportion of commercial chinook catch by day in area Y-1 during the years 1961 1980.

(dashed line of positive slope, Fig. 2) was slightly greater than one, which is reasonable since Flat Island is encountered by the migrating salmon just before they enter the fishing district, so that the mean date of Flat Island catch should slightly precede the mean date of commercial catch if both means were perfectly measured. The approximate 95 percent confidence interval on the slope of the major axis also included unity, which is consistent with the hypothesis that there is no significant difference between the measures of timing by the test and by the commercial catches. The approximate 95 percent confidence interval on the slope intercept of the major axis contains zero, which is also consistent with the hypothesis of no difference. Thus there is reason to believe that the commercial catch accurately reflects the mean date of migration at least as recently as 1978.

Having decided to base the analysis on commercial catch data, it was necessary to determine if the performance curve, the daily cumulative proportion of the catch (or CPUE), was really the least variable characterization of historical performance in the fishery. Is it not possible that the average catch or CPUE on a date is less variable than the cumulative proportion of catch or CPUE on the date? Since the magnitudes of the catches and proportions of catch differ widely, the coefficient of variation (CV) was chosen as a basis for comparison. The standard deviation as a percentage of the mean is a particularly good way to compare the variability between dates within a performance curve, since the variance of the cumulative proportion of the catch or CPUE as a function of time has a predictable behavior (Fig. 3). The variance is initially small because cumulative proportions early in the season are very close to zero. As the season progresses, the average cumulative proportion increases in magnitude, and so does the variance. But since each annual performance curve must go to unity at the

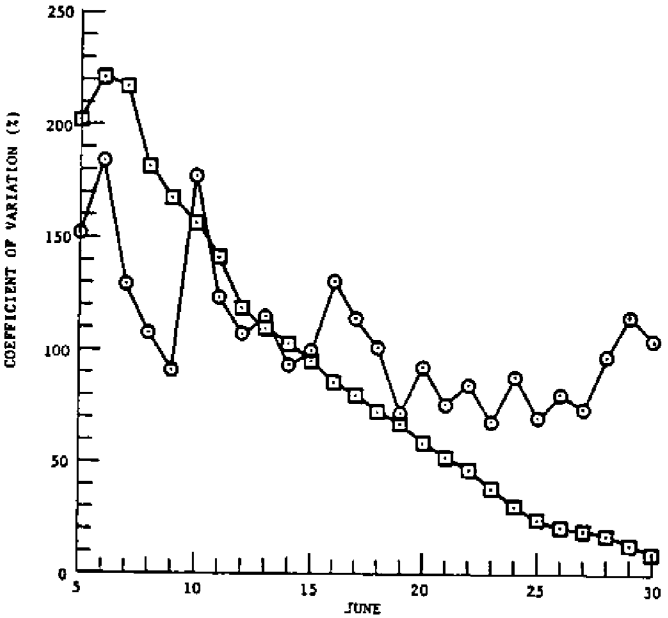

Figure 4. Coefficients of variation of cumulative proportion of CPUE (squares) and daily proportion of CPUE (circles) for the years 1961–1980.

end of the season, the variance declines to become zero once again at the end of the season. It is the speed with which the variance declines in relation to its mean which is of interest for predictive purposes.

To summarize quickly, the CV's of cumulative catches and of CPUE's, and the cumulative proportions thereof, declined rapidly and predictably, whereas the CV's of the daily data did not (Fig. 4). The CV's of the cumulative proportionate data declined more rapidly than did the CV's of the cumulative numeric data (Fig. 5), and the CV's of the cumulative proportion of CPUE declined most rapidly of all (Fig. 6). The performance curve based on catch per boat/hour is the historical record of choice for harvest control (Fig. 7), but there is really little difference between catch and CPUE in this case, probably because effort is relatively constant on each time interval, and because catchability is roughly constant within a year, although not necessarily across years.

Having chosen the best performance curve, much work remained to be done, since the variability observed was so extreme that prediction of future performance seemed almost impossible. We knew that the mean date of the migration of chinook salmon in the waters of the Yukon delta had been observed to occur between June 13 and June 29 from 1961 through 1980, but that was little more than the managers knew at the beginning of the study. The result was not unexpected, since the migration is composed of an enormous number of spawning stocks spread over a complex geography spanning 330,000 square miles.

But one advantage of the quantification of the time distribution of abundance by its moments is that sources of variability in migratory timing can be systematically evaluated. For

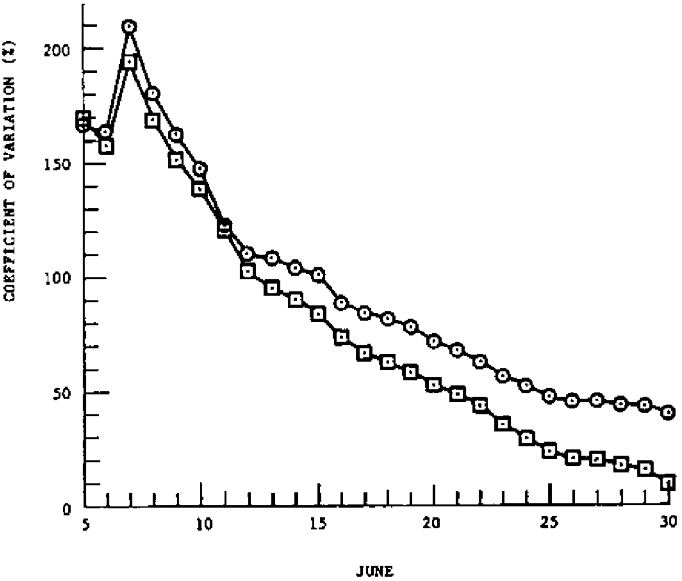

Figure 5. Coefficients of variation for cumulative proportion of CPUE (squares) and cumulative CPUE (circles) for the year 1961-1980.

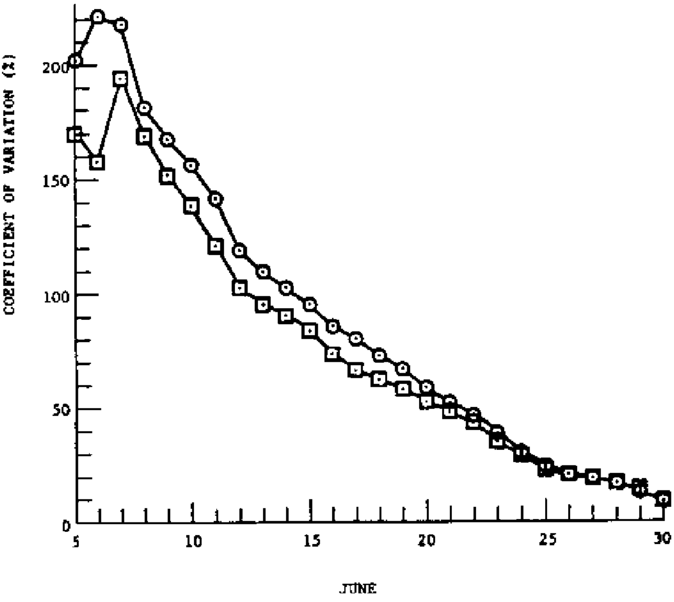

Figure 6. Coefficients of variation of cumulative proportion of CPUE (squares) and cumulative proportion of catch (circles) for the years 1961–1980.

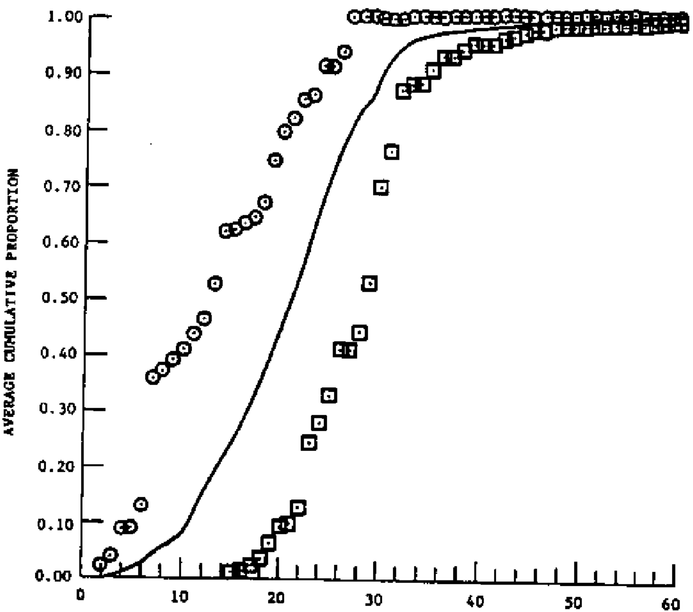

Figure 7. Maxima (circles), minima (squares), and averages (solid line) of the cumulative proportion of CPUE of the commercial chinook fishery, area Y-1, 1961 1980.

Table 1. April mean air temperature (°F) at Nome, the coded mean date of migration based on catch in area Y-1 and the timing class of each year, 1961–1980 (N = 20).

YEAR	TEMP	CODED MEAN DATE
80	23.8 +	18.7 –
79	25.5 +	17.1 –
78	24.9 +	20.2
77	9.4 –	26.0 +
76	9.7 –	28.3 +
75	13.4 –	26.0 +
74	20.9 +	16.1 –
73	18.3	20.5
72	11.9 –	25.1 +
71	12.9 –	27.8 +
70	15.1	22.0
69	21.8 +	15.1 –
68	14.4 –	20.0
67	23.0 +	14.1 –
66	15.2	21.8
65	20.4 +	20.8
64	13.4 –	26.4 +
63	17.9	18.8 –
62	18.4	22.2
61	18.0	18.1 –
$\bar{X}$	17.4	21.2
S	4.93	4.23

+ Observation is greater than upper bound of 95% of CI on $\bar{X}$

– Observation is less than lower bound of 95% CI on $\bar{X}$

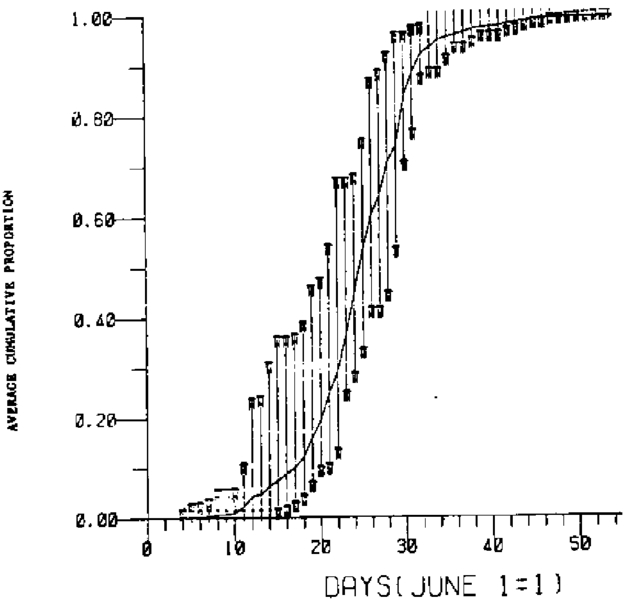

Figure 8. Maxima, minima, and average curve of the cumulative proportion of CPUE, cool temperature stratification of the data of Fig. 7.

example, the head harvest control biologist, Michael Geiger (another FRI alumnus), suggested that factors related to climate had a strong influence on the migratory timing. We chose the most obvious index of climate, air temperature, for investigation, as had others before us in other salmon populations (see Burgner, 1978). After examining weather data from Bethel, Cape Romanzof, and Nome from various time periods preceding the appearance of chinook on the Yukon delta, mean air temperature at Nome in April was found to be a fairly reliable covariate of the mean date of commercial catch over certain ranges of mean air temperature (see Table 1).

