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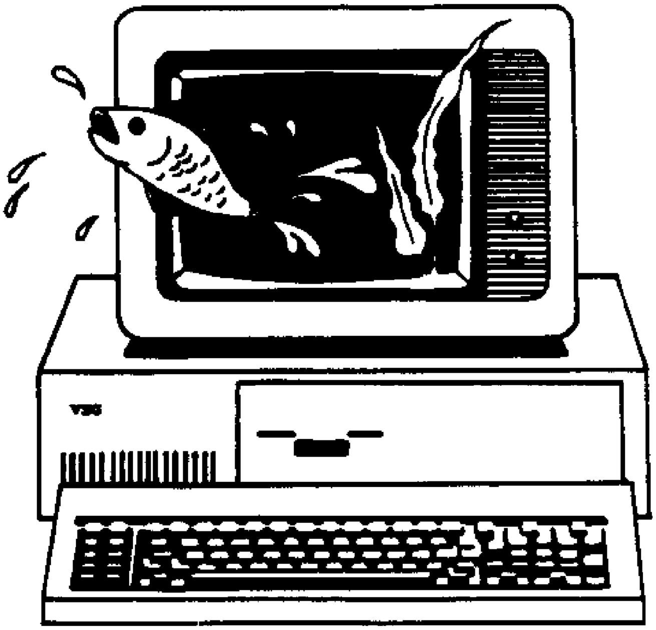
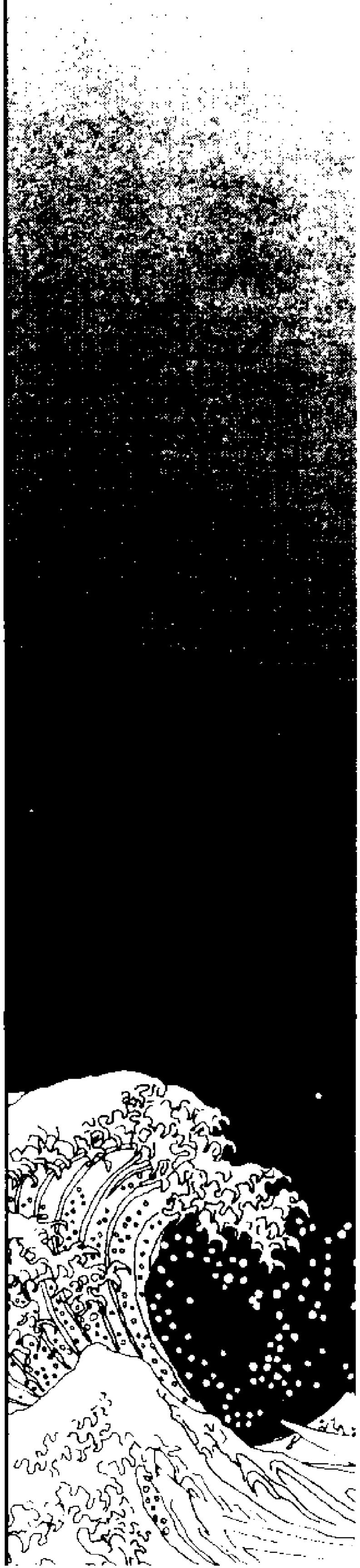


The Application of Artificial Intelligence and Knowledge-Based Systems Techniques to Fisheries and Aquaculture

James D. Palmer, Editor

VSG-89-03



This work is a result of research sponsored in part by the National Sea Grant College Program of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, under Grant No. NA86AA-D-SG042 to the Virginia Marine Science Consortium and the Virginia Sea Grant College Program. The U.S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notation that may appear hereon.

The Application of Artificial Intelligence and Knowledge-Based Systems Techniques to Fisheries and Aquaculture

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This Workshop was supported by the National Oceanic and Atmospheric Administration under Virginia Sea Grant Contract No. 5-29721

Acknowledgments: A special citation is due to Saul Saila for his drive in initiating this Workshop, his effort in preparing material for the final report and his time in providing editorial services for the fisheries sections. Stephen Stewart prepared the aquaculture report materials, circulated these and edited the material in preparation of the final report. Richard Kolf has been ever present in his activity to make this a most successful Workshop and his contributions, both professionally and administratively, have been most laudatory.

October 2, 1989

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The Application of Artificial Intelligence and Knowledge-Based Systems Techniques to Fisheries and Aquaculture

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Abstract

A Workshop on Artificial Intelligence and Knowledge-based systems Applications for the Fisheries Sciences and Management and Aquaculture disciplines of Marine Sciences was held to establish research areas of mutual interest to both groups. A small number of experts was brought together to discuss the pertinent aspects of each discipline relative to the development of expanded computer applications in fisheries sciences and management and aquaculture. The purpose of the Workshop, entitled "KBS Applications in Marine Sciences," was to explore ways in which the considerable body of knowledge developed in these computer related disciplines may be considered for fisheries sciences and management and aquaculture applications.

Summary papers were given from each of the relevant areas and these are included in the Appendices of this report. Recommendations from both areas for research and development activities and support were developed and are presented in this

report. A research protocol for fisheries sciences and management and aquaculture was developed and this protocol is presented.

Major outcomes of this Workshop are that joint research and development activities involving fisheries sciences and management and aquaculture scientists and researchers from artificial intelligence and knowledge-based systems areas should be supported and specific research and development activities encouraged. A summary of the recommendations for joint research and development activities is provided.

Introduction

The use of computers in Marine Sciences has a long history of success. The primary activities associated with the use of computers centers around applications that involve significant amounts of numerical calculations and the use of undersea robots for scientific exploration. As in other areas of scientific inquiry, the role of computers is constantly being evaluated for greater support. One of the more fertile fields of computer applications that was discussed at this Workshop was support from knowledge-based systems (KBS), artificial intelligence (AI), decision support systems (DSS), and expert database systems (EDB) focused on the needs of fisheries sciences and management and aquaculture.

In a prospectus for the development of Knowledge-based Marine Systems, Dr. Saul B. Saila, Graduate School of Oceanography, University of Rhode Island, pointed to the many successful applications of knowledge-based information technology in both industry and the university. Although substantial contributions have been made in the application of this technology, there were few instances of applications specifically aimed at providing assistance in the fisheries sciences and aquaculture.

This Workshop has defined a research protocol for applying advances in knowledge-based systems to the analysis or solutions of problems in fisheries science and management and aquaculture. A major outcome of this Workshop was the determination that a distinct need exists to examine the potential for knowledge-based systems applications in fisheries sciences and aquaculture. This requirement is one that will take advantage of advances in computer sciences and apply these to needs in fisheries sciences and aquaculture.

Fisheries Sciences and Management Recommendations

Summary of Fishery Group Discussion Leading to Proposed Application of AI and Expert Systems

The fisheries sciences and management group convened to discuss the proposed application of AI and expert systems. To provide a framework for the discussion, a flow diagram representing the fisheries biological/decision making cycle was presented and discussed. This served as a context for the group's deliberations. This diagram appears in Figure 1.

It was noted that all elements of the model represented by the flow diagram are affected by environmental uncertainty except for the fish manager's decision itself. Considerable effort is currently expended on the sampling process. It was initially suggested that AI might help in resource allocation with respect to the sampling process.

A dynamic model is seen as the basic building block of the system. Expert systems might be used to challenge the validity of parameters in the dynamic model. Neural nets might help in refining parameter values in the model. The question was raised as to what the sensitivity of the crisp decision by the fish manager was. It was initially concluded that fuzzy set theory, expert systems, expert database systems, and pattern analysis and clustering (cluster analysis), but not neural networks, all appeared to be of potential value, but that we need to go much further to specify their uses.

The topic of abundance was then discussed in some detail. A number of questions were addressed:

1) What is abundance?
2) Does abundance change in time and space?
3) How and why does it change in time and space?
4) How can we optimally measure abundance?
5) Should we use one or many methods?

It was noted that cost effectiveness and accuracy are both important in our approach to measuring abundance. Both age specific abundance and mortality were identified as necessary to model overall abundance. Several questions were raised:

1) What the fish manager was going to do if there is a 20% change in abundance?
2) What degree of accuracy is necessary, appropriate, and useful?
3) How does the change in quota effect the fishermen?

It was reinforced that the manager responds to economic, political, and social factors.

An expert system for making the decision to increase or decrease the quota and by how much was suggested. It was noted that not just the magnitude of an increase or decrease in the population, but also the absolute abundance is important in the manager's decision making processes. We must minimize the risk of the relevant fish stock falling below a specific amount. It was suggested that managers think more in terms of possibilities (fuzzy quantities) than in terms of probabilities.

Another direction that should be considered is the application of fuzzy logic control for management assistance. This could assist in the determination of what exactly does the fish manager need to know to make any decision to change the quota. Ideally, the fish manager needs to fully understand the likely impact (or possibilities) of any actions.

The primary criterion for the fish manager's decision making is that the optimum sustainable yield be maintained. We need to give the manger the most accurate estimate possible of the state (abundance) of the species and the likely impact of any actions. Data sampling, interpretation, correlation, and data fusion are key areas where help is needed. There is considerable variability among data from different sources and variable interpretations due to the application of different interpretive theories. Validation of models (of abundance) can occur only over years, as the sampling rates provide valid information only over extended time periods. The key questions are how the distribution and abundance of the fish stock varies in time and how these are affected by various factors.

In summary, then, we must find and explain patterns over space and time in fish abundance and species composition and relate these patterns to environmental and anthropogenic factors. Abundance is measured in terms of number of fish or biomass per unit area or unit volume. Good data on abundance exists for Lake Michigan, the Gulf of Thailand, and the East Bering Sea. Three possible expert systems are:

1) to optimize the interpretation of sampling;

2) to optimize sampling; and

3) one to assist in the design of a research program to help improve sampling and the interpretation of sampling.

There is a need for improved sampling tools, gear, methods, standard protocols, plans, and statistical analysis methods and plans. An expert system might assist in these domains.

Key environmental factors which must be taken into account in measuring and modeling abundance include temperature (at a particular depth), depth, thermocline level, oxygen concentration, location, salinity, primary production, substrate composition, currents, prey/predators/competitors, and food availability.

Important anthropogenic factors include the fishing effort, oil and toxicant releases, dredging, and solid waste disposal. Important behavioral and ecological features include longevity and guild structure. Any viable expert system must take all or most of these into account.

Our goal should be one that supports parsimony in a large numerical data set. Given immense volumes of data in databases, an expert system to lead the clustering process, as well as interpretation of the outputs, would prove valuable. We are seeking to recognize patterns in the data. Fuzzy descriptors/characterizations of data may prove valuable. We must first encapsulate all of the knowledge/data. Then we must determine what is to be done with the data and what types of conclusions we are seeking to draw. An example of an inference is that fish in temperate waters are more responsive to temperature variations than fish in tropical waters. We need to identify what data are valuable for what fish in what regions. We would then need to transfer this data to an expert system that controls clustering.

The following individuals participated in the "fishery" group discussion of candidate topics for AI use in fisheries sciences and management.

Ball

Brandt

Donnell

Fritz

Kandel

Kolf

Mackintosh

Saila

Swartzman

Wilkins

Zadeh

Following development of an outline of the data requirements in fisheries sciences and management (shown in Figure 1) candidates topics for fishery applications of AI were discussed and agreement reached on the recommendations shown on the following pages.

Recommendations for Fisheries Sciences and Management Research Activities

Background

Conservation, management, and rational use of living natural resources (including fish stocks, and stocks of other aquatic organism) is receiving increasing attention on a global basis. The reasons for this are numerous. It seems sufficient to indicate that the current annual harvest of living aquatic and marine organisms is more than 80 million metric tons. This represents a large and valuable resource capable supplying a significant fraction of the world's protein requirement.

To safely exploit these resources and to effectively manage fisheries while conserving the fish stocks, it is necessary to have accurate information on the abundance and ecology of the fishes and to be able to assess the probable effects of fishing and other factors; such as, pollution and habitat destruction, on the stocks. One important objective of fishery science is to provide methodologies and advice based on these methodologies to permit effective management of fisheries.

The application of knowledge-based systems to the various components of fisheries management is conceptualized in Figure 1. Historically, fishery scientists have addressed management problems by means of single species models and analyses, as exemplified by the lowest frame of Figure 1, where the yield from a single species stock is estimated from knowledge of rates of recruitment, growth, and natural deaths. This yield model is deterministic and usually no accommodation is made for environmental variability, inter-specific competition, or sampling variability. Clearly, this is a gross simplification of reality, but realistic models of multispecies fisheries incorporating environmental variability are not yet at hand. Let us briefly consider the elements of Figure 1. The first box represents an interactive biological system consisting of several species. This interactive system has a true abundance distribution ((box 2) which varies in both space and time. This variability may be due to exploitation, environmental variability, predation, competition

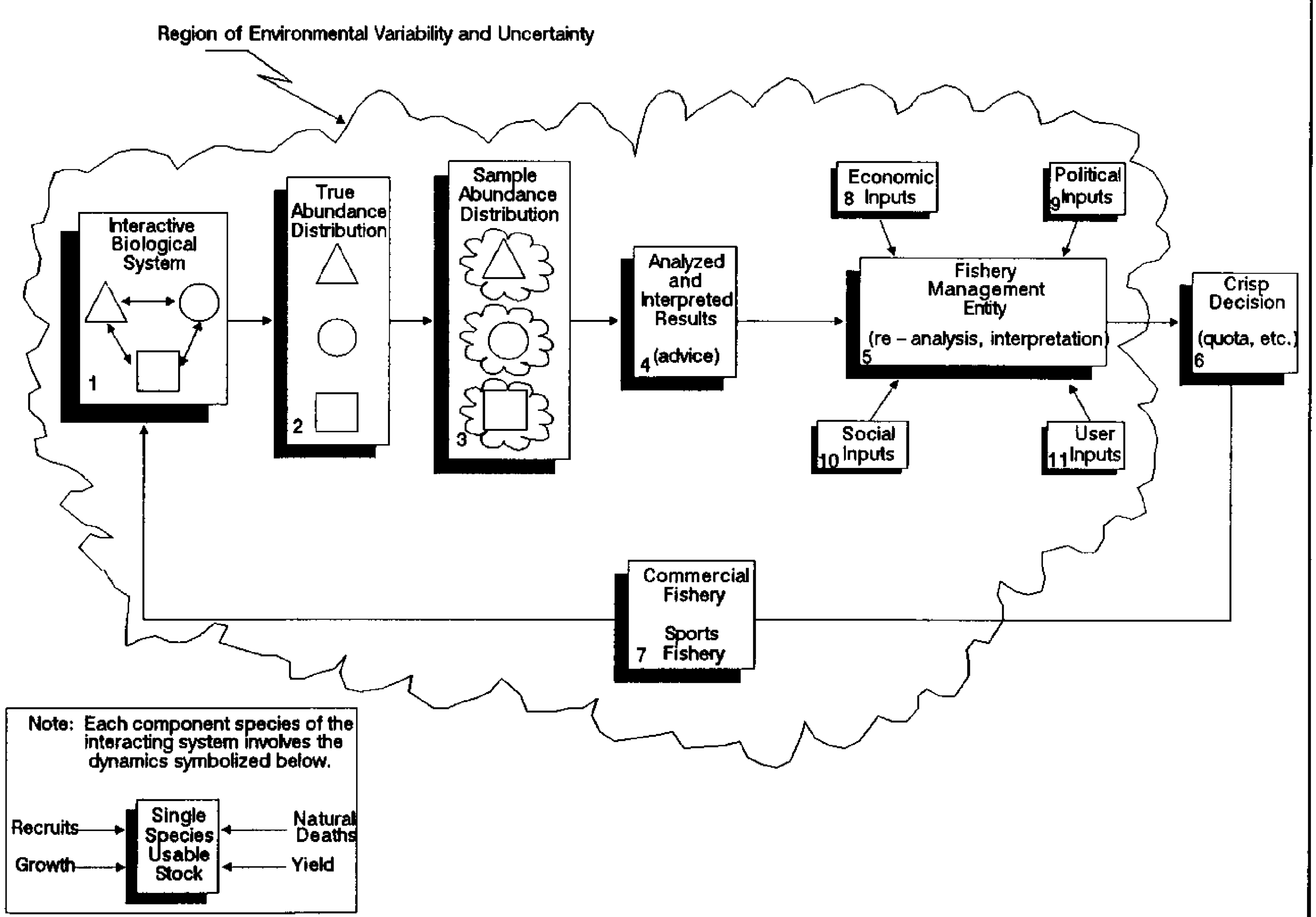

Figure 1. Simplified reproduction of some tasks and problems in fishery assessment and management

or some combination(s)of these. True abundances are estimated (box 3) using a variety of techniques ranging from net collections (e.g. trawling) to underwater acoustics. The experimental survey design is often based on geographic and bathymetric conditions. Since different species and sizes of fish can avoid or escape our sampling gear with different (and often usually unknown) efficiencies, our measures of abundance are often distorted. Data on population abundances provide the primary input to fisheries models and are used for management advice (box 4). At present results of analyses can vary depending on the type and interpretation of the model used. Advice is usually intended for use by some management entity (box 5). This management entity may re-analyze the data, re-interpret the results,and often will be provided with additional information involving economic, social, political, and user group input (boxes 8-11). Ultimately a crisp management decision is made (for example, a quota involving a specific tonnage which is called a total allowable catch TAC) that affects the harvest from the sports and commercial fishery (box 7). The results of the fishing activity then feed back to the interactive system, and the monitoring data is also analyzed and interpreted as input for the next management entity decision. Most of the biological activities in Figure 1 (boxes 1-5 and 7-11) operate within the context of environmental uncertainty. Each of the linkages between boxes seem suitable candidates for applications of knowledge-based systems, where fisheries-related research could be advanced substantially. One area of research was considered to have the highest potential for application of knowledge-based systems and a specific course of action describing how such a problem could be tackled was outlined. We then addressed several other problem areas which were considered important and which could benefit from the application of artificial intelligence concepts.