During the period 1961–1980, whenever the April mean air temperature was less than 14°F, the mean date of migration was greater than the upper bound on the 95 percent confidence interval about the grand mean date of catch (the run was late). When mean air temperatures were greater than 20°F, the mean date of catch was usually less than the lower bound on the 95 percent confidence interval about the grand mean date of catch (the run was usually early). Inside the interval, 14°F–20°F, the mean date of the catch was usually contained in the 95 percent confidence interval about the grand mean date of catch. Performance curves were developed from temperature strata and designated cool (Fig. 8), average (Fig. 9), and warm (Fig. 10). Clearly the range of maxima and minima had been reduced relative to the unstratified case (Fig. 7), but then, the number of years in each stratum is approximately one-third that of the unstratified case. Note that the shape of the cool curve is quite different from the warm. The slope of the cool curve is quite steep, while the slope of the warm curve is relatively shallow, and the slope of the average stratum is intermediate. The ranges of the maxima and minima are greater in the warm curve than in the cool stratum.

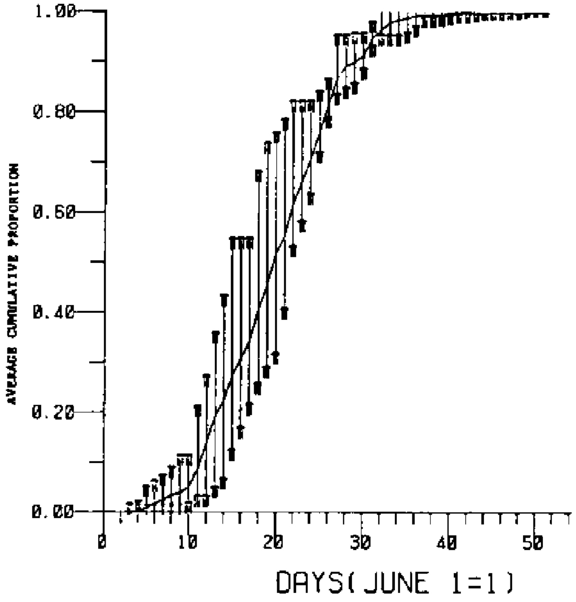

Figure 9. Maxima, minima, and average curve of the cumulative proportion of CPUE, average temperature stratification of the data of Fig. 7.

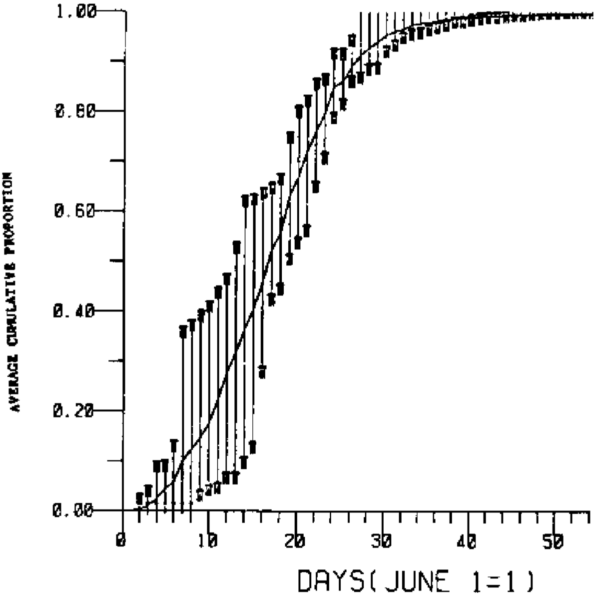

Figure 10. Maxima, minima, and average curve of the cumulative proportion of CPUE, warm temperatures stratification of the data of Fig. 7.

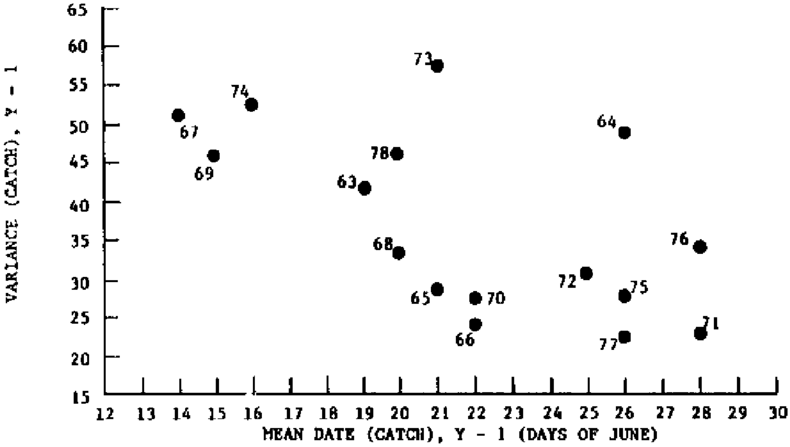

Figure 11. Variance versus mean date of catch in the commercial chinook fishery, area Y-1, 1963–1978.

One inference which can be drawn is that the rate of migration of chinook through the Yukon delta waters is inversely proportional to the mean date of the migration; the salmon move more slowly in warm years than in cool years. This obviously has strong implications for harvest control, since the rate of exploitation will be inversely proportional to the rate of migration in the lower Yukon. The slope of the performance curve is related to the variance of the time distribution of catch; a steep slope means a small variance and shallow slope means a large variance. Indeed, the inverse relation between the mean date of migration and the variance is seen on the Yukon delta (Fig. 11).

The proof of a performance curve is in its application. In 1982 the April mean air temperature was consistent with a late migration, and such was the case. The estimates of harvest by period and for the season which were based on the performance curve of the cool stratum did not differ from those of the harvest management biologist who has worked in the area for over fifteen years. While the performance curve did no better than the biologist, it is obviously a successful means of passing along state-of-the-art harvest control to the next generation.

The rules attached to the performance curve to determine openings and closings are apparently quite simple. If the cumulative catch is consistent with the guideline harvest level, then the predetermined pattern of openings will be continued. For example in 1982 the pattern was fixed at 12-hour openings on Mondays and Fridays, since this amount of effort at average population levels was expected to deliver the guideline harvest level. If the cumulative catch is over or below the level consistent with the harvest objective, it is a question of the magnitude of the deficit or excess. Assuming that the timing has been adequately categorized, a deficit could mean a low level of abundance and fishing may be curtailed. An excess probably means a migration which is more abundant than average, so that the guideline harvest level, actually a range of appropriate harvests, may be exceeded. Thus the apparent simplicity of the rules can rapidly decay into a complex series of value judgments which are characteristic of most commercial marine harvest control programs in my experience. It is here that the Yukon resembles every other commercial fishery, and so I depart for more general topics.

The Practice of Harvest Control

Most of the complexity of formulating rules around the performance curve can be defeated by (1) carefully evaluating the harvest objectives and the relative merit of the data categories before the heat of the season and (2) refusing to make any major adjustments in the agreed-upon logic (harvest control system) during the season. A further necessity is a *post mortem* examination of the harvest control program within a few weeks after the end of the season. Serious mistakes in judment have a way of appearing less and less serious as time goes by until the same serious mistakes are repeated season after season as "standard operating procedure." Clearly some formal review mechanism for the continual evaluation of harvest control programs is necessary.

One approach to the institution, evaluation, and renewal of harvest control procedures which I am attempting to implement in Alaska is to establish a computer program in each area which serves as the depository and showcase of all harvest control procedures and the associated data, such as performance curves. Computers are not magic panaceas to all scientific problems, but the often brutal, and never compromising, logic of higher level computer language is the perfect medium in which to describe the basis for the disposal of tens of millions of dollars of fisheries products each season. All of the objective components of the harvest control program are in the computer program, and the subjective components are outside the program. Confusion created by the attempt to justify social and political objectives in terms of the historical performance of the fishery is easily recognized and eliminated. It is easy to see where science ends and policy begins. It is also easy to distinguish between well founded hypotheses and those which need more work when it comes time to code the concept into computer language.

Evaluation and renewal are readily accomplished because anyone who desires to question the harvest control procedures can get exact specifications and performance curves from the computer program and attendant data files. Research personnel can prepare analyses for presentation at the *post mortema* and potential impact can be tested in simulation. Ultimately the individuals responsible for the consequences of the regulations must decide on the renewal of old concepts and the incorporation of new concepts.

The simulation aspect also opens up a new horizon in fisheries education. If the harvest control programs and data base management systems are designed to mimic the actual performance of the fishery, then by relatively minor modification they can be used as training devices for new harvest control biologists. Such "management by ATARI (R)" would allow a trainee to pit his or her skill against all of the historical information available for a fishery, reliving most of the critical experience of a veteran manager in the course of a few weeks. Experience never before available to veteran managers could be gained by the trainee if the simulation program had the ability to create migrations with different combinations of mean and variance which fall within the realm of possibility, even though never before seen in a particular fishery. Such a program of instruction would provide experience in discerning the limitations of fisheries data in a particular area of interest, and in general. The trial and error method of training apprentices in the techniques of harvest control would not be eliminated, but the process would be drastically shortened.