Recommendation 1

Find and explain patterns over space and time of changes in species composition and abundance and relate these patterns to environmental and anthropogenic factors.

Explanation

A key limitation to effective fisheries management is a lack of understanding of the factors that regulate the spatial and temporal patterns of abundance of fishes. Fish distributions are characteristically patchy and complex. Patch structure often correlates with the physical structure of the abundances of prey, predators and potential competitors. Our basic lack of understanding of these relationships stems, in part, from our inability to accurately measure fish abundances at a system-wide level and at space and time scale consistent with the environmental factors that help govern these distributions. The abundance patterns of particular species should be somewhat predictable within an established theoretical framework based on the physiological effects of the environment (e.g. temperature) based on fish and the expected response of a fish to potential prey, predators, and competitors. Knowledge-based systems that combine our basic understanding of fish behavior with a strong database should help provide problem definition and basic understanding of the spatial and temporal patchiness of fish abundances in relation to fish habitat.

We are aware of several existing databases consisting of region-wide surveys of fish abundances which have been carried out over several years. These databases were expensive to obtain, and likely contain more valuable information than has been extracted to date. Environmental data in the form of satellite imagery and oceanographic survey data may also be available from the same regions where the fishery studies were done. Potential problems of making the environmental data compatible to the temporal and spatial scales of fisheries survey data appear to be solvable.

The economic benefits and conceptual advances which are possible from addressing this problem using knowledge-based systems may be substantial and would aid in both analyzing data, drawing inferences, and designing future sampling programs.

ACTION PLAN

A sequence of activities considered necessary to achieve the stated goal is briefly listed as follows:

1) Data definition.
2) Identify and select a fishery survey area and database for analysis and identify the environmental database(s).
3) Perform classical statistical analyses on the data including the assembly and review of literature and reports generated from the region.
4) Identify and convene expert group.
5) Define the relationships among variables and determine scales and units of measurement.
6) Select an "off the shelf" expert system shell.
   Note: Although the fishery and environmental databases may be extremely large, it is perceived that the expert system itself would be within the limits of current personal computer speed and storage.
7) Build a prototype knowledge-based system
8) Generate output consisting of:
   a) patterns and clusters of fish abundances and environmental data
   b) fish abundance measures
   c) explanations of observations
9) publish prototype results
10) Validate the systems by:
    a) applying the system to a different location and data set.

b) test

Preliminary time and cost estimates and feasibility

A prototype is thought to be capable of being developed within a single calendar year. The current state of expert-based systems is believed to be such that this problem area can be addressed with current technology with a low risk of failure. A full-scale test would require an additional year or two.

The time and cost of data acquisition, quality checking, scaling, etc., is believed to be a significant factor in overall project costs.

Recommendation 2

Dynamic Sampling System

Explanation

Recognizing that most inferences and advice concerning fisheries are based on sampling of the environment or the organisms at various life history stages, we believe that a dynamic sampling system embedded in an expert system shell would significantly reduce costs of sampling and reduce bias in many instances. Fish often have very specific distributional patterns, yet fish survey designs are often determined a priori on the basis of geography or bathymetry. Real-time data on fish distributions can now be obtained relatively easily (e.g. underwater acoustics), but this information has rarely been used to change the survey design based on current sampling results. Knowledge-based systems may be used to interpret fish patterns and optimize an ongoing sampling program. This area of development is considered to have a very low risk of failure. Such a sampling system could become an operational tool for fishery experts for use in their research and survey work.

Recommendation 3

An expert system for population abundance estimation

Explanation

A knowledge-based system that incorporates some of the concepts in recommendations #1 and #2 could provide the framework for guidance in the design and execution of a field program to estimate fish abundance per se. Such a system is conceived as both educational, as well as an operational tool that could be used for laboratory and classroom instruction and research. A query-based system could be developed to provide advice and detailed methodology regarding the estimation of the abundance of populations (both closed and open).

Recommendation 4

A classification system for identification of population (stocks) within a higher level- as well as higher level groupings (e.g. guilds and size structure) of fishes

Explanation

Identification of fish stocks within a species is required for effective fisheries management. Likewise, for ecosystem-level studies fish can be classified into higher orders such as guilds, size structure, trophic status etc. The appropriate classification schemes and membership within classes may not be straight forward and the application of artificial intelligence techniques may be useful. This classification system is perceived as one which employs the latest methodologies in classification, including machine learning and various other more orthodox classification methodologies. This system would be embedded in an expert system shell which would permit the user to determine to determine the appropriate classification procedure(s) for a given sample size and for given numbers of variables.

Recommendation 5

An Expert System for Fishing

Explanation

This system should be designed to assess data from acoustics, temperature, recent catch, quotas, processor quotas (economies of scale), past catches (logbook data), to:

a) suggest areas to fish

b) diagnose the most probable type of school
sited.

The experts in this case would be high line fishermen. A database which could be built up for various fishing regions would be constructed.

Recommendation 6

Knowledge-based systems could be developed for fish migration in large dam systems

Explanation

Large dam systems (e.g. Columbia River) having anadromous fish have many logistical dimensions. These include:

a) spill

b) fish transportation

c) hatchery release

The whole system (all dams) could be coordinated on a knowledge-based decision system.

Aquaculture Recommendations

Summary of Aquaculture Group Discussion Leading to Proposed Application of AI and Expert Systems

The discussions of the Aquaculture group centered around well-defined requirements that have emerged from experience in the development and operation of aquaculture facilities. A major area of discussion related to the technological readiness of AI and expert systems technology and aquaculture technology. This lead to an assessment of potential risk for both disciplines in terms of the ability to meet the perceived requirements in a reasonable length of time. The particular areas of aquaculture that were considered are presented in the paragraphs that follow.

Continuing development of our aquaculture economic base will require a blending of highly automated intensive systems with extensive farming operations currently in common use. Computerized assistance systems are a must for economic viability of both labor intensive and control and monitoring tasks. Automation of some of these tasks and use of computer-based assistance systems would provide great benefits to a majority of our operations.

Site selection was characterized as a major need for those who are seeking to establish an aquaculture operation. It is necessary that the species to be cultured be matched with the environmental conditions required to nurture growth and development of the species. Information is generally available on site conditions, however, it is not easily accessible and usually is not in a form that is immediately useful to the potential user. A knowledge-based system to assist in the accessibility of information and the organization, structuring, and presentation of this material would aid immensely in the site selection processes. In addition to these aspects of site selection, environmental impact assessment is necessary both from the need for good water supplies and from the pollution potential from the site.

Another significant concern centers on the problems associated with disease diagnosis and treatment. The prior history of AI in the diagnosis of disease could be of assistance in aquaculture operations. Frequently, there are not adequate diagnostic capabilities available to operators and availability of diagnostic facilities and prescribed treatment in a timely manner will spell the difference between success and failure of the aquaculture operation.

Models of the impact of nonindigenous species for commercial aquaculture exploitation could be of significant assistance. Current thinking leads to the conclusion that without the introduction of nonindegenous species, commercial aquaculture will not grow into a major industry. Models that could assist in the determination of the consequences of nonindegenous species would be able to provide guidance for commercial development. These knowledge-based decision support systems could prove to be invaluable for initial site and species selection.

Other areas discussed related to classification in aquaculture production and processing and the capability to ascertain the physical properties measurements of aquatic species. The development of computer assistance for these activities could have a major effect on the productivity of aquaculture installations. Of special need would be the development of appropriate sensors to detect changes in the species, e.g. pre-molt identification of crabs and crayfish, and then perform operations via robot to carry out a desired action. Needed physical properties measurements include size, shape, hardness, and water content.

Aquaculture in the United States is characterized by both open and closed systems. Open systems include the numerous small-scale production units comprised mainly of ponds of less than one-fourth of an acre operated by individual entrepreneurs and large-scale commercial operations. Open systems account for an overwhelming majority of aquaculture production worldwide. Closed systems are generally commercial operations and are operated on a small-scale recirculating system. Computer-aided design of these systems permits experienced designers to reduce the time required for good designs. Increased capability of these design systems would permit more widespread use.

Finally, we considered the need for training aids and education. Training aids would be quite valuable for providing managers of aquaculture facilities expertise based on the experience of others. At present this material is not readily available. Simulation models could be developed to take operators through many possible scenarios to provide the necessary training opportunities. Growth of this industry has created demands for properly educated scientists, engineers, biologists, and economists. While present programs are adequate to serve these needs, new approaches and the introduction of new technologies is needed. This includes such technologies and combined approaches as laser disk technology applied to showing fish anatomy and use of hypermedia workstations to bring diverse information together in a synergistic way.

In summary it is imperative that we identify new approaches and new technologies for application to aquaculture. Many of these have been identified in the material that follows. Research and development in these areas will surely lead to additional opportunities for synergistic actitities between aquaculturists and computer scientists.

The following individual participated in the aquaculture group discussion of candidate topics for AI use in aquaculture:

Ball
Franklin
Friessen
Fritz
Malone

Michalski
Manzi
Palmer
Stewart
Wheaton

Recommendations for AI and Expert Systems Applications for Aquaculture

Recommendation 1

Monitoring and Control of Intensive Aquaculture Systems

Explanation

Our emerging aquaculture industries in the United States are finding themselves squeezed between the high technology approaches of the European countries and Japan, and the low labor and land costs of a number of developing countries. Development of a healthy aquaculture industry will require a blending of highly automated intensive systems with the extensive farming operations which are now in common use. Applications of the former should be used to enhance the rate of production from the lower cost pond systems. Economic viability will demand that the routine tasks of control and monitoring of the systems be handled by computerized systems. Continuous monitoring of parameters such as dissolved oxygen, pH, temperature, photoperiods, and salinity permit the development of sophisticated management schemes which provide for increased production. Automating routine tasks such as feeding, water exchanges, filter backwashing, and addition of water conditioners reduces the cost of production while raising the productivity of personnel. Systems showing high probability of short-term economic return include the production of fry and fingerlings in support of our finfish systems, spat production for the clam and oyster industries, and production of larvae in support of shrimp industries. All these applications deal with stock which have high economic value per unit mass, minimizing the physical requirements for their support while justifying advanced management techniques that can be implemented through automation. These applications also demand the production of algae, rotifers, and other foods whose production is compatible with the available computer technologies.

Four identified foci:

- global monitoring and control of intensive aquaculture systems
- automatic monitoring of fish growth and resultant feed allocation to optimize growth at different age classes
- parameter optimization for algae growth
- understanding and optimizing pond dynamics

The end users of this technology would primarily be system operators, and educators as through emphasis #11. Fuzzy logic appears to be a useful method for handling such parameters as light/dark, acid/base, fresh/saline. Neural nets might draw together relationships between environmental parameters. Other suggestions include:

- both research and production arenas for various species should be included.

- all environmental factors and their potential interactions should be considered.

- - an "Intelligent Control" system approach should be used, perhaps with a mix of symbolic and numeric approaches, and including a natural language user interface.

- the first goal should be a benchtop-level prototype.

- learning phase costs should be minimized; allowing the system to learn.

- an objective would be system water quality control (for dissolved oxygen, carbon dioxide, pH, ammonia, etc.).

Such a project would cover at least a 24 month time-frame. Some level of improved control is undoubtedly within the reach of present technology. The "risk" is dependent on the extent of expectations, and would vary from low to high for the AI perspective, and also from low to high from the aquaculture viewpoint.

Recommendation 2

Aquaculture Site Selection

Explanation

One adage in aquaculture is that there are three reasons why most commercial aquaculture ventures fail: site selection, site selection, and site selection. Although humorous, the above statement accurately reflects the importance of site selection for any aquaculture business. It is necessary to accurately match the species to be cultured with an environment suitable to provide maximum growth and minimum mortality. In addition, the economic ramifications of the site including existing infrastructure, pollution potentials, and proximity to marketing networks must be considered. Finally, the local and regional permitting climate must be analyzed and potential conflicting interest must be accessed. In short, site selection rests first with biological considerations, but rapidly expands to include economic and political elements.

Another aspect of site selection for both new and existing aquaculture industry relates to the carrying capacity of a particular area. Often a site will be suitable for small scale culture, but lacks the innate productivity to support large scale commercial production. The site selection process must not only determine how appropriate a site is for a particular species, it must also approximate the value of the site in regards to its capacity to support intensive commercial culture.

At present, the site selection process is extremely tedious and cumbersome. Individual sites are evaluated independently by entrepreneurs, consultants, state agencies, and financial institutions each using limited and unlimited databases. Much information, although available, is not easily accessible, making the compilation of a complete review of existing data difficult. The entire process could be simplified and legitimized by the construction of knowledge-based systems that can assist in the site selection and decision process. One of the principal problems with establishing new aquaculture ventures is the difficulty involved with site selection and permitting. An improvement in these processes and a shortening of the time necessary to accomplish them can greatly stimulate aquaculture development.

- The suggested approach is a "Knowledge-Based Decision Support System", with an open architecture capable of working with multiple databases.
- All parameter types should be considered, i.e. biological, physical, economic, sociolegal.
- Elements to be considered would include species, climate, water quality, land availability, waste management capability, existing marketing infrastructure, and stock availability.
- The Decision Support System should function proactively, as in selecting good potential sites for future aquaculture development, and reactively, as in analyzing the appropriateness of a particular site for a particular type of aquaculture.
- In the proactive mode, GIS-type databases and abilities could be incorporated.
- The model should include a natural language user interface.
- The databases which are utilized should be generally accessible and externally maintained, rather than located and maintained internally.

- This model should be compatible with those developed under recommendations #8 and #9 (Aquaculture System Design and Environmental Impact Assessment of Aquaculture) in order to take advantage of a modular approach to shared databases.

The timeframe for this project is estimated as between 18 and 60 months. The "risk" from the AI perspective is modest, but from the aquaculture viewpoint it is modest to high.

Recommendation 3

Aquatic Organism Disease Diagnosis and Treatment

Explanation

Disease diagnosis and treatment in aquaculture is a significant problem at present. There are few specialists and even fewer texts available to support the industry. Subsequently, disease problems often create unnecessary and lengthy periods of decreased production and often jeopardize the success of a new venture. It is often the case that diseased organisms must be shipped off to experts before a diagnosis be made and a treatment can be recommended. Although most technical managers in the aquaculture industry have some biological training, it is difficult to identify a pathogen or to recognize a particular disease syndrome. The stage is set for the construction of an expert system for disease diagnosis in aquaculture. Such a system would provide immediate access to the best available information on disease diagnosis, treatment, and control.

- There are a large number of potential users with only a small number of experts available.

- A "Knowledge-Based Decision Support System" is suggested. It should have the facility to diagnose fish diseases, suggest treatment regimes, and provide explanations for those suggested diagnoses and treatments.

- Good databases exist for most species of interest.

- A natural language user interface should be included.

- A regional approach is suggested, centralizing the hardware and facilitating remote access.

- In its fully developed state, these models might include high quality images to supplement text, and reference searches from optical disk storage.

- End users would include aquatic disease experts, aquaculture system operators, fisheries managers, and educators as through emphasis #11.

The timeframe is estimated as from 12 to 24 months. The risk is low from the AI viewpoint, and low to moderate from the aquaculture perspective.

Recommendation 4

Nonindigenous Species Introduction Assessment

Explanation

Many species that appear to be excellent candidates for commercial aquaculture exploitation would constitute a nonindegenous species introduction. In certain cases, these introductions have already occurred, e.g. the Pacific oyster, Crassostrea gigas in Washington, brown trout, Salmo trutta in the United States, and the Atlantic salmon in several countries around the world. In truth, it is highly unlikely that commercial aquaculture will grow into a major world industry without the continued introduction of species throughout the world. There are, however, well-founded concerns in regards to the introduction of exotics. These include (1) local species being displaced by the new species, (2) disease or parasites being introduced into the area by the new species, or (3) symbionts or predators accompanying the introduced species become established in the new environment. Any or all of these are certainly possible and can result in ecological catastrophe. A knowledge-based system to assist in decision making by providing information on likely scenarios would be a beneficial addition to the tools available to the regulatory agencies considering the introductions.

- Since the introduction of non-indigenous species can have a positive or negative effect, the decision system should answer the question of whether introduction of exotics would be prudent.
- Decisions would be made on a case-specific basis, not general decisions for a geographic region.
- A "Deep Model" approach is suggested, looking at cause and effect relationships and/or reasoning by analogy.
- A natural language user interface should be included.
- End users would include state/regional/national fisheries managers, and educators as through emphasis #11.
- The timeframe is estimated as at least 24 months.

The AI risk is low; the aquaculture risk is considered low to moderate.

Recommendation 5

Machine Perception and Classification in Aquaculture Production and Processing

Explanation

One of the major problems in aquaculture is determining the difference between two or more objects that are related but somehow different. Examples include determining if a crab or crayfish is a hard shell or soft shell, determining which fish eggs in an incubator are contaminated with fungus and which are not, determining which crabs or crayfish are close to molting, and determining which oysters on a conveyor belt have a desired orientation. Typically, these decision processes, and the appropriate following actions, are carried out manually by human operators. Such labor intensive activities tend to be expensive, and are often boring for workers because of their repetitive nature.

Potential exists for completing these operations with the assistance of computers, appropriate sensors, and mechanical activation devices such as those that would remove a softshelled crab from a tank. Computer vision, optical and acoustic sensors, and other sensing devices coupled with computers operating on the appropriate algorithms can be used to sense and make decisions about appropriate actions. The computer can then control the activation device (a robot arm, for example) to carry out the desired action. Advantages of such systems include 24 hour a day operation, reduced costs for completing operations, timeliness of operations, and greatly increased reliability.

Three identified foci:

- Pre-molt identification of crabs and crayfish
- Post-molt identification of soft crabs, crayfish and potentially other crustaceans

- Automated detection (for removal) of fungus-infected salmonid eggs (eggs turn white and fuzzy)

- A "Machine Perception and Classification" approach is suggested, using sensor interpretation and object identification capabilities (potentially using visual, acoustic, infrared, and other clues.)
- A natural language user interface should be included.
- End users should be primarily aquatic product producers and processors, those who design such processing facilities, and educators as through emphasis #11.

The timeframe is estimated to be from 3 to 5 years. The AI risk is low. The aquaculture risk appears moderate.

Recommendation 6

Physical Properties Measurement of Aquatic Products

Explanation

A major impediment to the development of processing equipment is a lack of basic information on the physical properties of aquatic organisms or products made from them. Physical properties such as size, shape, hardness, special physical characteristics (such as the shape of a hinge line on an oyster), water content, etc., are required to design processing equipment. Collection of this information requires the application of a variety of technologies including but not limited to computer-based acoustic, optical, chemical and mechanical methods.

- A "Machine Perception and Classification" approach, using a wide array of potential parameters. This makes this a multisensor problem.

- A natural language user interface should be included.

- End users would be principally aquaculture product processors, those who utilize such processing facilities, and educators as in emphasis #11.

The timeframe is estimated to be from 1 to 5 years. The AI risk ranges from low to high. The aquaculture risk appears to fit in the same categories.

Recommendation 7

Computer Integrated Processing of Aquatic Products

Explanation

Aquatic products processing involves manual, mechanical and automatic unit processes. Unfortunately, manual processes often predominate. Rising labor costs and the need for more uniform product quality all favor automation of aquatic products processing lines. Automation will require new sensors, new methods and techniques, and improved acceptance of new approaches to processing. Automation will, however, reduce costs, improve quality, and provide more marketable products. Computer integrated processing is designed to view processing operations as a system and the objective is to produce a system that approaches optimum conditions. Computer control and a reduced need for labor and/or subjective human input are hallmarks of these systems. Unit operations are fit into the system such that the system, not necessarily the unit operator, are optimized. Computer control allows optimal system operation.

- A "Computer-Assisted Processing" approach is suggested, including a natural language user interface. Improvements in terms of quality control as well as labor cost reductions are expected.

- Rather than tackle the entire processing system immediately, an "Islands of Integration" approach within the existing processing environment should be used.

- As computer control packages become available, they would be integrated into the base design of new facilities.

- End users would principally aquaculture product processors, and educators as in emphasis #11.

The timeframe is estimated to be 3 to 6 years. The AI risk is low. The aquaculture risk is moderate.

Recommendation 8

Aquaculture System Design

Explanation

Challenges to the design of aquaculture systems can be split into those relating to open systems, versus closed types. Open systems include a variety of aquaculture production methods, including but not limited to pond, raceway, rack, net pen, and cage culture systems. Open systems currently account for an overwhelming majority of aquaculture production in the United States as well as worldwide. Design of facilities for open culture systems must take into account the species cultured, environmental needs of the crop, the natural environment and changes expected in it (e.g.: storm waves), physical strength, and other parameters. Fouling of culture systems by undesirable aquatic organisms is also a major problem. In the design of any system, integration of all these factors is time consuming and difficult. The use of Artificial Intelligence in the design of these systems will reduce design time and help integrate the many variables that need to be considered in each design. Use of databases containing water quality, soil type, weather, species and environmental needs data can be quickly accessed and integrated into a design which will reduce design costs and increase reliability of the system. Recirculating systems provide an environment conducive to high density production while releasing the facility from its linkage to source waters or discharge impacts. However, designing a closed recirculating system requires that management of several critical water quality parameters be optimized within the framework of a physical configuration providing for support, observation, and harvesting of the species of interest. Computer-aided design permits experienced designers to reduce the design time while facilitating the transfer of specialized knowledge to the less experienced. Particular emphasis needs to be placed upon the development of design aids for recirculating systems which provide for reaeration, nitrification, solids removal, and pH control. In addition, commercial operators would benefit from comprehensive design packages that link system design to economic performance.

- A "Knowledge-Based Decision Support System" approach is suggested, including a natural language user interface.
- This Decision System would address the design problems associated with both open and closed systems. It would consider all important design factors and their interactions.
- The System should be compatible with those developed under recommendations #2 and #9 in order to take advantage of a modular approach to shared databases.
- End users would include aquaculture entrepreneurs system designers, and educators as through emphasis #11.

The timeframe is estimated to be at least 18 months. The AI risk is low. The aquaculture risk is also low.

Recommendation 9

Environmental Impact Assessment for Aquaculture

Explanation

Aquaculture in the United States is an industry which falls under the jurisdiction of a number of local, state and national regulatory agencies. Many of these agencies require applications for permits or licenses and some validation of existing or potential environmental impact. Aquaculture, through both its use of large quantities of water and additives to this water (feeds, temperature modification, drugs, etc.) has the potential to be a serious polluter. The industry, however, must rely upon good water quality to maintain its high density culture methods and is generally as interested in maintaining water quality as the regulating agencies.

It would serve the industry and the regulating agencies to establish a knowledge-based system to assist in decision making involving permitting various aquaculture activities in various areas. At present, most regulatory agencies are not aware of the specific environmental ramification of various aquaculture operations. Therefore, they are extremely conservative in their permitting procedures, often misapplying regulations or denying permits when no real problems exist.

- A "Knowledge-Based Decision Support System" approach is suggested, with a natural language user interface. This should be compatible with those developed under recommendations #2 and #8 to take advantage of a modular approach to shared databases.

- The System would be used for caged culture systems, enclosed systems, and the area of processing of wastes as well.

- It should include the perspective of both the aquaculturist and regulatory agencies making land use decisions.

- End users would include resource managers, aquaculture facility designers, aquaculture operators, and educators as through emphasis #11.

The timeframe for the initial prototype would be one year, but this system would be modified indefinitely with new knowledge. The AI risk is moderate. The aquaculture risk is low to high.

Recommendation 10

Training Aids in Aquaculture

Explanation

Currently, development of aquaculture management skills is learned through a costly trial and error process. Managers lacking advanced training in process design and operation develop rules which assure successful operation of the system. However, many small aquaculture operations do not survive the learning phase since management errors can rapidly result in the loss of an entire season's production. Computer-assisted learning and instruction provide an inexpensive means of refining management skills in an environment that avoids the costly ramifications of error. Modelers should consider the impact of management decisions dealing with topics (e.g.: feeding, water quality control, stocking densities) impacting growth rates, survival, and product quality. Emphasis should be placed upon development of training models that link decisions to economic performance.

A training model should be developed that would take operators of aquaculture systems through decision paths, showing results through the use of simulation or other appropriate interactive methods. End users would include aquaculture system operators, and educators as through emphasis #11.

- the training regimes should include opportunities that reflect acts of omission as well as commission on the part of the operator

- an "Intelligent Computer-Assisted Learning & Instruction" system approach

Such a project has an estimated 3 to 5 year timeframe. The risk of failure is moderate from the AI perspective; moderate also from the aquaculture perspective.

Recommendation 11

Educational Programs for Aquaculture

Explanation

Growth of the aquaculture industry has created demands for biologists, engineers, economists, and other highly educated people. Formal educational programs at the bachelors, masters, and doctoral levels are currently meeting these needs and will do so in the future. The educational process, however, requires new approaches, methods, and materials to transfer knowledge and to assure that the most current data is available to students. Needed developments range from additional courses, new methods of transferring information (laser disk technology applied to showing fish anatomy, for example), and new ways of organizing information, to ways of getting students to understand basic principles, and a host of other developments. Failure to meet these educational needs will result in a shortage of or poorly educated experts to serve the aquaculture and fisheries sciences and management industry. In the long term, this lack of well-educated people will impede development of the industry.

- An "Intelligent Computer-Assisted Learning and Instruction" system approach is suggested, building on all of the above suggested research, and featuring a natural language user interface.

- End users would principally be educators and students of aquaculture. This would be applicable to formal classroom format, or targeted workshops.

Since this is dependent on completion of the research projects listed above, the timeframe would be at least 5 years. The AI risk is moderate; the aquaculture risk is also moderate.

Summary of Generic AI Approaches Proposed for Aquaculture Applications:

Emphasis	Possible AI Approach
1	Intelligent Control
2	Knowledge-based Decision Support System
3	Knowledge-based Decision Support System
4	Deep Model
5	Machine Perception and Classification
6	Machine Perception and Classification
7	Computer-assisted Processing
8	Knowledge-based Decision Support System
9	Knowledge-based Decision Support System
10	Intelligent Computer-Assisted Learning & Instruction
11	Intelligent Computer-Assisted Learning & Instruction

Summary by AI Approach for Aquaculture Applications:

A) Intelligent Control

#1 - Monitoring and control of intensive aquaculture systems

B) Knowledge-based Decision Support System

#2 - Aquaculture site selection

#3 - Aquatic organism disease diagnosis and treatment

#8 - Aquaculture system design

#9 - Environmental impact assessment for aquaculture

C) Deep Model

#4 - Nonindigenous species introduction assessment

D) Machine Perception and Classification

#5 - Machine perception and classification in aquaculture production and processing

#6 - Physical properties measurement of aquatic products

E) Computer-assisted Processing

#7 - Computer integrated processing of aquatic products

F) Intelligent Computer-Assisted Learning & Instruction

#10 - Training aids in aquaculture

#11 - Educational programs for aquaculture

NOTE: In all applications, a Natural Language User Interface was suggested

Appendices

Appendix A: Workshop Participants

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Appendix B: Workshop Agenda

The objectives of the Workshop were 1) to define a research protocol for applying advancements in the field of knowledge-based systems to the analysis or solution of problems in a) fisheries science and management, and b) aquaculture and 2) bring senior scholars and researchers in fisheries science and management and aquaculture together with those in knowledge-based systems to seek collaboration and explication in this research agenda. The enclosed agenda was designed to achieve these objectives.

The Workshop began with the circulation of background papers in advance of the actual meeting dates. Papers from respected researchers in the several fields were prepared and circulated. The nature of these papers was such as to inform participants of underlying principles of the specific disciplines and to provide tutorials that aided in understanding of the fields.

This was followed by three days of intensive interaction between knowledge-based systems researchers and marine science researchers. Position papers and tutorials were presented for the purpose of developing a common ground upon which to explore the problems and methods of the respective disciplines. This was followed by breakout groups that discussed specific topics in greater detail. Finally, members of each breakout group convened to develop the initial drafts of the research protocol. Since the objectives were to define a research protocol and to encourage collaboration among scholars and researchers, specific tutorial sessions were interspersed throughout the first two days.

The agenda that ensued for the Workshop was as follows:

Agenda

Sunday Evening May 21, 1989

Arrival:	Participants meet together in a casual get-together session at the Holiday Inn, Fair Oaks at 7:00 PM

Monday May 22, 1989

8:30 AM	Discussion of problems and methods in fisheries sciences and management by fisheries participants Saul Saila
9:30 AM	Discussion of underlying principles of AI, including expert systems Jude Franklin
10:30 AM	15 minute break
10:45 AM	Discussion of the needs and problems associated with aquaculture John Manzi
12:00-1:00 PM	Lunch together
1:00 PM	Discussion of uncertainty and imprecision in artificial intelligence Lotfi Zadeh
2:00 PM	Discussion of special needs of fisheries science and management with regard to information technology Gordon Swartzman
3:00 PM	15 minute break
3:15 PM	Discussion of machine learning principles with particular application to scientific discovery Ryzard Michalski
4:15-5:00 PM	General session to discuss the materials brought forward during the days work. The session leaders will be the tutorial presenters.
6:00 PM	Evening open. However participants will be expected to break up into groups of four or five for dinner and discussion on Workshop objectives.

Tuesday May 23, 1989

8:30 AM	Continuing discussion of the needs and requirements of aquaculture Ronald Malone

9:30 AM	Discussion of knowledge acquisition, knowledge-based systems and knowledge programming Mike Donnell
10:30 AM	15 minute break
10:45 AM	Continuing discussion of the needs and requirements of fisheries science and management Steven Brandt
12:00-1:00 PM	Lunch with all participants
1:00 PM	Discussion of expert database systems applications to related problems in science and industry Douglas Mackintosh
2:00 PM	Continuing discussion of the needs and requirements of aquaculture Frederick Wheaton
3:00 PM	15 minute break
3:15-5:00 PM	General open discussion concerning any of the topics presented and the emerging research agenda
6:00 PM	Dinner. During dinner and thereafter, two groups will be formed based on fisheries sciences and management and aquaculture.

Wednesday May 24, 1989

8:00-12:00 AM	Separate groups meet to discuss and prepare written recommendations concerning applications of AI systems to fisheries sciences and management and aquaculture.
12:00-1:00 PM	Lunch with all participants
1:00-2:30PM	Rapporteur prepare and make presentations of recommendations and comments from participants for guidance in preparation of the final report.
2:30 PM	Workshop adjournment.
3:00-5:00 PM	Selected representative group remains to prepare draft final report and recommendations for a research agenda.

Appendix C: A Brief Summary of the Elements of Fishery Science

I. Introduction

The purpose of this summary is to briefly introduce the non-fishery scientist to some facets of fishery science. Clearly, the subject is a broad one and much has been written about it. Selected references which provide a reasonable coverage of the subject area are included.

We will include a discussion of some of the common topics in fishery science. Specifically, we will cover those areas that lead to an understanding of this field related to topics that appear to be amenable to the application of knowledge-base technologies.

II. Abundance estimates

Mark and recapture techniques are used to estimates population size (abundance) and to provide several other estimates. These estimates include the rate of exploitation, population size, survival rate from one time interval to the next, and rate of recruitment to the population.

Acoustic methods are described in another section of this workshop by Brandt.

Other gear and methods, such as trawl surveys, are also utilized for abundance estimation purposes.

III. Mortality estimates

The rate of survival ($-\log_e Z$) can simply be estimated if the initial number of fish in two broods (age t and t+1) were the same as if they were subjected to simple morality at corresponding ages. Then $S=N_{t+1}/N_t$.

Similarly, if one plots the logarithm of frequency against age directly, one has a catch curve. The descending limb of this curve provides an estimate of total morality under some simplifying assumptions. Other methods include estimates of survival and rate of fishing from a time series of catch and effort. Swartzman describes catch at age analysis based on fishery catch data in another section of this workshop report. It is evident from this work that several estimates of population size and fishing mortality can be obtained from the various catch at age techniques.