Summary and Conclusion

The basic simplicity of a harvest control system composed of a performance curve and a set of rules for its interpretation is intellectually appealing, and it is also an accurate reflection of the way harvest control now operates in most commercial marine fisheries. At present the performance curve may simply be carried in the mind of an experienced harvest control practitioner and the rules may be unwritten tradition, but wherever fishing operations are actually directed to achieve some objective, such a system exists. The challenge is to describe and quantify the harvest control system so that knowledge can be advanced. If fisheries management, and in particular the harvest control of commercial fisheries, is ever to be more than a cottage industry staffed by somewhat gifted amateurs, then the process of defining and interpreting the harvest control system to general audiences must go forward. Mathematical complexity is no substitute for facing the hard questions surrounding contemporary harvest control. It remains to identify those readily comprehended, elemental building blocks which can unite and sustain the profession of harvest control of commercial marine fisheries.

Acknowledgments

In February of 1977 John Gilbert addressed a Bristol Bay Interagency Meeting sponsored by the Alaska Department of Fish and Game (ADF&G) in Anchorage. At the time he was an executive with Bumble Bee Seafoods and he presented a view of "fisheries management" which I thought was far too simplistic: "fisheries management is conservation, orderly fishing, and product quality in that order." Once I realized that Mr. Gilbert was talking about harvest control of salmon fisheries, I found his definition more to the point. As should be obvious, I now believe that the straightforward simplicity of John Gilbert's definition can be applied to harvest control of all commercial marine fisheries, and I take this opportunity to publicly thank Mr. Gilbert for this contribution to my education.

Professor Ole A. Mathisen has opened many doors for me over the years and this lecture series is no exception. I appreciated the opportunity to teach some of the world's most talented fisheries students.

I thank Dr. John H. Clark, Chief Fisheries Scientist, State of Alaska, for giving me the opportunity to develop these ideas in the best laboratory for harvest control research imaginable. Of course there are many harvest management biologists who have contributed to the development of these ideas who cannot be mentioned here, but I must credit Kenneth Middleton, ADF&G retired, for his patient tutelage of me in some of the world's most exasperating fisheries. Al Kingsbury, ADF&G, is responsible for the term, "management by ATARI(R)," and I give him full credit.

My graduate students and research assistants continually contribute new perspectives and fresh insights to the diversity of problems encountered in our research, so that no small part of the credit for my current understanding goes to them: Dr. John E. Clark, Howard Schaller, Erik Barth, Anne Babcock (Hollowed), Michael Matylewich, John Hollowed, Mario Paula, and Louis Rugolo.

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Part II.

MANAGEMENT OF THE NORTH PACIFIC HALIBUT FISHERY

SAMPLING CONSIDERATIONS

Terrance J. Quinn II

Fisheries management is a rather broad concept, embracing data collection to monitor both the fish population and the fishery, data analysis to estimate population parameters, and decision-making based on the analytical results. Generally, the goals of fisheries management are to conserve the fish resource, to control fisheries when overexploitation is a problem, and to maximize or optimize the yield from the resource in terms of biological, sociological, and economic parameters. Because data collection and sampling programs to achieve these goals may often be limited or improperly designed, the concept of sampling design to provide management information requires more attention than has been given in the past.

Previous lectures in this series have provided a comprehensive overview of techniques used in salmon management. This and the final lecture in this series will shift the focus to management of nonanadromous marine fish populations and, in particular, of the Pacific halibut resource. This lecture will be devoted to sampling techniques for the data collection phase of fisheries management with emphasis on the monitoring of population abundance. The subsequent chapter by Dr. Richard B. Deriso will present quantitative techniques for analysis of fisheries information and the detection of population responses in relation to fisheries management.

There are three major sampling procedures used by the International Pacific Halibut Commission (IPHC) for monitoring population abundance:

1. Collection of catch and effort statistics from fishermen,
2. Sampling of juvenile and adult populations using station or grid survey approaches,
3. Sampling for age composition of the commercial catch of fishermen.

In this paper, the current sampling program is described for each procedure with emphasis on assumptions and limitations in interpreting the data as a measure of abundance. Sampling programs are reviewed annually by IPHC staff to detect deficiencies. The development of sample-size requirements is discussed in terms of reducing variability of estimation. Finally, certain estimates of abundance as obtained by the procedures are contrasted.

Background

A comprehensive overview of the Pacific halibut population, fisheries, and management is found in IPHC (1978). The Pacific halibut is a long-lived, bottom-dwelling, migratory flatfish living to a maximum of 40 years and a maximum weight of 500 pounds. Pacific halibut are found from California northward into the Bering Sea (Figure 1). Adult halibut (older than age 8) migrate seasonally from spawning grounds in winter to feeding grounds in summer.

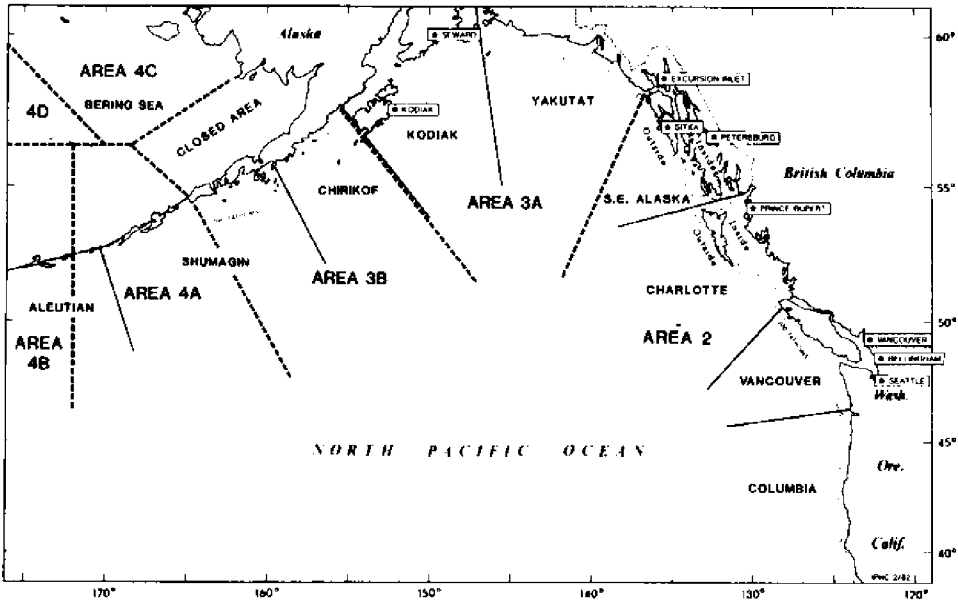

Figure 1. IPHC regions, regulatory areas, and principal sampling ports.

Eggs are spawned in deep water, and eggs and larvae are carried northward and westward in the Pacific Ocean. Juveniles migrate in the opposite direction, presumably to counteract the larval drift and to replenish the adult population (Skud 1977). The species exhibits sexual dimorphism in growth, maturity, and mortality, with females growing to larger size and older age.

Several fisheries affect the Pacific halibut population. A longline (hook-and-line) fishery on adults has operated continuously since the 1880s. Bell (1981) provides a good description of the early fishery and its development to the present. Fixed-hook gear has been most prominent in the longline fishery, with hooks attached to the groundline with gangions at a fixed hook-spacing. The proportion of other types of longline gear (snap and automatic-baiting gear) has increased in recent years, because these can be used with a smaller crew to reduce fishing costs. The availability of easier-to-use gear and the advent of limited entry or reduction in fishing seasons in fisheries for other species such as salmon has resulted in a great increase in the number of vessels fishing for halibut. By 1983 this increase in fishing effort had reduced the season length to five days in southeastern Alaska and seven days in the Gulf of Alaska, with further reductions likely in 1984.

Incidental fisheries also have a large impact on Pacific halibut and include foreign, domestic, and joint-venture bottom trawling, shrimp trawling, and crab fishing with pots. Halibut caught with these gear types are not allowed to be retained, but mortality from capture has resulted in estimated annual losses of 10 to 20 million pounds. Because the halibut caught incidentally are generally small fish aged one to six years, the loss affects the amount of fish available for commercial longline catch. Recently, incidental catch losses have accounted for 30 to 50 percent of the estimated total surplus production.

Sport fishing for halibut has become increasingly popular, with a current annual coastwide catch of at least one million pounds (IPHC 1982). IPHC intends to monitor this rapidly increasing fishery closely.

IPHC has managed the Pacific halibut resource since about 1932, with responsibilities for both research and regulation. Principal IPHC regions and regulatory areas are shown in Figure 1. Its regulatory activities have included imposition of catch limits, time-and-area closures, minimum size limits, licensing of vessels, gear restrictions, and other controls (IPHC 1978).

The North Pacific Fishery Management Council in the U.S. has responsibility for developing management plans for many fisheries in the Gulf of Alaska and the Bering Sea, and has been instrumental in developing restrictions on incidental catch of halibut. The Council may also develop a limited entry program for the United States halibut fishery. The Department of Fisheries and Oceans serves a similar role in Canada.

Catch and Effort Sampling

A description of the collection and processing of catch and effort statistics used by IPHC is given by Myhre et al. (1977), along with detailed catch and effort information since 1929. The estimation framework and methods of combining catch and effort data over geographic regions are given by Quinn et al. (1982), together with reference to data collection systems of other organizations.

The collection of catch and effort data is directed toward two goals: recording the total amount of fish caught, and developing estimates of catch per unit of effort (CPUE) as an index of population abundance. The first goal is achieved through the requirement by other agencies that all fish processors fill out a fish ticket containing catch and price information for each landing of fish. All fish ticket information is eventually collected by IPHC personnel.

The second goal is achieved through the requirement that all fishermen log their daily catch, effort, and location of fishing. Not all information from logbooks can be collected or used, because there are too many fishermen, many in remote locations, and often the information provided is inadequate. Sampling of catch and effort data is necessarily opportunistic: IPHC personnel stationed at ports where a large number of vessels land fish attempt to obtain as many logs as possible. Figure 1 shows many of these ports. At present, only logs from vessels with a fixed hook spacing are used in the CPUE index, but logs are collected from other gear types as well. Effort information is standardized based on the spacing of hooks. Currently, usable log information for the CPUE index is sampled from 25 percent of the total catch in Canada, 14 percent in southeastern Alaska, and 30 to 40 percent in the Gulf of Alaska and Bering Sea.

CPUE is estimated from catch (C_i) and standardized effort (E_i) from each logbook (i) using a ratio estimator (Quinn et al. 1982)

$$\widehat{CPUE} = \Sigma C_i / \Sigma E_i$$

Total catch (C) is known from fish processor records, and total effective effort (E) is estimated by

$$\hat{E} = C/\widehat{CPUE}$$

The distribution of CPUE is frequently skewed in fisheries where a few fishermen catch a larger quantity of fish than the majority. Furthermore, the estimator of total effective effort has CPUE in the denominator, which makes its distribution uncertain. Thus, care must be taken when making statistical inferences about CPUE or total effective effort.

The principal assumption regarding CPUE is that catchability, the probability of catching a fish with one unit of effort, is constant over space or time. CPUE is a valid index of fish density when this assumption is true, in the sense that its large-sample estimator shows the same trend as density. If sample size is not large, then the variability in CPUE may still preclude its utility as an index. For Pacific halibut data, one study suggested that if the coefficient of variation of CPUE exceeded 7.5 percent, then the sample data were inadequate (Quinn et al. 1982).

One problem with CPUE is that areas of fishing concentration may shift over time. The CPUE index will be biased in this case, unless fishermen distribute themselves geographically in relation to fish density. One solution to this problem is to stratify CPUE data by region and to weight each CPUE by the bottom area occupied by the population (Quinn et al. 1982). However, a comparison of effort-weighted and area-weighted CPUE's using Pacific halibut data showed no essential differences in trends, suggesting that this problem may not be major.

Another problem with interpretation of CPUE data involves the entry of substantial numbers of new fishermen into the Pacific halibut fishery. Not only are many of them inexperienced, they often fish with smaller vessels using snap-on gear in different areas than the more experienced fishermen using fixed-hook gear and larger vessels. Several problems with the analysis of CPUE data have resulted from this increased effort. First, the length of the season has become substantially shorter in most regions. The effect of a shorter season may be to increase CPUE due to the aggregation of fish in spite of local depletion of the population. Secondly, problems of gear competition, with more vessels operating, would act to lower CPUE. Third, the relative amount of catch due to fixed-hook gear has decreased, especially in southeastern Alaska, increasing the variability in CPUE. A study to determine the standardization factor for snap-on gear has been completed (Myhre and Quinn, 1984) showing that fixed-hook and snap-on gear have equal efficiencies for catching Pacific halibut. However, results from logbook data have not been consistent among years, regions, or months, or with experimental studies. Thus, a pressing concern for IPHC is to develop a set of selection criteria for logbook data to assure the quality control of information.

Even if the former three problems are dealt with, the assumption of constant catchability is subject to question. Environmental, ecological, or biological factors are probably involved in the response of fish to hook-and-line gear and the probability of the target species, such as halibut, being captured in the presence of other species. For Pacific halibut, substantial evidence suggests that catchability is not constant over time or area. Recently, estimates of coastwide halibut abundance have increased about 5 percent per year, while estimates of CPUE have increased 10 to 20 percent per year. An analysis of CPUE data using a delay-difference model (Deriso 1980; Deriso, unpublished) produced annual estimates of catchability, which vary considerably over time (Figure 2), especially in recent times. An example of potential changes in catchability in Canada is currently under study. Dogfish populations are currently at high levels, while CPUE of halibut has not increased, in contrast to other areas. If

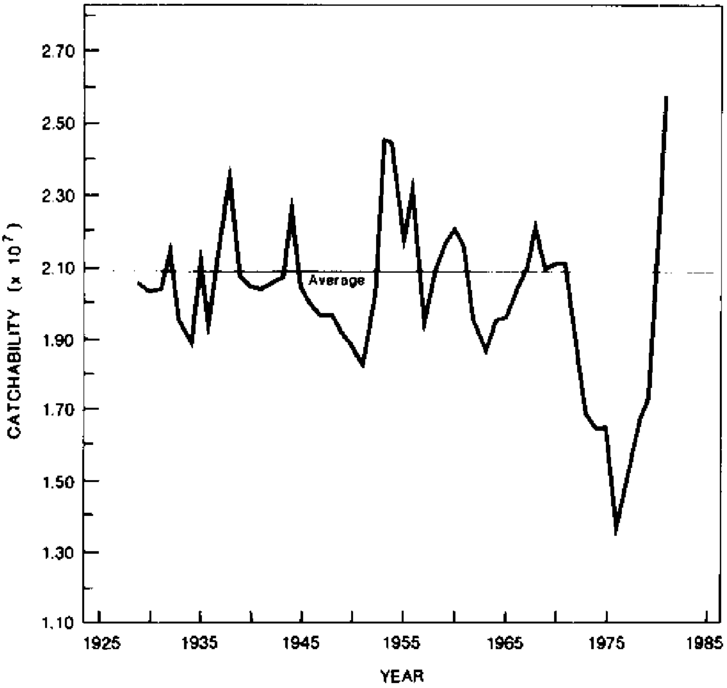

Figure 2. Estimates of annual catchability based on application of the delay-difference model to setline catch and effort data for halibut of the northeastern Pacific Ocean.

dogfish are caught by the gear before the gear reaches the bottom, then CPUE of halibut is underestimated. Other potential effects of other species on halibut CPUE, such as feeding satiation or niche separation, are not well understood. Thus, interpretation of CPUE as a measure of abundance must be made with caution.

Survey Sampling

An alternative method to commercial fishery statistics for monitoring abundance is to design scientific surveys of the population, generally using a collection of stations, grids, or transects over a fishing ground or region of interest. These surveys can be classified by life-stage and/or purpose: eggs and larvae, juvenile, adult, spawning ground, feeding ground, tagging, gear testing, etc. Surveys using trawl gear are frequently used for monitoring abundance. A comprehensive volume of papers related to trawl survey design and analysis has been completed (Doubleday and Rivard 1981). Trawl surveys for Pacific halibut juveniles are described by Best and Hardman (1982). Longline surveys for Pacific halibut adults are described by Hoag et al. (1980).

Interestingly, only one egg and larvae survey has been carried out by IPHC, and that was in the 1930s (Thompson and VanCleve 1936, Skud 1977). These surveys are quite expensive and take many years to complete. Furthermore, eggs and larvae are not easily found, because they are carried great distances in deepwater currents. Timing of spawning may vary annually, and in some areas such as British Columbia spawning concentrations are difficult to find. If the study could be properly designed and money were available, a new survey of eggs and larvae would be extremely helpful in understanding current population dynamics of halibut.

Trawl surveys of juvenile halibut have been conducted since 1963. IPHC has annually surveyed from five to ten major regions from Canada to the Bering Sea. Trawl gear is selective for small fish (ages one to six) and hence is preferable to longline gear for surveying juveniles. Some regions have offshore stations, which are surveyed with trawls of 90 mm mesh for 30-minute tows, and others have inshore stations which are surveyed with trawls of 32 mm mesh for 15-minute tows. The major purpose of the juvenile survey is to forecast future adult abundance, with subsidiary purposes of determining growth, sex and age composition, and migration (Best and Hardman 1982).

The major problem with juvenile surveys is the tendency of juveniles to aggregate. About 80 percent of fish species are found in schools as juveniles and 20 percent continue to school as adults (Burgess and Shaw 1979). Adult halibut are probably more territorial and evenly distributed than juveniles and hence are easier to sample. CPUE from trawl gear is actually a measure of concentration rather than abundance, because the data generally do not include search time in fishing effort (Quinn 1980); therefore the results for schooling juveniles are highly variable. Furthermore, concentration of juveniles may vary over season, time, and region, reflecting the distribution of temperature, patterns of deepwater currents, and probably other environmental conditions (Best and Hardman 1982). These factors are difficult to handle in experimental design. IPHC has attempted to account for this problem in the Bering Sea, where juveniles are sampled on the shallow flats. Because the concentration appears to be temperature-dependent, sampling on the flats is continued in one direction until no juveniles are found (Best and Hardman 1982). Still, the interpretation of trawl CPUE data remains problematic due to variability.

Another problem with juvenile survey data is that the estimates may not be a reliable forecast of future abundance. In Figure 3, juvenile CPUE in the Bering Sea and the Gulf of Alaska is plotted over time. The median age of survey juveniles is about three years. Hence, these estimates should be correlated with the estimated number of eight-year-olds five years later. This estimated number, which is fairly accurate except for the last few observations, is derived from updated cohort analysis (Quinn et al. 1984) and is plotted in Figure 3 over time. Contrary to intuition, there is a negative, if any, correlation for either region between survey CPUE and abundance (Table 1). If the estimates of eight-year-olds are not lagged, the correlations are significant and positive (Table 1). These correlations are biologically difficult to interpret. Perhaps availability of fish over all ages may be affected by environmental conditions, and thus catchability of both longline and trawl gear would be affected over time. Due to problems of this sort, a thorough investigation of the IPHC juvenile survey is being conducted by C. Schmitt (M.S. Fisheries thesis, University of Washington, in preparation).

The adult stage of halibut has been sampled in two index regions: the Kodiak region in the Gulf of Alaska and the Charlotte region in Canada (Figure 1). The first set of surveys was completed in 1963–1966 and included other regions as well, but the surveys were discontinued.

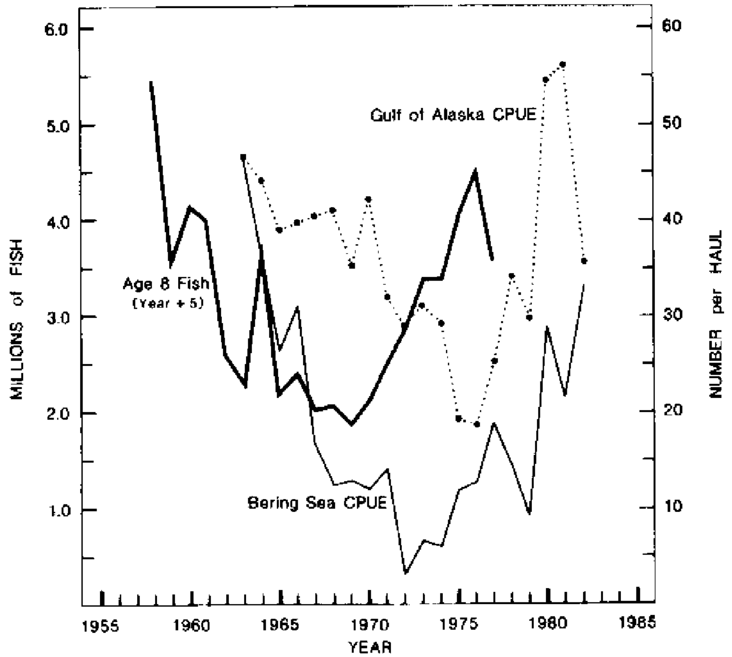

Figure 3. Survey CPUE (number per haul) in the Bering Sea and the Gulf of Alaska and estimated number of age-eight fish five years later from cohort analysis.

Table 1. Spearman rank correlations of survey CPUE's in the Bering Sea (BS) and Gulf of Alaska (GA) with estimated number of eight-year-olds (N8) from cohort analysis. The number of eight-year-olds is lagged by five years in the first analysis to equate year-classes among the data sets. The number of eight-year-olds is unlagged in the second analysis to suggest catchability effects.