IV. Growth estimates and models

Markings on the hard parts (particularly scales and otoliths) are regularly used not to only compute the age of fish but also to calculate fish length at the end of previous growing seasons. In some cases, scales and otoliths even indicate the age at which the fish first spawned.

An important application of age determination is to develop an age-length key from a representative sample. This can be used to convert observed distributions to age.

In estimating true growth rates, the usual method involves determining age from scales and making measurements to successive annuli, establishing a relation of scale to fish size, and back-calculating length from the scales.

An expression commonly employed to describe growth in length is due to von Bertalanffy and is as follows:

$$l_t = L_\infty(1-e^{K(t-t_0)})$$

where

l_t = length at time t

L_∞ = asymptotic length (a growth curve parameter)

K = a rate coefficient (another growth curve parameter)

t_0 = (a growth curve parameter) a hypothetical age at which the fish would have been zero length if it had grown in a manner described by the equation.

There are numerous other equations which are used to describe individual and population growth. The logistic equation is often employed for population growth, and some stock production models are based on it.

V. Rate of reproduction

Most exploited fish populations are highly fecund. Over one million eggs may be produced by one mature female during a single spawning. However, survival during early life history stages is very low. Details of stock/recruit relations will be provided in a later section of this report.

VI. Yield Models

In the past, two general types of single species model have been employed. They are so-called stock production (lumped parameter) models and the so-called analytical models. The assumptions of the stock production models are:

a) A fish population grows to the carrying capacity of the environment (B_∞).

b) B_∞ more or less corresponds to the original stock.

c) Growth in time of the fish toward B_∞ is described by a logistic curve, the first derivative of which (dB/dt) has a maximum at $B_\infty/2$ and zero value at B_∞ and $B = 0$.

From the above, two features of these models emerge: (a) growth of the stock is a function of its size only, and (b) a stock should respond instantaneously by changes in its growth rate to changes in its size by fishing. That is:

$$dB/dt = r_mB(B_\infty - B)/B_\infty \qquad (1)$$

where

B = stock size
B_∞ = environmental carrying capacity
r_m = intrinsic rate of growth of the stock

Assume the equilibrium by the subscript E. Then

$$Y_E = dB/dt = F_E \times B_E \qquad (2)$$

This states that the equilibrium yield per unit time, Y_E, is equal to the net growth rate of the stock, F_E, maintained by a fishing mortality, B_E. Combine and rearrange Equations 1 and 2 to get:

$$Y_E = r_mB_E - (r_m/B_\infty)B_E^2 \qquad (3)$$

Equation 3 has the form of a parabola. The first derivative of equation 3 with respect to B_E can be equated to zero and solved for B_E to yield:

$$B_{opt} = B_\infty/2 \qquad (4)$$

The usual analytical equation for estimating yield per recruit or yield isopleth diagrams is:

$$Y/R_{r2} = Fe^{-mr}{}_2W_\infty\{1/Z - 3e^{-kr}{}_1/Z+K + 3e^{-2Kr}{}_1/Z+2K - e^{-3Kr}{}_1/Z+3K\} \qquad (5)$$

where:

Y/R_r is yield per initial number of recruits

$Z = F+M$

$r_1 = t_c - t_0$ (age at first capture - t_0 [the von Bertalanffy parameter])

$r_2 = t_c - t_r$

$r_3 = t_{max} - t_c$

K = von Bertalanffy parameter

W_∞ = von Bertalanffy growth parameter (asymptotic weight)

VII. The Ricker Stock-recruitment relationships (SRR)

It is evident that the above models are both simplistic and deterministic. They are single species models, although production models have been applied to mixed species biomasses. It should be clear that there is a strong need for further understanding of multispecies fisheries and environmental effects on these fisheries. The present commonly available methodology is inadequate for this purpose.

An effort will have to be made to provide a little more detail on stock recruitment relationships and their uses. This section and the next will review two models that are more robust.

Ricker's form of the stock-recruitment relationship (SRR) describes a dome-shaped curve where recruitment declines exponentially with the number or biomass of spawners when they increase above the level at which maximum recruitment occurs. The mathematical form of the SRR is:

$$R_t = \alpha P_t^{(-\beta P_t)} \qquad (6)$$

where R_t is the recruitment index for the year-class (t) produced by the spawning stock P_t in year t and (α) and (β) are parameters estimated from the data. While α corresponds to the slope of the line tangent to the curve at the origin, the parameter β is the exponential rate at which recruitment declines at large stock sizes due to some form of density-dependent mortality.

Annual instantaneous rate of fishing will be denoted by F and referred to as "fishing mortality" or "fishing rate." On the other hand, the actual fraction of the stock removed by the fishery, often referred to as total fishing mortality or finite fishing rate will be denoted by u and referred to as "exploitation rate." The relationship between these two fishing rates is as follows:

$$F = 1 \log_e(1-u) \qquad (7a)$$

$$u = 1 - \exp(-F) \qquad (7b)$$

A typical Ricker SRR curve is shown in Figure 1 together with some auxiliary lines and reference points. The straight line through the origin and the point (E) on the curve is the replacement line for the unfished or virgin stock when only natural mortality rates operate. When the stock if left unfished long enough, the progeny (on average) exactly replace the spawners (i.e., the line through E has slope = 1). Thus, the spawning stock corresponding to (E) is the reference point P rep or "replacement level of the stock" [Ricker 1954]. The obvious significance of this reference point is that surplus production is only possible at stock sizes less than P rep. When the stock is under exploitation at some constant fishing rate F, the number of spawners eventually declines to a new equilibrium size (C), and the stock production (distance C-A in Figure 1) generates a surplus (B-A) equal to the annual take of the fishery. Thus, the so-called optimal or "maximum sustainable yield" (MSY) [Ricker 1954] occurs at the equilibrium stock size at which surplus production is maximum (not shown, but somewhat to the left of C in Figure 1). Accordingly, the fishing rate F_{MSY} which brings the stock close to the size that produces maximum surplus is the elusive management target for many commercial fisheries. When the stock is overfished well beyond the MSY level, both the stock itself and the fishery yields begin to decline rather rapidly. In the limit, when F increases to a value equal to $\log_e\alpha$ the stock collapses. Thus the parameter α in Ricker's model (Equation 6), or more generally the slope at the origin of any SRR curve, determines the limiting fishing rate of the stock. The relationship between the logarithm of the slope at the origin and the value holds true for

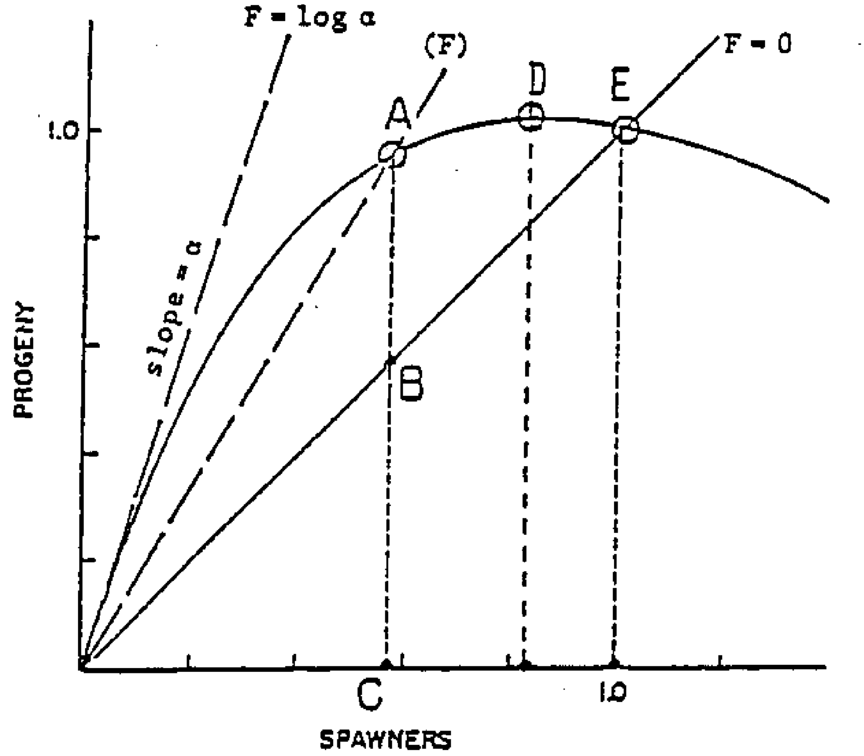

Figure 1. The form of Ricker's stock-recruitment relationship and some points of reference (redrawn from Figure 11.1 in Ricker 1975)

any line through the origin that intersects the SRR curve anywhere between the origin and the reference point (E) in Figure 1. At (E), where the slope of the replacement line is 1.00, F is 0 ($\log_e$ of 1 is zero). Similarly, at any arbitrary point (A) the value of F is the logarithm of the slope of the line from the origin through the point. Finally, the point (D) in the figure is the reference point called "maximum recruitment" which occurs at the peak of the SRR curve. The interest in this reference point is that it describes the inherent recruitment potential of the stock and that it corresponds to the stock size P max above which density-dependent processes become dominant (i.e., recruitment declines with increasing stock sizes). Ricker [1975; Appendix iii] provided the equations that follow to calculate positions of all these reference points once the two parameters of the SRR curve have been estimated:

Replacement level of the stock:

$$P_{rep} = \log_e\alpha/\beta \qquad (8)$$

Stock for maximum recruitment:

$$P_{max} = 1/\beta \qquad (9)$$

Maximum recruitment (when $P=P_{max}$ and where e = 2.718, the base of natural logarithms):

$$R_{max} = \alpha/e\beta \qquad (10)$$

Stock for maximum sustainable yield (P_{MSY}) is calculated by solving for P (through integration) in the following equation:

$$e^{-\beta P} = \alpha(1 - \beta P) \qquad (11)$$

Fishing and exploitation rates at MSY:

$$F_{MSY} = -\log_e(1 - \beta P_{MSY}) \qquad (12b)$$

$u_{MSY} = \beta P_{MSY}$ (12b)

Equilibrium stock for fishing rate F:

$P_e(F) = = \log_e(\alpha e^{-F})/\beta$ (13)

VIII. The Shepherd stock-recruitment relationship

Shepherd's form of the stock-recuritment relationship (SRR) has three parameters, and it can describe various types of recruitment behaviors ranging from monotonically increasing to Ricker-type dome-shaped curves (Figure 2). Although this SRR is more difficult to fit directly to the data than Ricker's two-parameter curve, its flexibility and ease with which it can combine with yield-per-recruit equations make it very useful for assessment and fisheries management work. The mathematical form of this SRR is:

$R_t = \alpha p_t/(1 + \{P_t/K\}^{\beta})$ (14)

where:

R_t is the recruitment index for the year-class t produced by the spawning stock P_t in year t

α, K, and b are parameters estimated from the data.

As in the Ricker SRR (Equation 6) the parameter α is the slope at the origin of the curve determining the limiting fishing rate of the stock. Although β also describes the strength of the density-dependent processes, its relation to compensatory mortality is less direct than in Ricker's β. In addition, Shepherd's β determines the type of curve, which may be dome-shaped only for β values approaching 2. Finally, the third parameter K, called the "threshold biomass," exactly corresponds to Ricker's reference point P_{max} or spawning stock for which recruitment is maximum. The significance of K is that, like P_{max}, it defines the stock size above which density-dependent processes dominate recruitment. Although the spawning stock in Shepherd's equation can be expressed in other units than biomass, many of the calculations

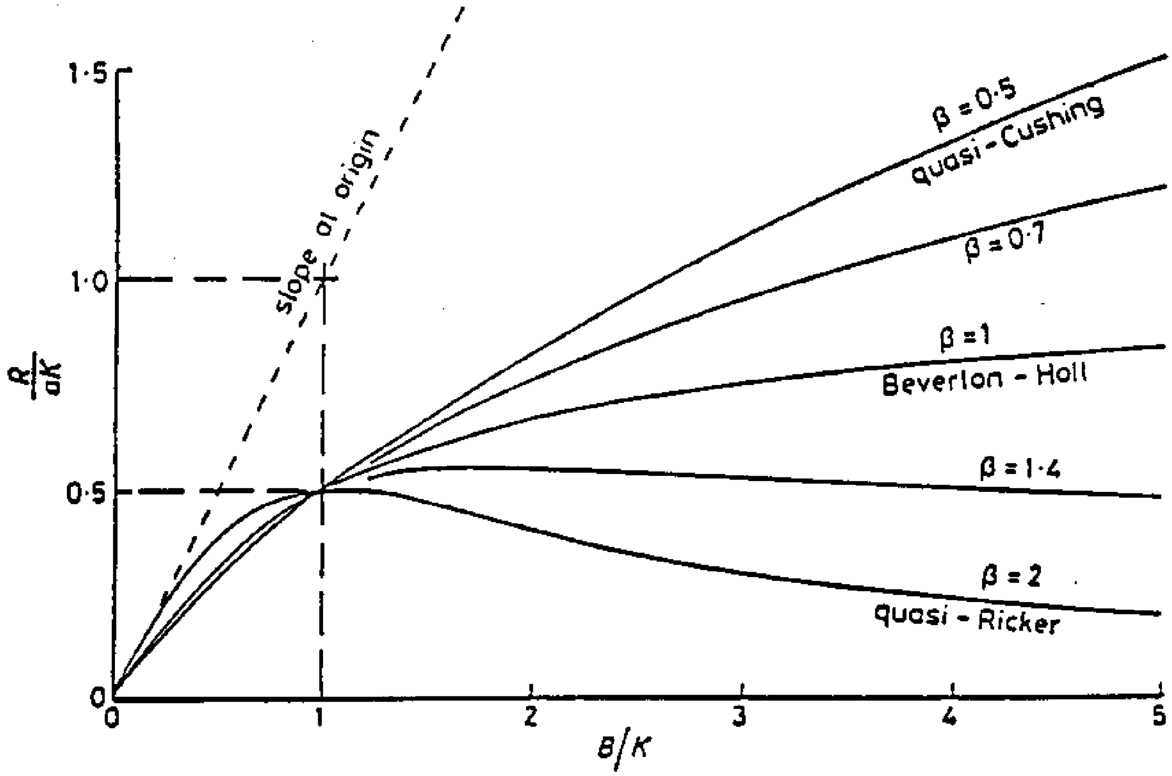

Figure 2. The form of Shepherd's stock-recruitment relationship (redrawn from Figure 1 in Shepherd 1982).

described by Shepherd [1982] are only valid when the units of recruitment are fish numbers, and the spawning stock is scaled as biomass.

Shepherd's SRR reference points are the same as for Ricker's SRR and also have identical interpretation when the former is a dome-shaped curve. As mentioned above the reference point P_{max}, or stock size corresponding to the peak of the curve, is given directly by the parameter K. There is no simple way to calculate P_{MSY} other than graphically by finding the maximum surplus production directly on the curve fitted to the data. The equations given below can be used to calculate the remaining reference points.

Replacement level of the stock:

$$P_{rep} = \exp\{\log_e(\alpha - 1)/\beta + \log_e K\} \qquad (15)$$

Maximum recruitment (when P = parameter K):

$$R_{max} = \alpha K/2 \qquad (16)$$

Equilibrium stock for a given fishing rate F:

$$P_e(F) = \exp\{[\log_e(\alpha e^{-F} - 1)]/[\beta + \log_e K]\} \qquad (17)$$

Unlike the Ricker SRR, non-linear regression methods do not work well for fitting Shepherd's model to stock and recruitment data. Shepherd [1982] advised against this approach except when high quality data were available over many years. He suggested estimating the parameter α directly from the data and then fitting the other two parameters by regression methods. He also suggested using the slope of the line through the origin and the point corresponding to the highest recruitment index in the data as a conservative estimate of α.

It should be appreciated that the input data for stock-recruit relation are not easy to obtain, and that they may be subject to considerable uncertainty. Indeed, present stock-recruit functions do not fit very well and explain only a small amount of the variability observed in the data unless other parameters such as environmental variation are included.

It seems evident that further progress in fishery science must necessarily involve other methods of assessing stocks and for providing management advice which in some way can account for both sampling variability and environmental variability. We believe that the fishery-related recommendations of this workshop are related directly to these matters.

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Appendix D: Aquaculture Production Systems Research and Development Trends in the U.S.[*][+]

John J. Manzi[1], Robert P. Romaire[2], and Robert Stevens[3]

Aquaculture production has rapidly escalated over the last decade. Total annual world production for 1985 was estimated at nearly 12.5 million metric tons. This includes 5.7 million tons of finfish, 2.9 million tons of mollusks, 3.5 million tons of seaweeds and about 280 thousand tons of crustaceans. These production figures represent increases in production from 1975-85, of as little as 50% (in mollusks) to over 800% (in crustaceans and seaweeds). Aquaculture production systems have evolved rapidly over this period, keeping pace with, and in certain instances, stimulating increased productivity. Research on aquaculture production systems originally focused on hatcheries and nurseries for production of stockable quantities of commercial aquaculture candidate species. As reliable systems were developed to produce seed stock, research shifted to systems for extensive and semi-intensive growout. Today, production R & D is focused on intensification of growout systems, production of specialty products (production derivatives) (e.g., soft-shell crayfish) and improved nursery operations. Mechanization of hatchery, nursery and growout operations has also received significant contemporary attention. Future efforts in aquaculture production R & D will certainly continue in the field of aquaculture engineering for mechanization in this expanding industry. In addition, however, production systems will greatly benefit from research on carrying capacities of natural systems, harvesting and on-site processing equipment development, disease treatment, pollution monitoring and control, water quality aspects of production, as well as operational responses to improved genetic production lines and more efficient and economical feeds.

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[*] Publication No. 269 of the South Carolina Marine Resources Center. Address presented at the International Symposium on Aquaculture Research Needs for the Year 2000, New Delhi, India, November, 1988.

[+] Submitted for publication in the International Journal of Aquaculture Research and Technology

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1. Introduction

World fishery landing statistics collected over the last decade seem to indicate that total annual fishery production is beginning to stabilize at between 80 and 90 million metric tons [FAO, 1986]. Most fishery scientists believe that the ocean's total annual wild harvest is at, or near, its maximum sustainable yield (MSY). Estimates of demand for fishery products however, is expected to continue to increase. One recent report [Sandifer, 1988] projected an increase in demand for fishery products of nearly 40% by the year 2000 (40 million metric tons higher than the projected MSY). The difference between demand and natural production has been, for the most part, accommodated through aquaculture production. In 1985, total world fishery production was nearly 85 million metric tons [Nash, 1987] with nearly 12 . 5 million tons or 14 . 7% attributed to aquaculture (Table 1) .

Table 1. World Aquaculture Production (Thousand MT) by Species Group: 1975-1985 [International Aquaculture Foundation, 1985]

Group Change	1975		1985		%
Finfish	2,629	(53.7)	5,697	(45.8)	116.7
Seaweeds	265	(5.4	3,526	(45.8)	1,230.6
Mollusks	1,961	(40.1)	2,886	(23.2)	47.2
Crustaceans	30	(0.6)	282	(2.3)	840.0
Other	11	(0.2)	39	(0.3)	254.5
TOTALS	4,896	(100.0)	12,430	(100.0)	153.9

* Numbers in parenthesis are percent of total for each year's landings.

The total value of the 1985 aquaculture harvest exceeded $17 billion dollars (U.S.), of which finfish comprised over 65%, seaweeds over 15%, mollusks nearly 10%, and crustaceans about 8% (Table 2) .

Table 2. Value of Aquaculture Production in 1985 by Species Group

Group Total	Value/kg $USD	Total Value Millions USD	% of
Finfish	2.02	11,515.6	66.7
Seaweeds	0.74	2,597.8	15.1
Mollusks	0.59	1,700.8	9.9
Crustaceans	4.92	1,384.8	8.0
Other	1.29	50.3	0.3
TOTALS	---	17,249.3	100.0

World aquaculture production has historically been dominated by Asia. The 1985 aquaculture production figures indicate the continuation of that trend. Asian aquaculture production for 1985 was nearly 10.5 million metric tons or 84% of the total world production. Europe, by comparison, was the second highest production continent at nearly one million metric tons or approximately 8% of total production. The remaining 8% of world production was attributed to the rest of the world, primarily North America. The Peoples Republic of China is a significantly higher producer of aquaculture products than any other country, producing in 1985, over 4.5 million tons of aquaculture products. They were followed by Japan at about 1.1 metric million tons, Indonesia at 0.8 metric million tons and Korea at about 0.6 metric million tons. The ten leading producer countries account for about 8.8 million metric tons of aquaculture products or over 70% of the total world production.

The need for increased aquaculture production to supplement fisheries' landings has impacted production. Recent trends in aguaculture production shows a rapidly escalating industry. A comparison of the ten year change (1975-85) in world aquaculture production (Table 1) shows increased of 117% for finfish, 47% for mollusks and 848% for crustaceans. The total world increase in aquaculture production over this time period was about 67%. Aquaculture production increased were led by Norway (over 1000%), the USA (340%) and France (220%). Projections for world aquaculture production show a rapidly growing industry. Table 3 shows aquaculture production projections to the year 2010. World production is projected to more than double and United States production to more than triple over that period. These projections assume that present research and development (R & D) activities will be reasonably successful and will lead to profitable modifications in existing aquaculture production systems. It is also assumed that future R & D activities in aquaculture production will be aimed in the proper direction. This paper reviews the status of general production technology research in aquaculture in the United States and speculates on future trends in research and development.

Table 3. World and United States Aquaculture Production (x 1,000 metric tons) Projections [International Aquaculture Foundation]

Area	1985		1990		2000		2010	
	MT x 1,000	%	MT x 1,000	%	MT x 1,000	%	MT x 1,000	%
Other Countries	12,120	97.5	14,040	97.2	19,602	96.9	26,543	96.4
United States	310	2.5	405	2.8	628	3.1	992	3.6
World	12,430	100.0	14,445	100.0	10,230	100.0	27,535	100.0

2. Status of Production Technology

In the United States, several Species of mollusks, finfish and crustaceans are reared in commercial aquaculture systems (Table 4). Among the mollusks are oysters (Crassostrea virginica and c. gigas), clams (Mercenaria mercenaria), and mussels (Mytilus edulis). Finfish include the channel catfish (Ictalaris punctatus), rainbow trout (Salmo gairdneri), several species of anadromous salmon, and a number of tropical fish species. Commercially reared crustaceans include the southern crayfish (Procambarus clarkii), the freshwater prawn (Macrobrachiam rosenbergii), several species of penaeid shrimp, and the soft-shelled blue crab (Callinectes sapidus).

2-1. Mollusks

Molluscan aquaculture production in the United States has not increased as steadily as other groups. In the last five years (for which statistics are available), total U. S. aquaculture production has increased over 170% with finfish and crustaceans nearly increasing threefold (Table 4). Molluscan aquaculture, on the other hand, has had no increase over this time period. This, however, is misleading. Table 4 shows that while total molluscan aquaculture production has been flat, clam and mussel culture has increased considerably. Oyster culture has actually declined over the same period, giving an overall poorer picture of total molluscan aquaculture since it numerically dominates the statistics. Mussel and clam culture have increased substantially and both show the potential for significant additional growth in the near development and application of efficient hatchery and nursery technology [Burrell, 1985; Manzi, 1985]. Hatchery-produced bivalve seed are normally placed in land-based or field nursery systems for intermediate growth. Land based nurseries are usually raceway or upflow systems which allow for the intermediate culture of marine bivalves at extremely high densities. Field nurseries include raft and tray culture systems and pond culture, particularly in conjunction with temporally limited crustacean culture.

Table 4. United States Aquaculture Production (metric tons) by Species Groups in 1980 and 1985 [data from Rhodes 1988; 1989]

Group	1980	1985	% increase
Baitfish	10,000	11,540	14.5
Catfish	34,855	148,290	325.5
Salmon	3,455	33,741	876.6
Trout	21,836	23,129	5.9
FISH TOTAL	70,146	216,610	208.8
Clams	255	1,137	345.9
Mussels	-	547	n/a
Oysters	10,755	10,925	1.6
MOLLUSK TOTAL	11,010	12,609	1.5
Crayfish	10,849	44,218	307.58
FW Prawn	136	81	(4.0)
Marine Shrimp	-	614	n/a
CRUSTACEAN TOTAL	10,985	44,913	308.86
Other Species	-	7,029	n/a
ANNUAL TOTAL	92,141	281,161	205.1

Nursery produced juvenile bivalves are then planted in a variety of field culture systems depending upon geographical location and local environmental characteristics. In the northeast, subtidal cage culture and free planting are practiced almost exclusively. In the southeast, intertidal cage or pen culture, subtidal cage culture, and subtidal bottom culture are practiced. In the Pacific northwest, which has shown a dramatic increase in oyster production, intertidal bottom culture and rope or stake culture are generally practiced. Recently, triploid oysters (c. gigas) have been produced in commercial quantities and are marketed seasonally to provide a half-shell commodity during those periods that are normally characterized by sexually mature adults (an unsalable product for the half-shell trade).

2-2. Finfish

Major finfish culture systems in the United States today utilize earthen ponds, tanks/raceways, net pens and cage culture. Pond culture of channel catfish (Ictalurus punctatus) has become the major United States aquaculture industry [Tucker, 1985]. Beginning in 1960 with only 160 ha of earthen ponds in co commercial production, the industry has grown to over 50,000 ha of earthen ponds. Most of these ponds are located in the southeastern United States which offers a long growing season, suitable soil for constructing ponds and abundant ground water. As catfish farmers have gained experience and knowledge, the average production has increased from less than 2,400 kg/ha to about 4,400 kg/ha. High producers frequently achieve 7,500 kg/ha. Current production per year is about 127,000 metric tons [USDC, 1988].

Ponds are typically 1 to 2 meters deep and 2 to 8 ha in surface area. Smaller ponds are used for spawning of broodstock and for rearing of fry to fingerling size before stocking in the grow-out ponds. The industry is totally dependent on pelletized food which is readily available from fish food manufacturers. Protein content of such rations vary from about 40 percent for fry to about 30 percent for growing the fish to market size (0.7 kg). Harvesting is accomplished by seining the marketable portion of the crop while leaving the smaller fish for further growth. Draining of the pond for harvest is very seldom done because it is wasteful of water and the cost of pumping to refill the pond is expensive. Major problems include insufficient dissolved oxygen, diseases, and parasites, off-flavor and predation by birds.

Rainbow trout have been cultured in the United States for over a century but the commercial industry has been in existence only since the 1940s. Commercial trout production can be found anywhere in the United States where sufficient cold water springs are available. However, because of very large springs located in the Snake River Valley of Idaho, over 70 percent of the total production is located there. These great springs emanate from cliffs overlooking the Snake River. The water is passed through rectangular raceways as it flows to the river. The water is naturally oxygenation and of an ideal growing temperature. Supplemental aeration is needed when the density of the fish being reared is high.

The current annual production of rainbow trout in the United States is about 23,000 metric tons. Harvest is easily accomplished by seining the raceways or by simply pumping the fish into tank trucks. Fry are produced by manually stripping the brood fish and incubating of the eggs until hatching occurs. The rainbow trout industry is also based on pelleted food. Average protein content for trout food is 50% for larval forms and about 40% for growout. Disease and parasites constitute major problems for the industry. Several species of Pacific salmon along with the Atlantic salmon are part of a small but growing industry based on cage and pen culture in estuaries such as the Puget Sound in the state of Washington. In this culture, fingerlings are obtained from commercial producers, placed in cages and simply fed pelleted food until harvested. Current annual production in the United States is about 35 thousand metric tons. Major problems include diseases and maintaining the cages in good operating conditions.

2-3. Crustacean

Crustacean culture in the United States is practiced exclusively by pond culture although the size, shape and conformation of ponds varies widely with species and production intensity. Although crustacean aquaculture comprises only a small percentage of global aquacultural production (Table 1), the growth and development of crustacean aquaculture has been phenomenal over the past Decade. Crustacean aquaculture in the United States is practiced almost exclusively in the sub-tropical climate of the southeast and tropical Hawaii and Puerto Rico. Commercial aguaculture is relegated to only a few species including freshwater crayfish, several species of marine shrimp, freshwater prawns, and soft crabs. Of these species, only freshwater crayfish and soft-shelled crabs comprise significant aquaculture industries. The crayfish industry is the only large-scale crustacean aquaculture industry in the United States at present [Avault and Huner, 1985] and is second only to channel catfish as the largest U.S. aquaculture industry. Although several species of crayfish are cultivated in the USA, the red swamp crayfish (Procambarus clarkii) and the white river crayfish (P. acutus acutus) dominate production. In 1988, crayfish were cultivated on 63,000 ha in the southern USA with annual estimated production of 48,000 MT and a dockside-value of $60 million. The growth in the crayfish industry has increased by 6-12% annually since 1980.

Crayfish aquaculture utilizes an extensive production regime in earthen ponds. Self-sustaining populations of crayfish are established in ponds which are filled and drained of freshwater to simulate hydrological conditions that are optimal for production of the species in natural habitats [Avault and Huner, 1985]. Ponds range in size from 2 to 1,000 ha but the most common commercial ponds are 10 to 25 ha in surface area. Ponds are stocked with 50 to 75 kg per ha of brood crayfish in the spring prior to the initial production season. Crayfish are grown in fall, winter and spring and ponds are dewatered during the summer. sNo hatcheries are used to produce juveniles for stocking ponds nor are formulated rations used to feed the crayfish. Females spawn in subterranean burrows in late summer through early fall. Volunteer vegetation, semi-aquatic plants, or seeded forage, such as rice, are cultivated as forage Ponds are refilled with water in the fall and crayfish are harvested in fall, winter and spring with small baited basket wire traps. Average production of crayfish from farms is 800-1,000 kg per ha per year, although well-managed ponds produce in excess of 2,500 kg per ha. Most common production problems are associated with poor water quality and inadequate feed.

The culture of penaeid shrimp is in its infancy in the U.S. with less than 2,000 ha producing about 1,000 MT with dock-side value of $6.5 million USD. Texas is the leading producer of farm-reared penaeid shrimp with about 500 metric tons, followed by South Carolina (250 metric tons), and Hawaii (250 metric tons). The major cultured species in the USA are the non-native Pacific white shrimp, (Penaeuf vannamei), and the blue shrimp, (P. stylirostris). Of the native penaeid species, only the Gulf white shrimp, (P. setuferys), has shown potential for commercial aquaculture. Numerous factors restrict profitable shrimp farming in the U.S. and these include climatic limitations, site suitability and permitting problems for commercial development in sensitive coastal zone areas, legal constraints regarding the use of non-native shrimp species in certain states, broodstock availability, high labor costs, and financing.

Marine shrimp are cultivated in earthen ponds located in coastal areas where salinity is conducive for production. Shrimp grow-out ponds can be extensive, semi-intensive or intensive [Chamberlain, 1985]. Extensive systems are greater than 10 ha and produce less than 500 kg per ha (heads on) annually. Stocking density in extensive systems is typically less than 5 per square meter. Semi-intensive production systems as practiced in Texas and Hawaii produce 1,200 to 2,500 kg per ha annually in 4 to 10 ha ponds stocked with 8-15 PLs or juveniles per square meter. Intensive shrimp production systems are generally less than 4 ha and produce shrimp yields greater than 2,500 kg per ha annually at PL stocking densities of 15 to 25 per square meter. Most of the cultivated shrimp cultured in the USA is practiced in semi-intensive systems. Shrimp are fed formulated diets of 25-35% protein. The high cost of producing shrimp in the USA compared to production costs in Latin America and Southeast Asia make marine shrimp farming a high risk business endeavor that is unlikely to see major growth without significant increases in production intensity and cost efficiency.

The Malaysian prawn, (Macrobrachium rosenberaii), is a tropical freshwater prawn native to the Indo-Pacific where it is principally cultivated (Malaysia, Thailand, Taiwan and Indonesia). The prawn was introduced into Hawaii in the mid-1960s and its potential for culture has been studied extensively in Hawaii, Florida, South Carolina, Texas and Louisiana. Presently, commercial prawn aquaculture is limited to Hawaii and Puerto Rico with about 250 ha of grow-out ponds. Current annual production is about 500 metric tons with a wholesale value of $5,000,000 USD. There are no large-scale commercial freshwater prawn aquaculture operations in the continental USA and several attempts at commercial prawn production in Texas, Louisiana, Florida and South Carolina have failed. Prawns are cultured in earthen ponds containing freshwater and using semi-intensive or intensive management procedures similar to marine shrimp [Sandifer and Smith, 1985]. Semi-intensive ponds range in size from 4 to 10 ha and intensive ponds normally less than 2 ha. Prawns are fed formulated rations of 20-25% protein.

The primary constraints to profitable prawn monoculture in the continental U.S. are the lack of a reliable and inexpensive source of PLs or juveniles for stocking, the restricted 6 to 7 month growth season, variable yield and size at harvest, lower meat yield than penaeid shrimp, questionable product and storage quality, and competitive price disadvantage for medium sized prawns compared to marine shrimp Prawns grow well in polyculture with channel catfish, and several hundred kg of prawn per ha can be produced. The polyculture of prawns and bait minnows has also shown potential but further research is needed.