	FIRST ANALYSIS (Lagged)	SECOND ANALYSIS (Unlagged)
Years of Survey Index	1963-1977	1968-1982
Years of Cohort Estimates	1963-1982	1963-1982
Correlation of BS and GA (P- value)	0.52 (.023)	0.61 (.002)
Correlation of BS and N8 (P- value)	−0.11 (.347)	0.83 (.001)
Correlation of GA and N8 (P- value)	−0.60 (.009)	0.62 (.002)

The need for an alternative estimate of abundance was reaffirmed by IPHC during the population decline of the 1970s, and the Kodiak and Charlotte surveys have been conducted almost every year since 1976 (Hoag et al. 1980). In 1982, the survey system was expanded to include the Shumagin and Southeastern Alaska regions as well. The survey is standardized by using only fixed-hook longline gear, fishing the same stations each year, and keeping the same setting and hauling schedule, bait type and ordering on hooks and, when possible, time of year. The survey has the primary goal of obtaining an unbiased index of CPUE that is not influenced by distribution of fishing effort or other gear-related factors. Furthermore, the survey obtains information on the size, age, and sex composition of catchable fish, including those below the minimum size limit for commercial catches. Sex composition of the commercial catch cannot be obtained, because the fish are eviscerated at sea.

Some of the same problems of catchability that affect commercial CPUE will also affect survey CPUE. Furthermore, the amount of survey fishing effort is far lower than in the commercial fishery, and the lower sample size undoubtedly increases variability in estimated CPUE. On the other hand, the careful design of the survey eliminates many other catchability factors, so that survey CPUE may turn out to be a better index of regional abundance.

The available data show promise in determining characteristics of the catch, although the short time series of survey data at present precludes substantial analysis. In the Charlotte survey, CPUE is much lower than commercial CPUE (Figure 4), because part of the survey extends beyond commercial fishing grounds. Recently the CPUE for both survey and commercial CPUE's have been somewhat lower than in the 1960s, and both data sets since 1976 have shown no trend in population abundance. Average weight of fish in the survey catch has been between 25 and 35 pounds and the percentage of females has been roughly 80 to 90 percent by weight. The percentage of females by number is lower, about 60 to 70 percent, because average female weight is higher. The sex information has been particularly useful in explaining the low CPUE in Charlotte in recent times. Analysis of survey and commercial catch data has suggested that a change in the minimum size limit in 1973 shifted effort from grounds with smaller male halibut to grounds with larger female halibut, with an impact on reproductive value of females (Deriso and Quinn 1983). Without the survey data, this hypothesis would have been difficult to examine.

In the Kodiak region, survey CPUE and commercial CPUE have been fairly close over time, and both have increased greatly since 1976 (Figure 5). Average fish weight of 40 to 50 pounds is higher than in the Charlotte region and reasonably constant over time. The percentage of females is about 80 to 90 percent by weight, similar to the Charlotte survey.

Sampling for Age Composition

A comprehensive volume of papers related to sampling of commercial catches for age composition has been completed (Doubleday and Rivard 1983). A thorough review of the sampling of commercial Pacific halibut catches is found in Quinn et al. (1983a), and a shorter summary of current sampling design is presented in Quinn et al. (1983b). The primary goal of these sampling programs is to analyze the catch by age, which then can be used to infer the population age structure (Quinn et al. 1984). The primary sampling approach for age composition is two-stage sampling, wherein a length frequency sample of fish is taken in

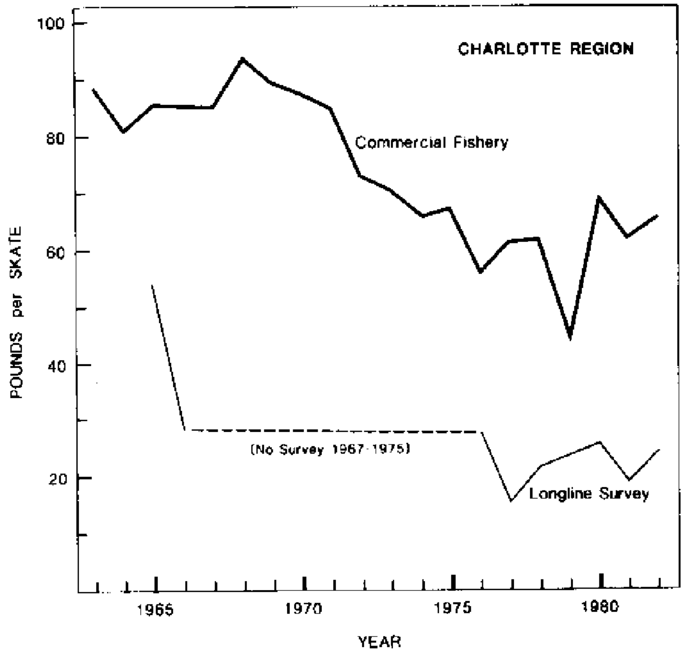

Figure 4. CPUE in pounds per skate in the commercial fishery and the longline survey, Charlotte region.

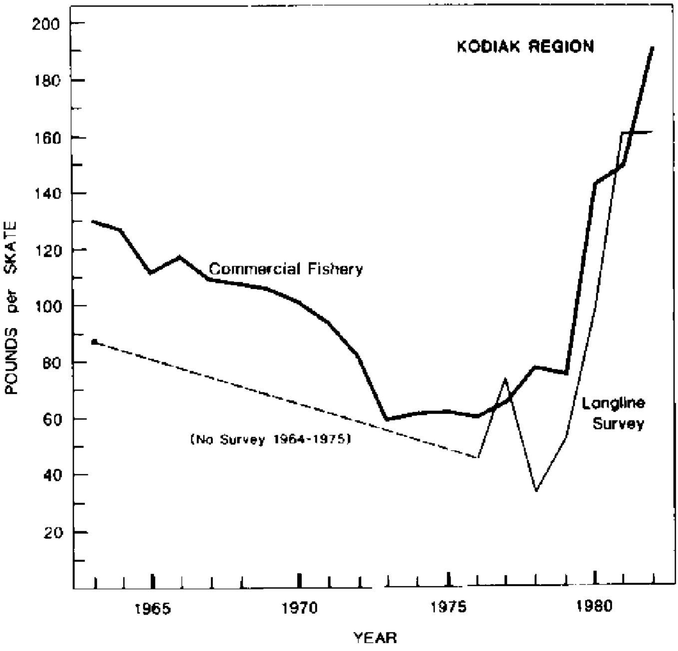

Figure 5. CPUE in pounds per skate in the commercial fishery and the longline survey, Kodiak region.

the first stage, and a subsample of fish from the length sample is taken for aging in the second stage.

For Pacific halibut, the sampling design has been carefully constructed. Sampling is done at ports that receive a large portion of the catch (Figure 1). There are two important sampling considerations at a port: which vessels to sample and how many fish from each vessel to sample. Vessel selection follows a stratified random design, in that vessels are chosen randomly but according to strata based on landing size. Smaller landings are generally associated with smaller vessels which may fish different grounds than larger vessels. Samplers are able to determine the size of landing before sampling, because a vessel makes a "hail" upon arrival in port.

The sampling of fish from a vessel follows a systematic random design. Halibut are unloaded from a vessel in large cargo nets or slings. A sampler throws a die and samples all fish from the sling with that starting number and every sixth sling thereafter. Systematic sampling distributes effort throughout the landing and prevents sampler bias. The sampling rate is 1/18 (5.6 percent) of the fish from vessels landing at least 1,000 pounds at sampled ports, which translates into an overall sampling rate of 3 percent when data from unsampled ports and smaller landings are added in (Quinn et al. 1983a).

The mechanics of sampling are quite simple. The sampler opens the left auditory capsule of a halibut, removes the otolith (earbone), and stores it in a container. No other measurements are taken, because the length and weight of the fish can be estimated from the weight of its otolith. In the IPHC laboratory, a subsample of otoliths for determination of age is randomly selected by computer in proportion to the frequency of estimated lengths of the fish.

Estimation of age composition is based on three principal assumptions:

1. That the estimation of fish length and weight from otoliths is unbiased;
2. That the sampled length frequency is representative of the catch;
3. That the subsample for aging is chosen randomly.

First, catch in numbers C is estimated by

$$\hat{C} = T/\overline{W},$$

where T is the weight of all vessel landings in the region of interest and $\overline{W}$ is the average of the predicted weights of otoliths from samples taken in the region. Although $\overline{W}$ is in the denominator of $\hat{C}$, the variance of $\overline{W}$ is generally small, obviating distributional problems. Secondly, the proportion of age k fish in the catch θ_k is estimated by

$$\hat{\theta}_k = \Sigma_j \hat{\alpha}_j \hat{\theta}_{jk},$$

where α_j is the proportion of fish in length category j from the first stage of sampling, and $\hat{\theta}_{jk}$ is the proportion of age k fish in length category j from the aging subsample. Finally, catch at age C_k for the region is estimated by

$$\hat{C}_k = \hat{C}\hat{\theta}_k$$

Other formulae for age composition, variance estimates, methods of combining data, and sample size requirements are detailed in Quinn et al. (1983a). For Pacific halibut, at least 600 otoliths are collected from each month-region stratum, if possible, for a reasonable estimate of age composition.

A potential problem with IPHC's sampling program for age composition is the reliance on prediction of fish length and weight from otolith weight. The predictive relationships were developed with data collected in the past and may not apply to certain regions, seasons, or years. Consistent enhancement of the data base for developing or monitoring predictive relationships is essential for the validity of the procedure, but the collection of these data is often difficult to carry out in practice.

Logistical problems also arise in translating the sampling design into practice. The distribution of landings changes over time, making it difficult to obtain sufficient sampling in certain regions or seasons. Landing operations may change at some ports, making it difficult to sample at the specified rates, if at all. Fortunately, the current sampling design for Pacific halibut is fairly easy to carry out, so these problems are considered minor. In other fisheries, there are substantial sampling problems in practice (Doubleday and Rivard 1983).

Finally, the validity of age-determination techniques is an important consideration. For many fish species, no such valid technique has currently been developed or there is controversy over the appropriate technique to use (E. Best, IPHC, personal communication). Although errors in age estimation are not considered to be a major problem for Pacific halibut except for older ages, an oxytetracycline validation study is in progress to assuage controversy.