Soft-shelled crab production is a significant aquaculture industry in states bordering the Gulf of Mexico and the Chesapeake Bay area. Production is based on capture of hard-shelled blue crab (Callinecte sapidus) from wild fisheries and transfer to shore-based shedding facilities where crabs molt. Estimated annual production of soft-shelled crags is about 2,000 MT with a wholesale value of $25 million USD.

3. Research and Development: Present Activities and Future Demands

Present and future research and development activities are directed toward the goal of producing the highest quality product at the least cost while avoiding adverse effects upon the environment. The primary focus of R & D activities has been, and will probably continue to be, centered on four main areas: nutrition, genetics, engineering, disease diagnosis and control.

3-1. Nutrition

Nutrition continues to be a primary research interest in aquaculture. Defining complete diets for existing and potential aquaculture candidates as well as refining existing diets for various applications are significant ongoing programs. The importance of diet in the final nutritional value of the aquaculture product is well known and has inspired research to produce diets for a variety of effects (e.g., to prevent off-flavor in catfish, add color to salmon and sea bream flesh, and increase omega-3 fatty acids in pond reared fish).

Research on nutrition in aquaculture production systems will in the future be driven by some very real needs. First, sources of protein in feeds is rapidly becoming the basis of an economic tug-of-war. Fish protein concentrate and other fish meals are the protein sources of choice in most shrimp and carnivorous fish feeds. Fish meal is increasing in price and decreasing in availability as new "higher profit margin" products using fish meal are developed. Since as much as 60% of the operational costs of shrimp and fish farming may be related to nutrition, it will be imperative to find alternatives to fish meal as protein sources in diet formulations.

Nutrition and feed development will become even more important research priorities as the needs for pollution control and reproductive control become more critical. Self-pollution is a growing problem in aquaculture development and the formulation of feeds that reduce feed 1088 to the environment and that are more completely utilized can be a significant benefit. The role of nutrition in reproductive control is also an important R & D priority. The true domestication of cultured species depend, to a large extent, on the ability to have absolute control over reproduction. Nutrition in conjunction with physical and chemical} cues can not only control the temporal aspects of reproduction but can also play a dominant role in the quality and quantity of gamete production.

3-2. Genetics

The role of genetics in aquaculture research and development is substantial now and will increases in importance as the industry grows [Gall and Busack, 1986]. The success of commercial culture of triploid carp and oysters as well as the demonstrated advantages (and disadvantages) of breeding programs at salmonid hatcheries have reiterated the importance of genetics in commercial aquaculture development. It is doubtful that aquaculture will enjoy the success and productivity of agriculture unless true domestication of the cultured species is attained. Genetic applications can direct and speed the process of domestication, providing the derivatives of extant species that are most suited to culture.

Hybridization, once an extremely popular interest among research geneticists, lost is momentum as a genetic tool for aquaculture over the last decade. Not one hybrid has been brought to commercial aquaculture production although several show promise. Recently, hybridization has again become a prominent R & D interest in aquaculture production. The culture of hybrid striped bass (Morone saxatilis x M. chrysops) shows great promise in the southeastern U.S. [Stevens, 1984; Smith, 1988; Smith and Jenkins, 1988]. Studies have also indicated advantages in the culture of a hybrid catfish (Blue x Channel) and a hybrid oyster (Crassostrea virainica x c. gigas). Research is now ongoing and pending in hybridization of penaeid shrimp, salmonids and hard clams [Manzi and Castagna, 1988].

Ploidy manipulations have had some success with triploid carp and oysters but has not lived up to its expectations in either agriculture or aquaculture. Triploidy appears to impart growth and/or environmental vigor to some species but as yet, has not proved significant enough to stimulate commercial production. Future applications of ploidy manipulations may be found, to a large extent, in the production of sterile organisms for stocking in areas where introduction of exotics may be a problem or in ocean ranching production where stock enhancement is not a prime objective.

The development of transgenic methodology and advances in tissue culture capabilities have opened new and exciting genetic possibilities in aquaculture research and development. We are just beginning to determine the potential of these new genetic technologies but their future in aguaculture R & D is assured. There is, however, a general impression among aquaculture researchers that while the new qenetic technology will provide means to rapidly modify genetics, it will not, nor should it replace the basic breeding programs necessary to improve production stocks for commercial aquaculture

3-3. Engineering

Perhaps there is no aspect of aquaculture research and development that has received more attention in the recent past than engineering. The development of net pen culture system made the evolution of salmon culture possible. The harvesting and processing mechanization of mussel culture in the Netherlands made this commercial industry possible. Catfish farming in the southeastern U.S. has benefited greatly by the development of mechanized feeding systems, computer-assisted monitoring and control systems and automated processing lines. Subsequently, it is toward engineering that aquaculture R & D attention will focus for future development.

Areas of engineering interest literally cover the entire spectrum of aquaculture production systems. Several distinct research directions are developing however, including water reuse systems, multiple-use facilities and polyculture systems, water treatment methods, particularly for waste removal, drug reclamation or neutralization, and pathogen removal. Most experts agree that the world is rapidly approaching a water crisis that will impose restrictions on water use. Research in production aquaculture that investigates closed systems for water reuse, partial reuse systems, polyculture and multiple use production systems, and intensification of culture will become increasingly important. Additionally, technology in water treatment for the elimination of waste and drugs before reintroduction to the environment will be a high priority.

Mechanization will continue to be a high priority in R & D efforts in commercial aquaculture. As production increases and profit margins slip, the minimization of production costs will become an imperative. Mechanization of all aspects of production systems can lead to significant decreases in operating expenses. Increased efficiency may also make previously uneconomical species better aquaculture candidates. Many species previously discarded as unlikely for commercial aquaculture may become attractive as advanced engineering, genetics and nutrition begin to impact the industry.

Finally, the modelling of natural environments for intensive culture or ocean ranching will greatly influence future aquaculture production. Not only will a better understanding of the interaction of the environment with production systems be achieved but also a proper assessment of carrying capacities will reduce pollution and other problems related to over and under utilization.

3-4. Disease Diagnostic and Control

As production systems become more intensive and organism are reared in closer proximity to each other, disease and disease related problems will become an even larger research priority than it is today. Over 100 diseases are recognized as serious or potentially serious in commercial production in North American marine aquaculture [Sindermann and Lightner, 1988]. For many of these, effective and economical treatment or prophylaxis have been developed but many diseases are without effective treatment. Research relating nutrition with diseases susceptibility or investigating diet in disease treatment will also be a priority in aquaculture production R & D. Regulatory registration of prophylactics and therapeutic compounds will receive a great deal of attention through the next two decades.

The interest in polyculture will also provide impetus for disease research. The problems associated with possible disease introduction in multiple species culture or with multiple use of the same water or facilities will increase the likelihood of disease in production systems. Even disease treatment may have to be modified appreciably in multiple use Systems as the tolerances and Efforts of treatments may vary dramatically in different species.

4. Summary and Conclusions

Much of the future emphasis on aquaculture production research and development will probably be a direct result of more intensive utilization of resources. If we are indeed moving toward a water crisis, many of the R & D priorities will be directed toward the problems associated with limited water resources. This will include research on multiple water and facility use, monitoring and controlling culture parameters in real-time computer-assisted systems, modelling the carrying capacities of closed, partially open and open culture systems to efficiently utilize available resources, problems with aquaculture self-pollution, and water treatment. The conflicts that have developed and will develop in response to water use in a limited resource system will be the basis of other research priorities including the engineering priorities of growout systems that better utilize inshore areas and make possible the use of previously unusable offshore areas. The socioeconomic realities of conflicting uses of inshore areas will also demand research priorities from both the hard and soft sciences [Stickney, 1988].

The introduction of nonindigenous species for commercial aquaculture production is another area of potential conflict and thus the basis of a strong impetus for research on disease, ecological interactions and ecological modelling of aquaculture production systems. Potential problems with exotics also stimulate research interests in water treatment and water reuse and the intensification of closed or semi-closed systems.

Self-pollution of aquaculture growout systems is perhaps one of the premier issues in aquaculture research and development. The potential for pollution by certain growout methods (e.g. net-pen culture of finfish) is a primary concern of regulatory and management agencies and of the producers who fear destruction of the very habitat they require for production. These concerns are stimulating research in the development of new feeds, new-growout methodologies and new production systems to prevent or ameliorate pollution problems.

In summary, the research priorities of the future should and probably will address the aquaculture production problems of today. In addition, however, research priorities should be even more far-reaching, geared not only to solving today's problems, but also toward predicting the future needs of this rapidly growing and rapidly evolving industry.

Support for the International Symposium on Aquaculture Research Needs for the Year 2000 were provided by the U.S. Department of Agriculture, Office of International Cooperation and Development, and the Far Easters Regional Research Office of the U.S. Department of State. The Symposium was jointly sponsored by the Indian Council of Agricultural Research and the U.S. Department-of Agriculture. The authors thank the numerous scientists and extension specialists who contributed their thoughts on research needs to this paper. We particularly acknowledge input from Conrad Mahnken and the United States scientists participating in the UJNR Field Trip in October, 1988 in Hokkaido, Japan.

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Appendix E: Knowledge-based Systems

KNOWLEDGE-BASED (EXPERT) SYSTEMS

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Topics

DEFINITIONS

EXAMPLES

USES

MECHANICS

PRAGMATICS

TOOLS

REALISTICS

What are expert systems?

COMPUTER PROGRAMS THAT SOLVE PROBLEMS CONSIDERED TO BE DIFFICULT AND REQUIRING A GREAT DEAL OF EXPERTISE

"KNOWLEDGE-BASED" TO THE EXTENT THAT THEIR PERFORMANCE DEPENDS ON THE USE OF FACTS, BELIEFS, AND "HEURISTICS" USED BY EXPERTS

Some "famous expert systems

PROSPECTOR: Mineral Exploration

MYCIN: Medical Diagnosis

HEARSAY II: Speech Understanding

DENDRAL: Organic Chemistry

R1: Computer Configuration

INTERNIST: Internal Medicine

Some expert system "realities

PICK YOUR PROBLEM VERY, VERY CAREFULLY

MAKE SURE THERE ARE PLENTY OF ARTICULATE EXPERTS

MAKE SURE THAT A SUITABLE KNOWLEDGE REPRESENTATION STRATEGY EXISTS

PROCEED INCREMENTALLY

CONTROL YOUR RHETORIC...

Knowledge engineering/requirements analysis

THE IMPORTANCE OF TASK AND "DOMAIN" ASSESSMENT: "CAN THE PROBLEM BE IDENTIFIED AND MODELED?"

IS EXPERTISE AVAILABLE VIA HUMAN EXPERTS AND/OR CODIFIED FORM?

CAN THE KNOWLEDGE BE MODELED?

CAN A GOOD KNOWLEDGE ENGINEER BE FOUND?

-- TO SELECT A SUITABLE AI "PARADIGM"

-- TO SELECT A KNOWLEDGE REPRESENTATION STRATEGY COMPATIBLE WITH DOMAIN OBJECTS AND THE AI PARADIGM

-- TO ITERATE ON EXTRACTING EXPERTISE, RECODING AND POSSIBLY EVEN SHIFTING TO ANOTHER AI PARADIGM...

The five stages in building an expert system

1. Problem selection
2. System architecture selection
3. Prototyping
4. Knowledge acquisition
5. Evaluation and continued development

The Ideal Task

The task should have an easy and a hard version

The easy version deals with fewer objects or fewer attributes and is tackled first to allow the developers to avoid being initially overwhelmed

The hard version must be hard enough so that the need for a knowledge-based system is evident

The task should already be performed well by some person

The safest kind of task to tackle is one that is diagnostic in nature

Problem Selection: Management Issues

Effort required

A few days interaction among a few domain experts, a few knowledge engineers, and a few prospective users

The domain experts present several detailed case studies to the knowledge engineers and prospective users

The prospective users describe the kinds of assistance they would want if they were faced with the problems in the case studies

The knowledge engineers describe the kind of system it would be possible to build

Measuring success

Too early to tell

Identifying Tractable Task Domains

There are recognized experts

The experts are clearly better than amateurs

The task takes an expert a few minutes to a few hours

The task is primarily cognitive

The skill is (routinely) taught to neophytes

The task domain has a high payoff

The task requires almost no common sense

Some Sample Domain Types

Diagnosis and treatment

Configuration

Scheduling

Design

Diagnosis and Treatment

Task: To recognize problems or malfunctions, identify their causes, and propose treatment.

Example Systems:

ACE

Task: Identify cable problems

User: AT&T

CATS-1

Task: Find diesel locomotive faults

User: GE

Drilling Advisor

Task: Diagnose and recommend treatments for stuck drilling pipe

User: Elf-Aquataine

MUD

Task: Diagnose and recommend treatments for drilling fluid problems

User: N.L. Baroid

Factors to Consider

Is there a finite set of known problems?

Can expert assign a degree of support to each evidential consideration that can support a hypothesis?

Is there a core diagnostic procedure (eg, differential diagnosis) that provides empirically sound results?

Configuration

Task: To identify required components and integrate them into an acceptable system.

Example Systems:

R1

Task: Configure computer systems and produce plans

User: Digital

VT

Task: Configure elevator systems and produce blueprints

User: Westinghouse

Factors to Consider

How many different types of objects are there and how much must be known about each type?

How many different relationships can the average object enter into?

Can the configuration subtasks be performed in a fixed order?

Scheduling

Task: To determine and sequence actions that will achieve desired ends

Example Systems:

ISIS

Task: Job-shop scheduling and production management

User: Westinghouse

PTRANS

Task: Flow-shop scheduling and production management

User: Digital

Factors to Consider

How many different operations can be performed on the objects to be scheduled and what is the average number of operations that will be performed on a given object?

How many different types of constraints are there and how often is a particular scheduling task over-constrained?

How frequent is the need for rescheduling?

Design

Task: To create an object whose components are arranged in a way that satisfies (the most important) placement constraints and whose components have been selected to facilitate placement

Example Systems:

MOLGEN

Task: Plan molecular genetics experiments

User: Not yet in use

TALIB

Task: Propose cell layouts for integrated circuits

User: Not yet in use

Factors to Consider

How closely coupled are the selection and placement parts of the task?

How large is the set of plausible candidate objects in the selection part of the task?

How constrained is the placement part of the task?

The Design Specification

Represents the outcome of an analysis of task and domain

Describes the various tasks the system will perform and their interdependencies

Describes the problem solving strategies required in performing the tasks

Clarifies who is going to use the system and what they can be expected to know

Includes mock samples of interactions with the system

Proposes milestones

Changes over time

The Design Process

Design by implementing and re-implementing

Tackle the simplest and best understood versions of critical tasks first

Deal with the most familiar and accessible part of domain first

As soon as the shell can perform a few simple versions of the task, evaluate its potential

Architecture Selection: Management Issues

Effort required

A few days of analysis by one or more knowledge engineers to determine which, if any, of the available system building tools would be suitable

Several worker-years of effort on the part of experienced AI researchers to develop a tool if none of the available tools are deemed to be suitable

Measuring success

Has a system building tool suitable for the task been identified?

To be suitable, the tool must have adequate representational and problem solving power and must be reasonably efficient

Prototyping

Design an inference engine (unless you already have one that fits the task)

Try to give the inference engine knowledge

Evaluate the inference engine on the basis of the use it can make that knowledge

Redesign the inference engine so it can make better use of the knowledge

Re-represent the knowledge

Try to give the inference engine some more knowledge

Prototyping: Management Issues

Effort required

If an appropriately sized task has been selected, it should not take more than a few worker-months to develop an initial prototype

Most of the effort will come from one or more knowledge engineers, but the knowledge engineers need to be able to talk with experts and with prospective users whenever they have questions

The prototype may turn out to have insufficient potential to warrant further development, in which case a new prototype needs to be developed either with the same or with a different system building tool (or perhaps a new problem needs to be selected)

Measuring success

Does a prototype with enough potential to warrant further development exist?