The major scientific problem with sampling for age composition is the estimation of population size from catch-age data. Hoag and McNaughton (1978) applied cohort analysis to catch-age data to estimate historical abundance of Pacific halibut and they give a good review of its assumptions and limitations. Historically, abundance and CPUE show the same trends over time, although there are short-term discrepancies (Hoag and McNaughton 1978; Deriso and Quinn 1983; Quinn et al. 1984). The problem of obtaining recent estimates of abundance by updating cohort analysis has been studied by many authors (Doubleday 1976; Quinn et al. 1984; several papers in Doubleday and Rivard 1983), but several unresolved problems are still present. A new method of using auxiliary information (Deriso, Quinn, and Neal 1985) resolves some of these problems.

Conclusions

This paper has reviewed the assumptions, limitations, and application to Pacific halibut data of three sampling techniques for determining an index or estimate of abundance. Sampling by the use of data on catch and effort involves issues of constancy of catchability, of fish and vessel aggregation, and of data limitations. Survey sampling involves these issues as well as those of scope and limitations of survey design. Sampling for age composition involves issues of the validity of sampling design, of aging validation, and of statistical estimation. No one technique can be judged superior to another, because each has its peculiar strengths and limitations. Cross-validation is probably the best way to establish confidence in these three sampling techniques.

Acknowledgments

I thank Dr. O. Mathisen for inviting me to give this talk and the IPHC scientific staff for commenting on the paper. C. Doyer typed the paper and K. Exelby prepared the figures.

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STOCK ASSESSMENT AND NEW EVIDENCE OF DENSITY-DEPENDENCE

Richard B. Deriso

The United States and Canada have jointly managed the Northeastern Pacific and the Bering Sea halibut fishery since 1923 under treaty powers granted to the International Pacific Halibut Commission (formerly called the International Fisheries Commission). The sole objective of this management has been the maximization of sustained yield (Halibut Convention of 1953; the word "sustained" was changed to "optimum" in 1979). As with most fisheries, sustainable yields have not been possible, as seen in Figure 1. Setline catches range from a high of 71.6 million pounds in 1960 to a low of 21.3 million pounds in 1974. Changes in annual catches reflect changes in catch quotas set by IPHC, which in turn are based on changes in the productivity of the stock. IPHC Director D.A. McCaughran, speaking about current management objectives, states, "We still seek to maximize sustainable yield, but the emphasis now is on sustainable and not necessarily maximum. We try to avoid causing a boom and bust type fishery, as has occurred in the past."

Annual surplus production (ASP), a basic measure of stock productivity, is defined as the amount of catch that can be taken in a given year without changing the biomass of the stock left at the end of the year from biomass present at the beginning of the year. It is estimated by adding catch in a given year to the annual change in estimated stock biomass. In recent years, IPHC has relied heavily on ASP estimates for the establishment of catch quotas. When catches are set at a level less than ASP, such stock declines as the one that occurred in the 1960s (Figure 2), could not take place (by definition of ASP).

A goal of IPHC in recent years has been to rebuild the population. This is being accomplished by setting annual catches at about 75 percent of ASP and, thus, allowing 25 percent of the production to accumulate in stock biomass. An important task in our annual assessment of halibut stock is, thus, to provide a reliable estimate of ASP. Methods we use for this calculation are discussed briefly in this paper with references given for more detailed explanations.

Control of halibut abundance over intermediate time periods (say ten years) is easily accomplished provided ASP is known reasonably well. We need not know anything about population regulatory mechanisms such as density-dependent growth and survival. However, to control productivity of the resource, and in particular to maximize yields, is much more difficult. Management goals to increase stock size might actually decrease the productivity of the resource if density-dependent mechanisms act to decrease recruitment or growth when stock sizes increase. In this paper I present some of the data available on density-dependence in the population dynamics of halibut and examine what consequences, if any, this has on current management philosophy.

There are numerous aspects of the stock assessment program for Pacific halibut that will not be discussed in any detail here. Programs to monitor halibut abundance trends are

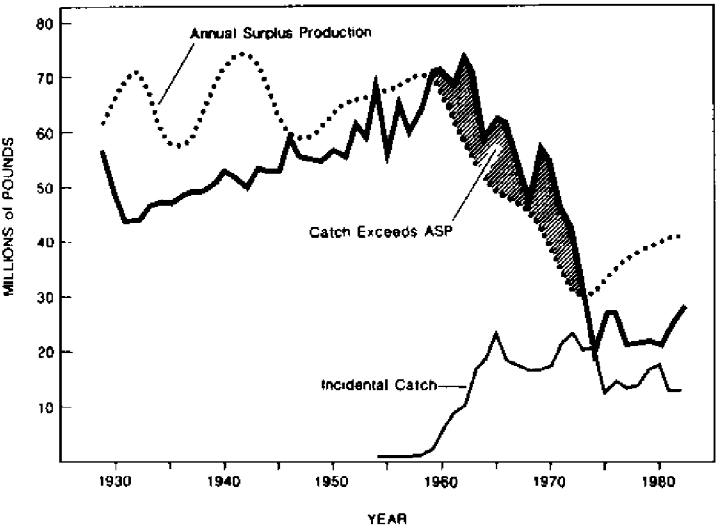

Figure 1. Halibut setline catch, incidental catch, and annual surplus production (ASP), 1929 1982.

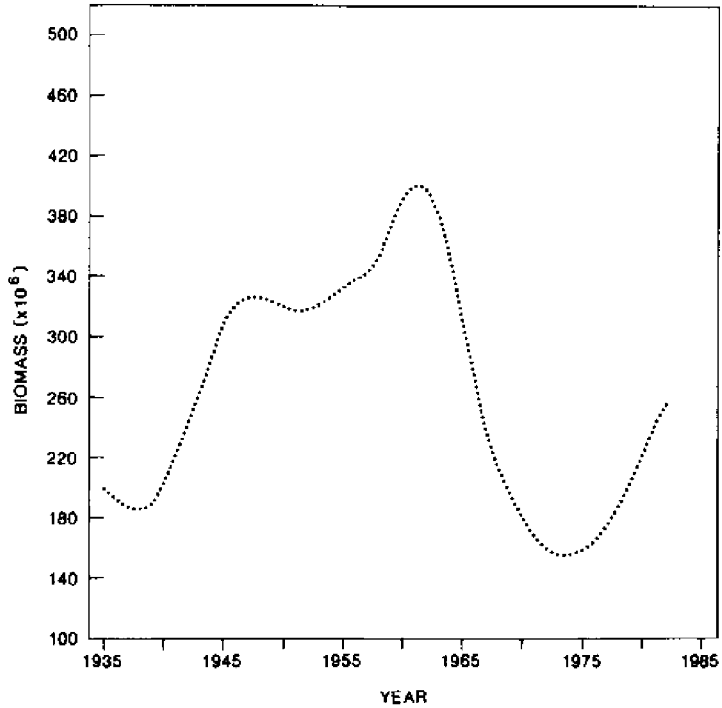

Figure 2. Smoothed estimates of exploitable biomass of Pacific halibut from cohort analysis. Units are given in pounds.

discussed by Quinn in Part I of this report. Other assessment topics are discussed in the IPHC Annual Report series, which feature current research programs undertaken during the particular year by IPHC scientific staff.

Stock Assessment Methods

Two methods are used at IPHC to estimate abundance and productivity of the halibut stock. The first method uses total catch (in weight) and fishing effort data as state variables in a delay-difference population model (Deriso 1980). The second method uses catch-at-age data in numbers of fish in a cohort analysis procedure for cohorts that have already passed their fishable age span (Pope 1972) and, for recent cohorts, a catch-at-age regression method which uses fishing effort to help stabilize estimates (Quinn et al. 1984 for a simplified version, and Deriso et al. 1985 for the results reported here). Both procedures provide similar estimates of ASP over the past fifty years) Quinn et al. 1984).

Catch quotas are set by IPHC for each of the regulatory areas shown in Figure 1 (in Part I of this report). In fact, subarea quotas are also set: in 1983 nine different subareas were given commercial halibut catch quotas, each with individual season dates for fishing (IPHC 1983). This cumbersome regulatory scheme allows IPHC a mechanism for spreading fishing over the major range of the single halibut stock. Estimates of ASP by subarea are currently made by first partitioning total stock abundance into subareas based on relative CPUE (basically using the method described in Quinn et al. 1982) and then calculating individual subarea ASP as the change in subarea abundance each year plus catch from the subarea.

Results and Discussion of Estimates From Catch-at-age Analysis

Commercial catch, annual surplus production, and incidental catch (largely by-catch from trawlers) are shown in Figure 1 for the years 1929 through 1982. Historical changes in stock biomass (Figure 2) can be related to changes in Figure 1 between levels of commercial catch and ASP. Prior to 1960 stock abundance shows a generally increasing trend during the same period that catches were held below ASP. Between 1960 and 1974 both abundance and ASP dropped precipitously. The stock decline can be attributed to the fact that commercial catch exceeded ASP during those years, while the decline in ASP is less clear. Certainly the rise in incidental catches is part of the explanation for the drop in surplus production available for commercial harvest. An analysis of this period of decline by Quinn et al. (1984) attributes the decline in production to essentially two interrelated factors: incidental catches and decreased stock abundance. The latter factor affects production, since a decreased stock produces fewer recruits if survival of the young is relatively constant.

Figure 3 provides data which support a hypothesis of reduced number of recruits into the halibut adult stock after 1955. This figure shows estimated numbers, biomass, and

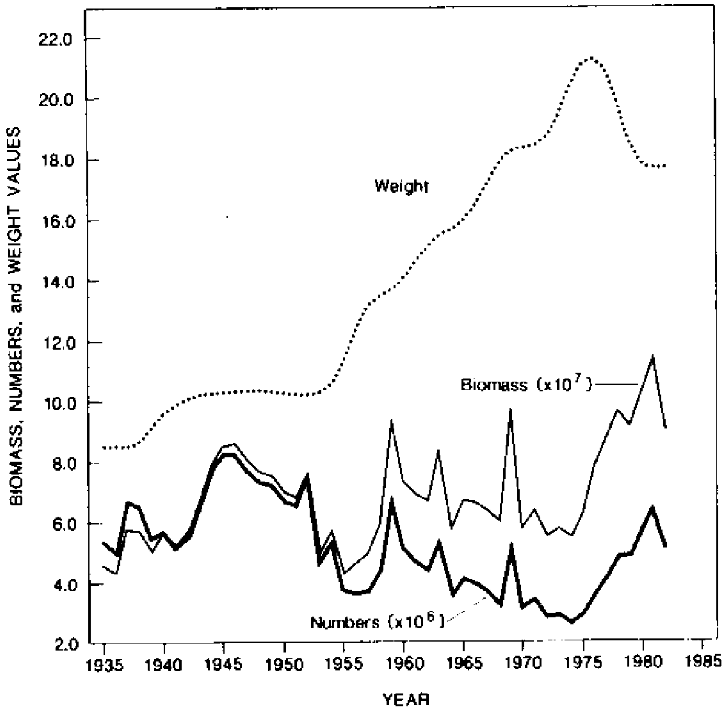

Figure 3. Biomass, numbers, and average weight of eight-year-olds. Numbers and biomass estimates from cohort analysis adjusted upward 30 percent to account for incidental catch losses. Biomass and weights are given in pounds.

smoothed average weight of eight-year-olds (the recruits) every year since 1935. These estimates of biomass and numbers are adjusted upward by 30 percent since 1960 to approximately account for pre-recruit mortality due to incidental catch and, thus, indicate natural changes in recruitment strength. The average factor was used primarily because the poor quality of incidental catch data does not justify more precision. Adjusting the estimates is especially important for the spawner-recruit analysis shown later. Biomass and numbers of eight-year-olds both were low in the mid-1950s, which adversely affected stock productivity for another ten years or so. Numbers of recruits continued to decline irregularly until 1974 with some recovery evident since then. Biomass recovered much sooner and from 1960 to 1975 fluctuated around the long-term average. Since 1975 biomass of recruits has increased substantially. To a large extent the stability of biomass between 1960 and 1975 is due to major increases in the average weight of eight-year-olds. These average weights in Figure 3 are based on smoothed estimates from catch statistics and may be somewhat affected by sex-ratio in the catch (Deriso and Quinn 1983) and other sources of bias. However, the change in weight is so large that a fundamental biological shift has likely occurred.

Recruitment does not decrease since 1978 as we would expect if both survival and growth of the young were relatively constant during those years. If anything, the fact that the very large year-classes apparent since 1978 have come from low spawning stocks in the early 1970s suggests that production of young is increased at low spawning density. It may also be

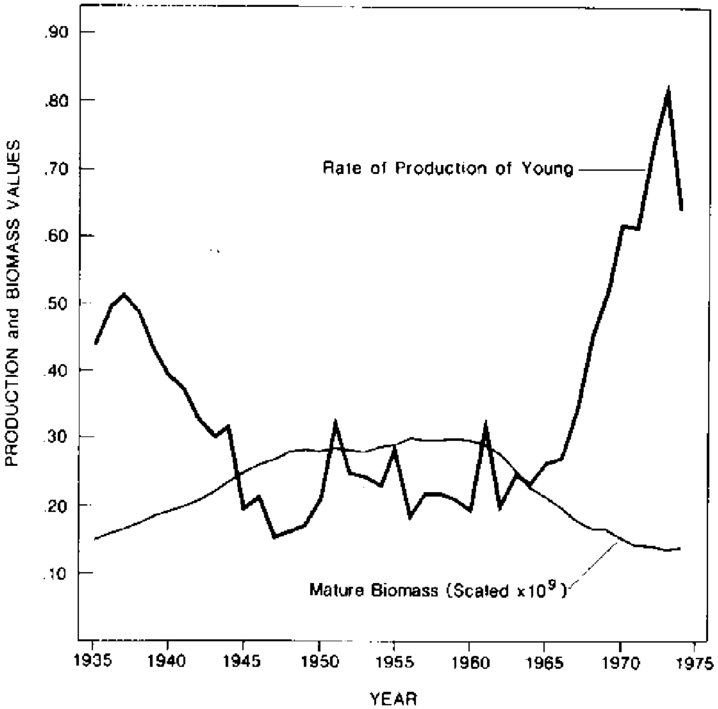

Figure 4. Rate of production of young halibut and spawning biomass estimates given for each year of spawn 1935–1974. Rate of production calculated as the ratio of eight-year-old halibut biomass to the mature stock biomass present in year of spawn. Biomass given in pounds.

that the failure of year-classes to continue increasing in the 1950s, despite large spawning stocks, indicates that high spawning densities suppress the production of young. These notions of density-dependence are supported by Figure 4, which gives annual rates of production of the young (biomass of eight-year-olds divided by biomass of the sexually mature stock) and mature stock biomass by year of spawning. The index of spawning here is the sum over age of age-specific mature biomass using the maturity schedule in Quinn (1981). Production rates are high from 1935 to 1943 and from 1967 to 1974, when mature stock biomass was low and vice-versa for the years 1944 to 1966.

If we focus in Figure 4 on the 1944 to 1965 time period analyzed in Quinn (1981) and in Deriso and Quinn (1983), it is easy to see why both studies supported a hypothesis of density-independent production. What a difference is made by another nine years of estimates! We remain somewhat unsure about recent production estimates as these progeny have been sampled by the fishery for only a few years, but nevertheless it is apparent that production rates have increased. What was originally thought to be an anomaly of high production between 1935 and 1943 now fits nicely into a picture of density-dependence.

A spawner-recruit analysis was made to further examine variations in year-class strength. Figure 5 shows the results of a least-squares regression of logarithms of production rate against mature stock biomass, as recommended in Ricker (1975) for a Ricker spawner-

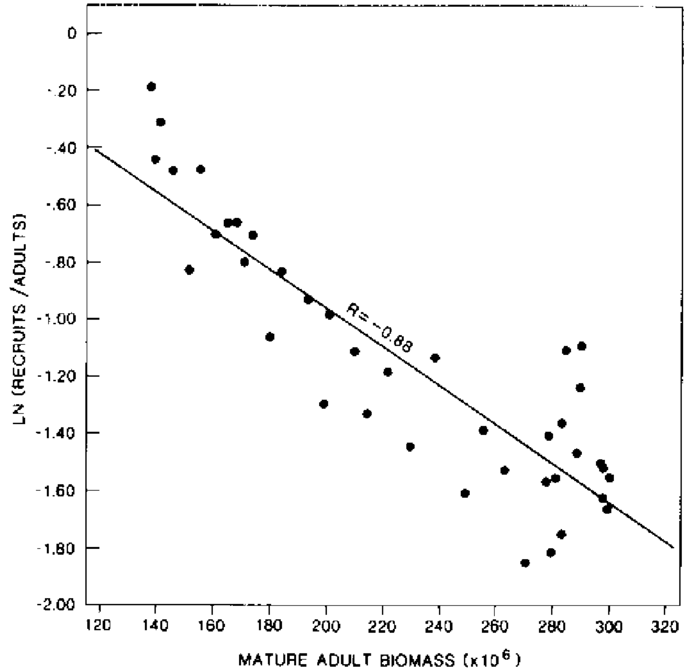

Figure 5. Logarithm of (recruit biomass/mature adult biomass) vs. mature adult biomass. Biomass given in pounds.

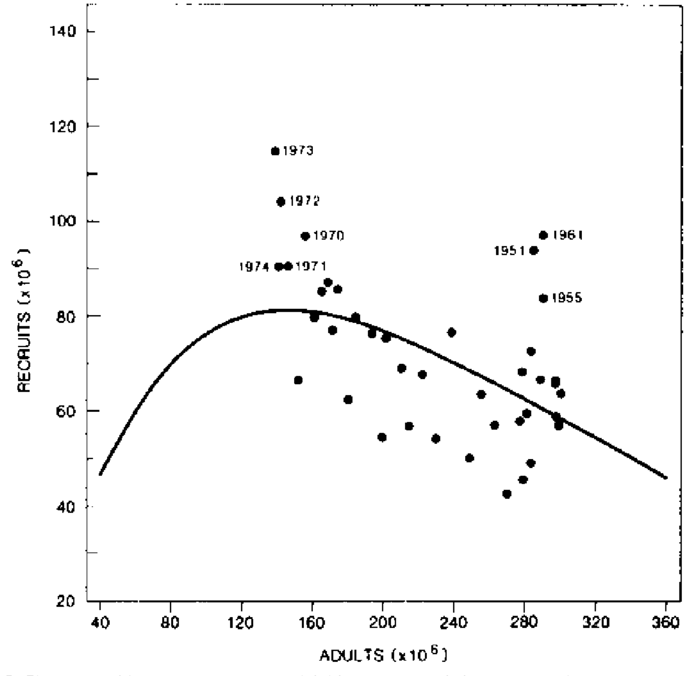

Figure 6. Eight-year-old biomass vs. mature adult biomass, lagged eight years earlier. Year given in year of birth. Units are pounds.

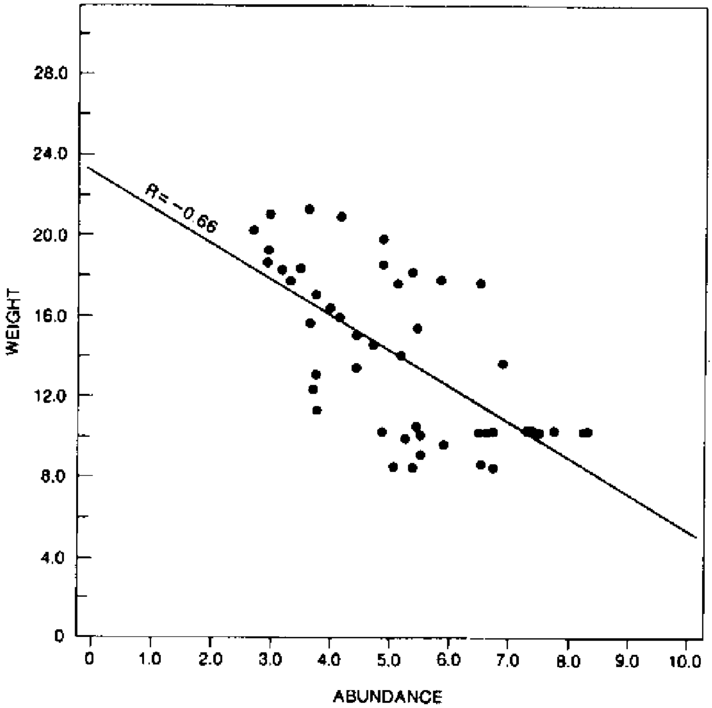

Figure 7. Smoothed average weight of eight-year-olds vs. cohort estimates of number of eight-year-olds (adjusted for incidental catch losses). Weight given in pounds and abundance given in millions of fish.

recruit curve fit. The tight correlation from this regression, R = -0.88, is somewhat misleading though, as my index of spawning stock is surely measured with error and it appears as a component in both the dependent and the independent variables in the analysis. Figure 6 plots recruits versus spawners along with the Ricker curve fitted in Figure 5. Aside from a few (15 percent) large recruit values (year-classes born in 1951, 1955, 1961, 1970, 1972, 1973), the recruitment appears to follow a mildly decreasing trend as stock size increases. Maximum stock recruitment of around 80 million pounds occurs on the Ricker curve for a spawning stock near the lowest seen in our time series (140 million pounds), whereas a potential recruitment of less than 60 million pounds might be expected from the spawning stock estimated to be present today (about 300 million pounds).