The Knowledge Acquisition Loop

Give the developing system a new task

Ask an expert to identify mistakes

Ask the expert to infer what knowledge is missing

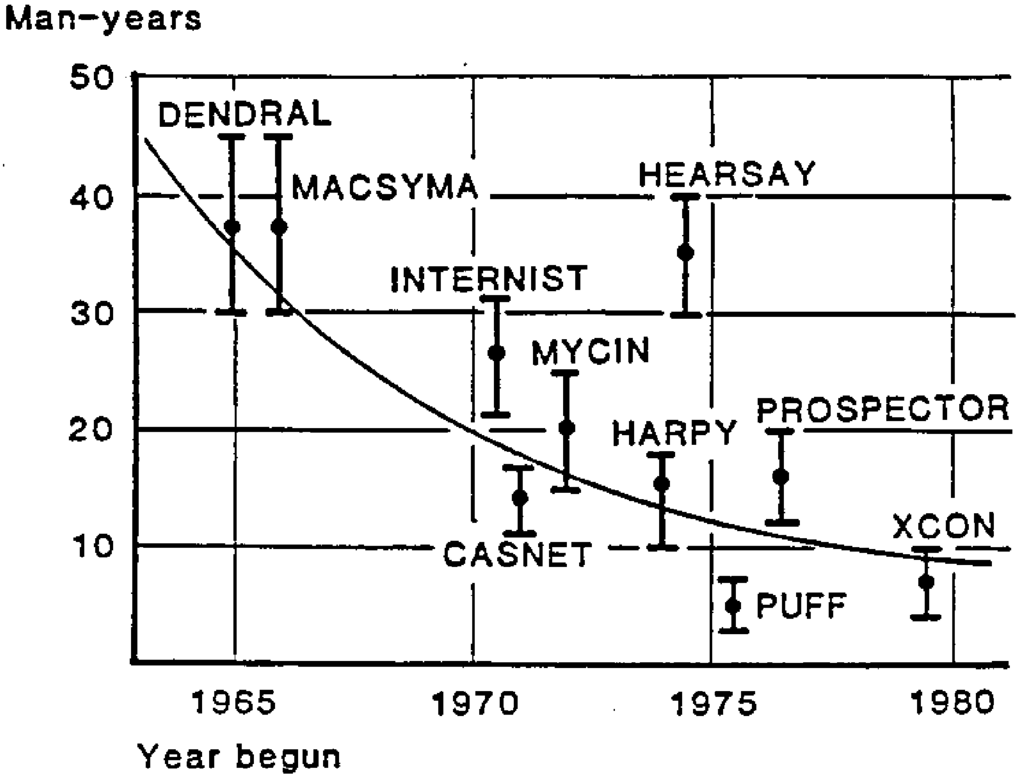
Add that knowledge to the system

Knowledge acquisition

THE TRANSFER AND TRANSFORMATION OF PROBLEM-SOLVING EXPERTISE FROM SOME KNOWLEDGE SOURCE TO A PROGRAM.

SOURCES OF KNOWLEDGE INCLUDE HUMAN EXPERTS, TEXTBOOKS, DATABASES, AND OWN EXPERIENCE.

KNOWLEDGE ACQUISITION IS A BOTTLENECK IN THE CONSTRUCTION OF EXPERT SYSTEMS.

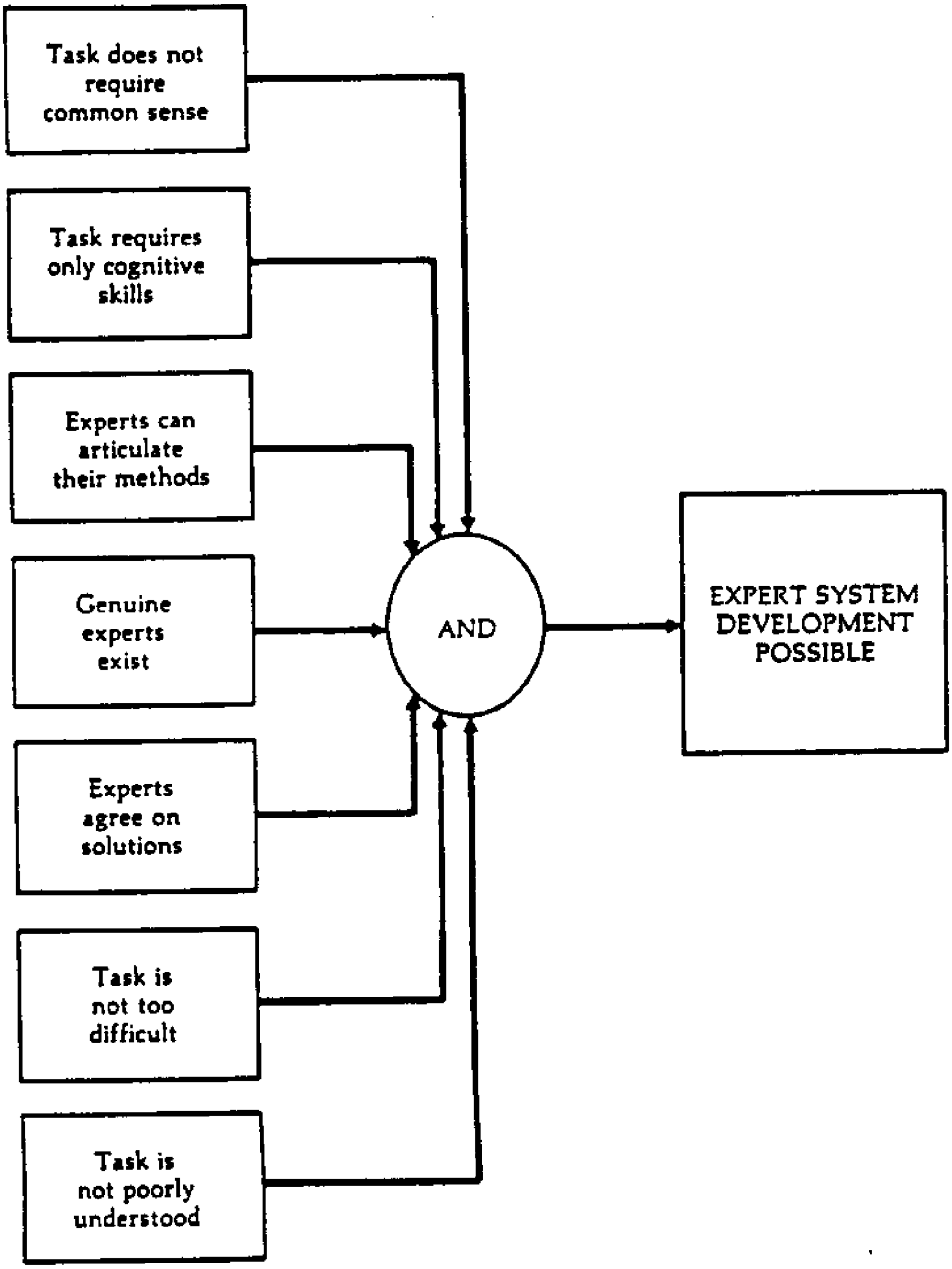


Time required to create various expert systems.

Resources Required to Develop Knowledge-Based Expert Systems

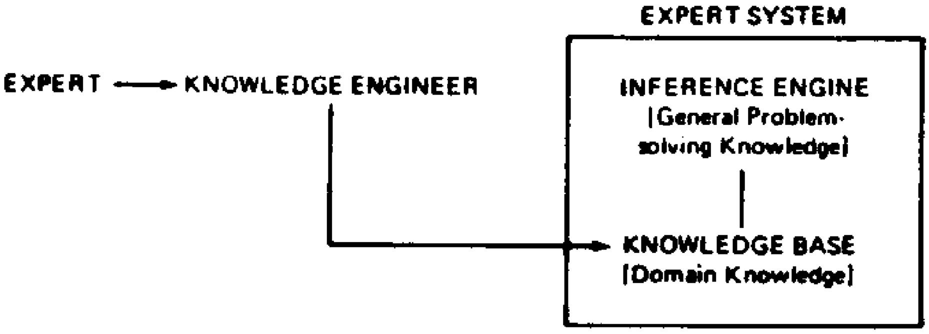
Considerations:	Type of System		
	Small	Large	Very Large
Rules	50–350	500–3,000	10,000
Tool available	Probably	Probably	Maybe
Person-years to develop	¼–½	1–2	3–5
Project cost	$40,000–$60,000	$500,000–$1 million	$2–$5 million

Note: included in costs: design, development, knowledge engineers, computing, overhead; excluded from costs: company expert, travel, fielding, transition.



Necessary requirements for expert system development.

Category	Problem Addressed
Interpretation	Inferring situation dscriptions from sensor data
Prediction	Inferring likely consequences of given situations
Diagnosis	Inferring system malfunctions from observables
Design	Configuring objects under constraints
Planning	Designing actions
Monitoring	Comparing observations to plan vulnerabilities
Debugging	Prescribing remedies for malfunctions
Repair	Executing a plan to administer a prescribed remedy
Instruction	Diagnosing, debugging, and repairing student behavior
Control	Interpreting, predicting, repairing, and monitoring system behaviors



Knowledge engineering—Expert to knowledge base via a knowledge engineer.

The Knowledge, Inference, and Interface Features of Various Tools

	Knowledge										Inference			
	Facts			Relationships				Uncertainty			Generating New Facts			
Key: ● Function present in tool ◑ Limited presence of function ○ Function could be programmed but is not provided as part of tool	A–V Pairs	O–A–V Triplets	Frames	IF–THEN Rules	"Variable" Rules	"Examples"	Multiple Objs.	Inheritance	Certainty Factors	Probabilities	Recognize–Act Cycle	*Modus ponens*	Resolution	Decision Tree Algorithm
EMYCIN		●		●			●	◑	●			●		
Small tools														
ES/P ADVISOR	●			●			○	◑					●	
Expert-Ease						●								●
INSIGHT	●	◑		●					●			●		
M.1	●	○		●	●		○	◑	●	○		●		
Personal Consultant		●		●			●	◑	●			●		
SeRIES-PC	◑			●								●		
K:base						●								●
Large, narrow tools														
EXPERT	●			●					●					
KES	●			●			●	●		●				
OPS5*	●	○		●			○				●	●		
S.1		●		●			●	◑	●			●		
TIMM						●			●					●
Large, hybrid tools														
ART	○	○	◑	◑			◑	◑	○	○		○		
KEE	○	○	◑	◑			◑	◑	○	○		○		
LOOPS	○	○	◑	◑			◑	◑	○	○		○		
SRL+	○	○	◑	◑			◑	◑	○	○		○		

Different versions have different features.

Inference							Interface										
Control Strategies							KE				User			Sources of Data			
Backward Chaining	Forward Chaining	Depth-First Search	Breadth-First Search	Procedural Control	Active Values	Event History	Knowledge Base Editor	Case Facilities	Trace and Probes	Graphic Display (Windows)	Explanations and Justifications	Line-Oriented Display	Prompted-Menu Display	Sensors	Instruments	Data Bases	Other Languages and Procedures
●	◑	●				●	●	●	●		●			○			
●		◑									●		●				●
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	●	○	○			●	○		●	○	◑	●					
●		●		●		●		◑		●	●			○	○	○	○
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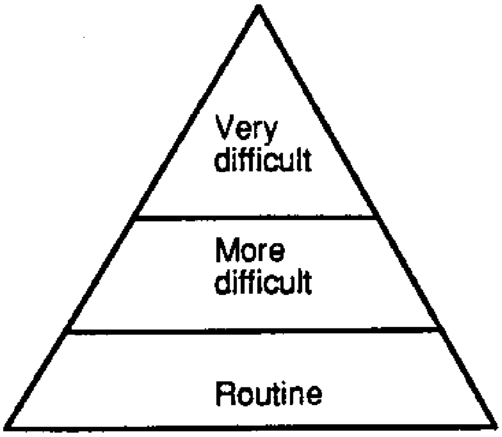
○	○	○	○	○	○	○		○	○	○	○			○	○	○	○
○	○	○	○	○	○	○		○	○	○	○			○	○	○	○

Appendix F: Applications of AI in the Military – Potential Applications to NOAA Marine Sciences

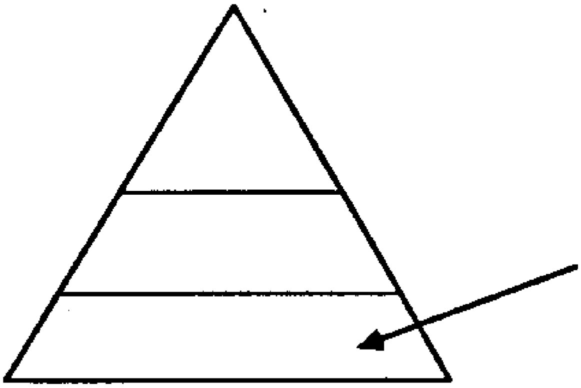
Jude Franklin, Ph.D.
Senior Vice President
Technology Division
Planning Research Corporation

EMHART PRC

Problem Spaces - Potential NOAA Marine Sciences Applications

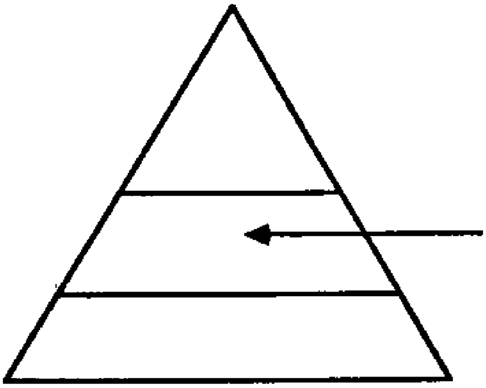


Problem Spaces - Potential NOAA Marine Sciences Applications



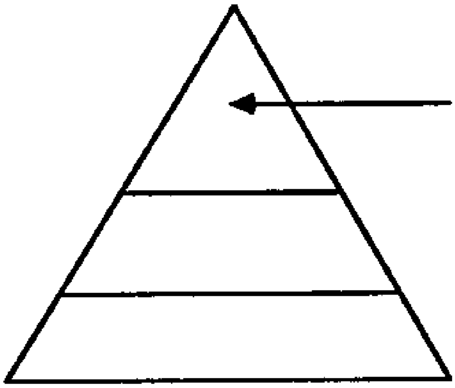
budget analysis/risk assessment
site analysis (potential problems)
machine allocation
detection
diagnostics
training
logistical management
design aids
- estimate fish population
- selection of best algorithm
- population dynamics

Problem Spaces - Potential EPA Applications



economic analysis of remedial alternatives
prediction and trend analysis
manifest tracking
learning - automatic algorithm adaption
report understanding
complex system design support
planning
intelligent storage and retrieval
software life cycle tools
data base management
qualitative models
    (physics, biology, chemistry)
penalty determination
emergency response

Problem Spaces - Potential NOAA Marine Sciences Applications



Sensor fusion
Strategic planning for congress
Classification
Global economic analysis
Tip off

Why Use AI?

- Small number of experts
- Missing and uncertain data
- Huge amount of data
- Large backlog of problems to be solved
- Potentially easier to design and modify

Some Military Examples Of AI Applications

- Expert Systems
  - Resource allocation
  - Radar interpretation
  - Target location
  - Diagnostics
- Natural Language
  - Message understanding and input to expert systems
- Distributed Problem Solving
  - Communicating cooperating expert systems

AI Potential For NOAA Marine Sciences Applications

- Sensor interpretation
  - steady state
  - transient
- Early detection of site problems
- Classification
- Trend analysis
- Target motion prediction
- Population prediction
- Economic analysis
- Tip-off to sensors
- Resource allocation
- Design and development
  - decision support systems
  - solution spaced search algorithms
  - learning to improve algorithms
  - hypothesis and test
- Report understanding
- Planning
- Sensor fusion
  - distributed problem solving
- Diagnostics

Key Issues In Expert Systems

- Knowledge principle
  - Lots of knowledge versus general inferencing techniques
- Knowledge acquisition
  - Bottleneck
  - Multiple sources of knowledge
  - Compleness issues
  - Deep knowledge of physics of the world
  - Manipulation of large knowledge bases
  - Interface technology
- System brittleness
- Common sense reasoning and analogical reasoning
- Handling uncertainty
- Learning
- Synergism among intelligent agents
- Generic expert systems
- Delivery machines
- Degree of expert in an expert system

Appendix G: Application of Knowledge-Based Systems to Fisheries Management and Acoustic Abundance Measures

Stephen B. Brandt[1]

I. Introduction

A principal goal of fisheries management is to set regulations that ensure the long-term stability and optimal use of a fishery resource (May 1984). The problem is complex because there are often multiple, competing uses of each resource. Setting the appropriate management strategy requires a quantitative understanding of the biological system and management decisions must be made within the context of environmental uncertainty and the prevailing social, political and economic field.