Density-dependent growth is suggested by results portrayed in Figure 7. Here, smoothed weight of eight-year-olds is plotted against the number of eight-year-olds from estimates given earlier in Figure 3. The negative correlation, R = -.66, is consistent with a hypothesis that competition between members of a cohort adversely affects their growth rate sometime prior to their age of entry into the fishery. The correlation using unsmoothed data is similar (R = -.67). The dependence of growth on density is of course not proven by this statistical correlation. The increase in growth in recent years could be caused by abiotic or biotic factors quite independent of changes in halibut abundance, or it could merely appear so because of poor weight estimates (since 1962 IPHC has estimated fish weight by extrapolating fish otolith size).

If growth does depend on density, when does it occur during the early life of halibut? Of particular importance to management is how much of the effect is felt after incidental catch losses have occurred. An indirect test of this question can be made using the weight data for eight-year-olds. Such a test was made by assuming that juvenile abundance is proportional to later eight-year-old abundance, corrected for incidental catch mortality (incidental catches occur primarily on halibut younger than eight years of age). This results in the abundance estimates in Figures 3 and 7, and in the correlation (R = -.66) between weight and adjusted cohort abundance. Without adjusting cohort strength for incidental catches, we obtain an estimate of year-class strength after incidental catch losses. The unadjusted abundance estimates were used as additional independent variables in a multiple regression against weight. A tighter multiple correlation is found, R = -.89, suggesting some dependence of growth on density occurs after the primary age of incidental catches. Based on a partitioning of the squared correlations, we can speculate that 44 percent of the variance in weight is accounted for by juvenile abundance, while another 36 percent of the variance is related to year-class abundance as measured after the age of incidental catch losses. Currently we are exploring the use of field measurements of juvenile size for analysis of growth density-dependence.

With respect to management policy, the implications of density-dependent growth and production of year-classes are twofold. First, if population density does prove an important factor in this respect, our concern at IPHC about the continuing high levels of incidental catches of immature halibut would be mitigated to some extent. The loss of reproductive capability in the incidentally caught fish could actually improve the production of future generations of offspring if current stock sizes are on the declining limb of a stock-recruitment curve. On the other hand, if density-dependence operates primarily in the early life-stages of halibut, prior to the occurrence of incidental losses, as suggested by growth results given earlier, then incidental losses represent direct losses of immature halibut available for commercial harvest. A second implication of density-dependent production of young is that the goal of IPHC in recent years to rebuild the stock should be altered if maximizing yield is our primary objective. In its place a goal might be to move the stock nearer its lower range of abundance. Increased variability in production might arise from such a major policy shift, however, and adversely affect the sustainability of current levels of harvest. The evidence does suggest that there is little advantage in any additional rebuilding of halibut stocks.

Results and Discussion of Estimates From Catch-Effort Analysis

In this section results are given from the analysis of data on total catch and fishing effort on Pacific halibut. This provides estimates independent of the age-structure data used in catch-at-age methods. Results are given for regression of CPUE data to three types of population models:

1. A delay-difference model (Deriso 1980) where all random errors in the regression are assumed to occur in the measurement of CPUE as an index of abundance,

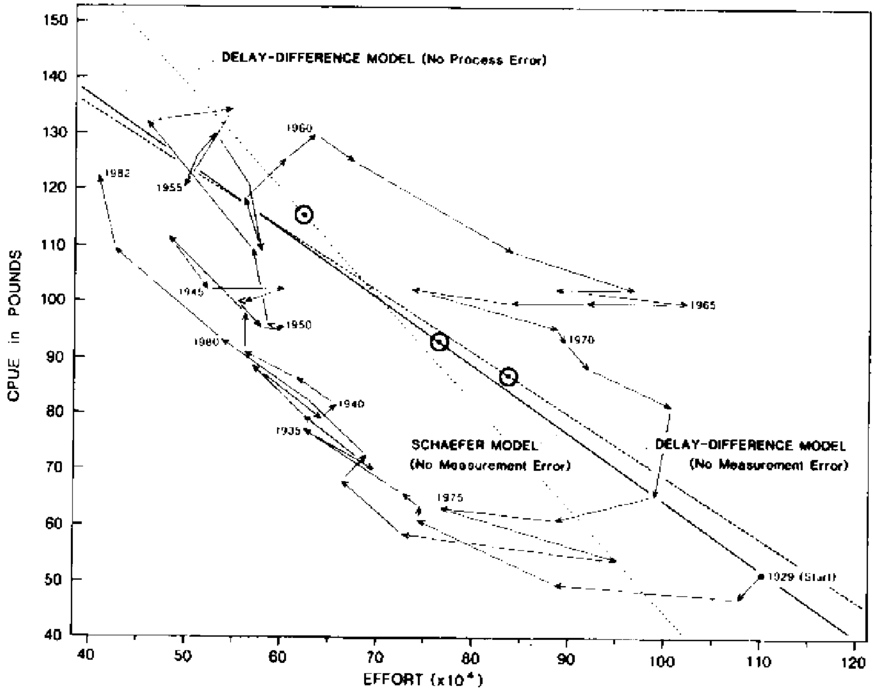

Figure 8. CPUE vs. effort phase plane. Isoclines (straight lines) are equilibrium conditions predicted from three model regressions. Arrows connect the time sequence of observed data, and MSY conditions are identified by points on the isoclines.

2. A delay-difference model where all random errors in the regression are assumed to occur in the population dynamics of halibut (so-called process error, Ludwig and Walters, 1981).
3. A discrete Schaefer model with only process error (Hilborn 1979).

The population models used here for CPUE analysis all have the potential to describe density-dependent population mechanisms. In the delay-difference model applications, a Ricker spawner-recruit relationship is used for the renewal part of this population model. In the Schaefer model, a logistic type (quadratic) function describes production of the stock. Commercial and incidental catches of halibut from the Northeastern Pacific Ocean and the Bering Sea are combined for catch data in the models with effort interpolated upward so that CPUE from setline data equals CPUE in the combined data sets. The models all fit 1929 through 1982 data reasonably well since R>0.90 in all regressions.

An interesting way to view parameter estimates from the model regressions is as isoclines on the CPUE-versus-effort phase plane in Figure 8. The lines drawn for each model define isoclines—the loci of points where the stock would theoretically be at equilibrium should conditions (e.g., fishing effort) be held constant for a number of years. The halibut data clearly do not portray a stock in equilibrium. Rather the arrows show a history of clockwise motion of CPUE values around the phase plane. The changes in halibut data below and

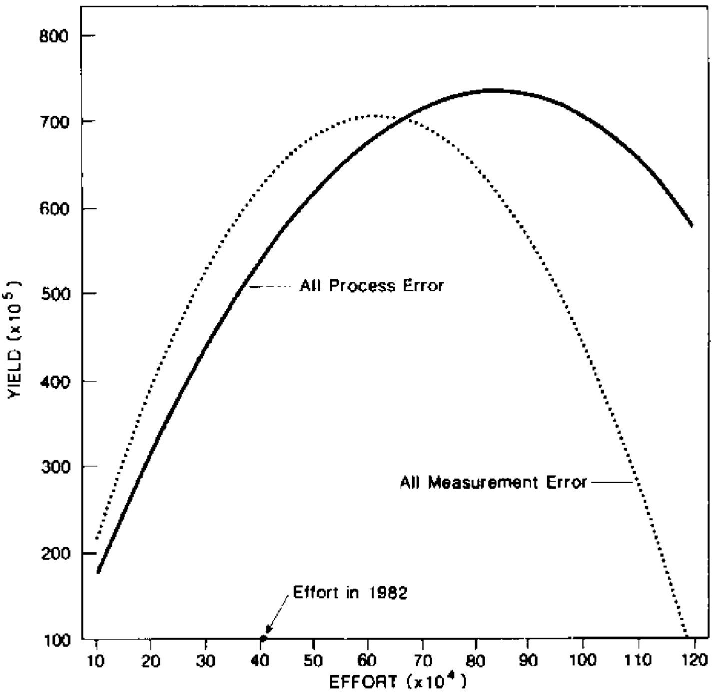

Figure 9. Equilibrium total yield (setline plus incidental) vs. adjusted fishing effort as predicted by two delay-difference model regressions. Yield in units of pounds. Adjusted effort in skates.

above the isoclines are consistent with model predictions: below the isoclines population abundance should increase, and above the isoclines abundance should decrease. Unfortunately, it is not clear whether lowered density-dependence or reduction in fishing effort was responsible for increases in CPUE when it was below the isoclines. These effects are clearly confounded in the figure, since effort was generally declining below the isoclines: conversely, for the declining trend in CPUE for values above the isocline, the effort was usually increasing at those periods. From an experimental point of view, to increase effort in the presence of low CPUE values would generate more contrast in the data and better determine the importance of density-dependent mechanisms in controlling population growth.

All models indicate density-dependence, as seen by the negative slope of isoclines in Figure 8. Maximum sustainable yields are indicated for each of the models by circles on the isoclines. These MSY estimates suggest the stock has never been held at MSY, but rather has oscillated around these points. Current CPUE of 124 (lbs/skate) is near the MSY abundance estimate of 112 (lbs/skate) predicted by the delay-difference model with the all-measurement-error assumption, but yields could be made higher by increasing effort approximately 50 percent (see also Figure 9). MSY fishing effort is even higher for the models with the all-process-error assumption (approximately a 100 percent increase from current levels). These predicted high MSY effort levels produce an increase in yield as shown in Figure 9 of some 25 million pounds from current levels. The marginal return on this additional fishing effort (in terms of additional yield) can be as low as 50 percent of the current catch per unit of effort, according to forecasts of the models with all process error, which suggests that economics plays an important role in any such management decision.

Conclusions

This report provides estimates of density-dependence in the population dynamics of Pacific halibut. Both age-structured data and CPUE data suggest that production of halibut is density-dependent. The implications of these population regulatory mechanisms for management of halibut suggests that there is little advantage to continuing the current goal at IPHC of rebuilding the stocks (if maximizing yield is of primary concern). The effect of increasing yields, and the sustainability and stability of future harvests if yield were increased, are topics not examined here, but they are of primary concern to management and should make interesting subjects for further research.

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