To understand how an ecosystem functions fisheries scientists need information on the abundance of the various components within the system and the rates at which material and energy are transferred between those components. Effective fisheries management, in particular, requires accurate measures of abundances of both the economically important species as well as the ecologically important species upon which fisheries production ultimately depends. Such measures of abundance are used to assess production, to set harvest and stocking levels, to set priorities for the management of fish habitats, and to provide a yardstick against which the system's response to management efforts can be evaluated. Key questions include; How many fish are present?, What harvest level can the population withstand?, How do changes in the abundances of one population affect changes in the abundances of other populations?, and How does the management strategy affect the long-term stability of the population and ecosystem? Few systems are well enough known

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for ecosystem oriented management to be quantitatively applied (May 1984).

It is extremely difficult to measure the absolute abundance of any fish population within a body of water. Many different types of gear have been used to sample fishes; all have certain limitations as to types and size of species vulnerable to the gear and the type of habitat that can be effectively sampled. Traditional fish sampling techniques, such as towing a net through the water, usually sample only a small percentage of the total fish habitat and can be biased by fish avoidance, escapement through the net meshes, or reliance of fish catch rates on the activity level of the fish [Barkley 1972; Nielson and Johnson 1983; Rudstam and Magnuson 1985].

Fish also have spatial distributions which are patchy and vary with specific habitat type and life stage of the species. Patchiness in fish distributions contributes to sampling bias and variance in estimates of stock abundances particularly if patch size and distribution are unknown and sample size is small [Steele 1978; Seber 1973; Pickett and White 1985]. Most techniques to assess fish abundance fit this description [Nielson and Johnson 1983]. The problem is compounded since the relative effects of patchiness and the level to which fish can avoid an approaching net or escape through the meshes cannot be differentiated. Fish that live in the midwater are particularly difficult to sample using traditional techniques because patch structure is three-dimensional and pelagic fish are able to respond quickly to habitat modifications and changes in water quality.

How do we assess the abundance of pelagic fish stocks when we are basically blind to the habitats and fish patch structure beneath the surface of the water? Do we have the sampling technology to sample the fish populations at the same level of resolution that we can measure the fishes habitat and in a time frame consistent with the speed with which the fish distributions are changing?

Acoustic techniques provide one potential alternative to net sampling for direct stock assessment. Sound travels efficiently in water and will reflect from targets that have a density different from that of water. This property has been used for over forty years to search for aggregations of fishes and measure relative fish abundances and distributions but, until recently, quantitative applications have been limited to ideal situations and required extensive fish sampling for calibrations and 'ground truthing' [Thorne 1983]. It is only with recent innovations in theory and technology that underwater acoustics has blossomed into an essential research and management tool. The ability to see and count what is under the surface of the water without disturbing the system is a key advantage of such acoustic systems. Continuous mapping of patch structure reduces many of the sampling problems created by the spatial heterogeneity of fish distributions.

Underwater acoustics for fish stock assessment is a relatively new and rapidly evolving technology and, as such, has not yet reached its full potential. The complexity and information-overload tendency of this technology suggest that the development of this field may benefit from the application of artificial intelligence and knowledge-based systems [Rauch-Hindin 1988]. Using examples form fish studies in the Great Lakes, I illustrate some abilities and limitations of current acoustic technology and the complexity of fish distributional patterns. I then suggest three general areas of potential application of knowledge-based systems; 1) intelligent interfaces in the equipment, 2) pattern recognition and the identification of acoustic targets, and, 3) in the analyses of the spatial and temporal patchiness of fish distributions.

II. Acoustics Background and Procedures

The types of applications of underwater acoustics to studies of fish are diverse. Acoustic technology has been applied by both fisheries managers and scientists alike in a wide variety of systems, ranging in size from small lakes and ponds to the open ocean. Thorne [1983] and Clay and Medwin [1977] provide good reviews. Echo sounders are the primary instrument for assessing fish abundances. Echo sounders operate by sending repetitive (e.g. one second intervals) pulses of sound into the water as a research vessel moves across the surface. The acoustic pulse is generated by a short time interval of high frequency (e.g. 12 kHz - 420 kHz) voltage to the pressure transducers. This pressure pulse causes a pressure wave which propagates radially from the transducer at the speed of sound in water. When the sound wave encounters a fish, or any other acoustic scatterer, an echo is propagated radially outward from the target and received at the surface as an echo. Echoes contain information on abundance (number of echoes), size, and distribution of fish targets. Echoes from biological scatterers are normally recorded digitally or processed in real-time aboard ship. Fish distributions are visually monitored with oscilloscopes and graphic representations of echo patterns (i.e. echograms). Since sound travels in seawater at ca. 1,500 meters per second, the entire water column can be quickly sampled and a continuous, detailed map of fish echoes is obtained. These data can be displayed in various formats (Figure 1). In many ways, the use of underwater acoustics to map fish distributions can be considered analogous to the use of satellite remote sensing to map sea surface temperatures.

Sound is transmitted into the water at a single frequency via a transducer. The specifications of the instrumentation such as pulse length, sound frequency, transducer directivity and transmitter power determine the resolution, sensitivity, depth of penetration of the acoustic system and the types and sizes of organisms that can be detected. Acoustic sensing of fish and other animals also depends upon the fraction of the acoustical energy reflected (backscattered) by the subject species and upon the variation of that backscatter due to changes in fish behavior. The strength of an echo is related to the biomass of the fish.

Echoes are received at the surface as time-dependent (i.e. depth of the water from which the echo was initiated) voltages. Echoes contain information on the depth of the target and on target size and abundance. Depth of the target is simply the length of time it takes for the sound to travel to the target and return to the echo sounder receiver but the complexity of the beam pattern of the transmitted sound makes it difficult to directly convert echo voltages to measures of fish size and abundance (i.e. number/biomass per unit volume). Recent innovations in acoustic technology, such as multiple beam transducers [Burczynski and Johnson 1986], and in acoustic signal processing theory [Clay 1983; Stanton and Clay 1986] have vastly improved our ability to convert echoes into quantitative measures of fish abundance and fish size. Such sophisticated signal processing can be done at sea using high-speed personal computers but analyses are often completed subsequently in the laboratory. Successful applications of acoustic stock assessment also require that the species of interest is well-behaved and acoustically accessible and that appropriate sampling strategies are used [Clay and Medwin 1977; Thorne 1983].

There are several disadvantages to acoustic systems. Fish that are near surface or near bottom (e.g. 0.5 m) cannot easily be detected

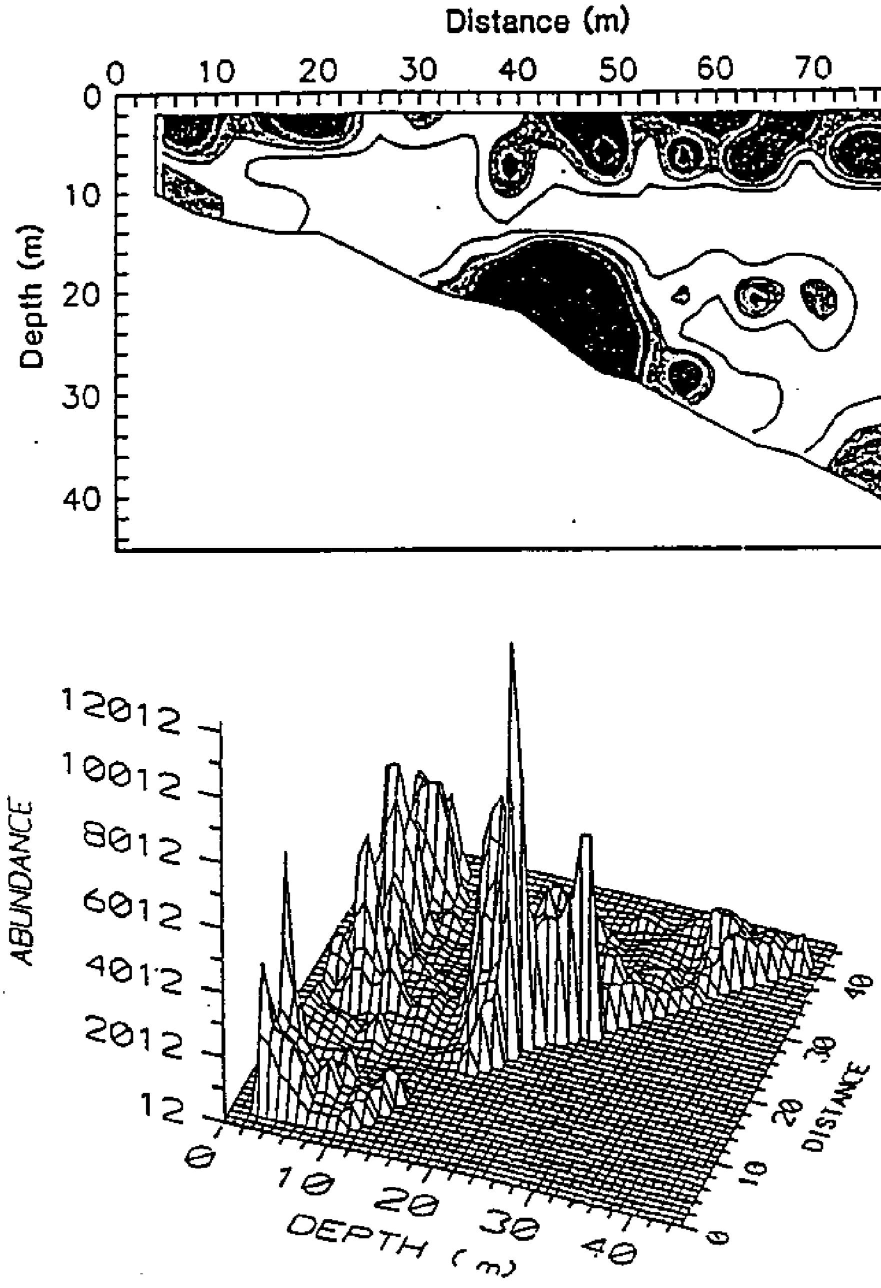


Figure 1. Contour (upper panel) and three-dimensional plot (lower panel) of fish scattering in Lake Michigan, off Waukegan, Illinois on 6 September, 1987. An acoustic value of 3,430 corresponds to approximately one fish per cubic meter.

acoustically. Acoustic data are complex and collected at a high rate. Acoustics have, as yet, little ability to identify species per se and provide little information on the biology (age, sex, diet) of the target species. Finally, there are few trained experts in this field.

III. Lake Michigan Examples

Introduction

Lake Michigan is one of the five Great Lakes of North America and is the sixth largest lake in the world. It has a surface area of 57,750 km, maximum depth of 282 m and mean depth of 85 m. The fish species community of Lake Michigan has changed markedly over the past 75 years. The marine alewife (Alosa pseudoharengus), a small herring-like fish that lives in midwater and feeds on zooplankton, invaded Lake Michigan in 1949. This species grew to dominate the fish community by the late 1960s. A second species, the rainbow smelt (Osmerus mordax), had invaded Lake Michigan by 1912 and was considered the second most abundant species in the open waters of the lake. Since the 1960s large numbers of trout and salmon have been stocked annually into Lake Michigan initially to control the abundant alewife and, subsequently to support an expanding sports fishery. Annual stocking now exceeds 16 million fish per year (Figure 2).

The main diet of stocked trout and salmon are the alewife and rainbow smelt [Brandt 1986]. Recently, alewife stocks have collapsed in Lake Michigan [Wells 1985] apparently in response to excessive trout and salmon predation [Stewart et al. 1981] and unusually cold winters [Eck and Brown 1985]. One of the native zooplankton eating species, the bloater (Coregonus hoyi) has taken the place of the alewife as the dominant midwater fish in the lake (Figure 2).

Alewife and rainbow smelt are also fished commercially in Lake Michigan. This creates an allocation problem for fish managers since the same fish that are being caught by commercial fishermen provide the main food for the larger species of fish sought by recreational fishermen. To determine the impact of the commercial fishery on the prey resources of the trout and salmon and to determine the impact of trout and salmon predation on the commercially fishery requires accurate measures of total alewife

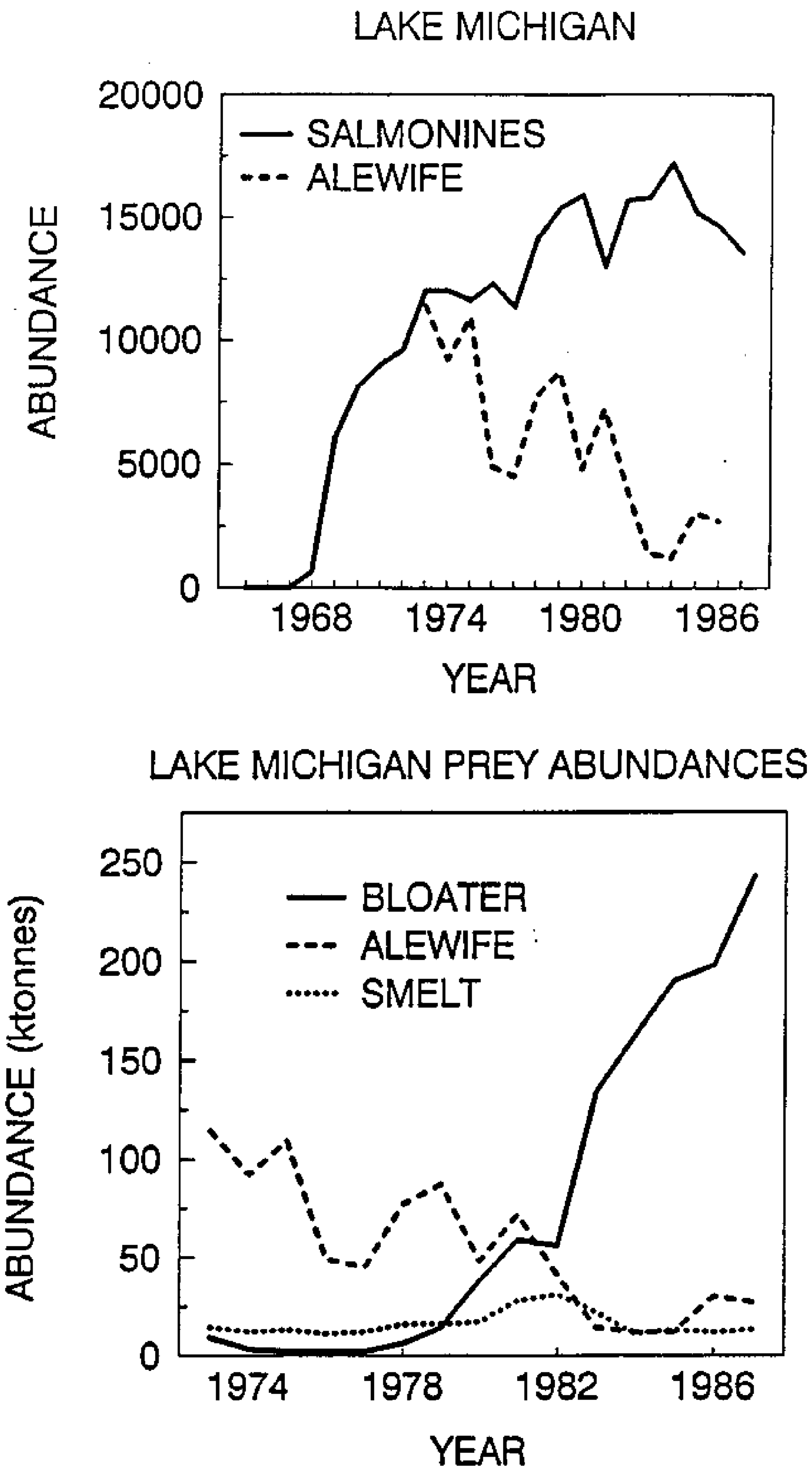


Figure 2. Stocking rate of trout and salmon in Lake Michigan (thousands of fish) and recent changes in relative abundances of alewife, rainbow smelt and bloater in the lake.

rainbow smelt and bloater abundances. Currently, the only information available is annual estimates of relative abundances of the prey species, bioenergetic models of the amount of prey that the trout and salmon can consume and measuress of the total commercial landings by species.

Our research forms part of a three-year program to acoustically assess total abundance of alewife, rainbow smelt and bloater in Lake Michigan and includes an evaluation of distributional patterns of pelagic fish that may be relevant to the development of optimal (statistically and economically) sampling protocols for long-term monitoring of fish abundances. To devise statistically valid sampling protocols for long- and short- term monitoring programs, requires studies on the diel and seasonal movements and behavior of the target species across various habitats. Identification of optimal sampling times are critical and species-specific.

Methods

During the past three years, five cruises have been conducted on Lake Michigan to assess biomass and temporal and spatial patterns of distribution of pelagic (midwater) fishes. The primary goal of this research was to assess the potential and limitations of acoustic fish stock assessment in Lake Michigan and to make recommendations for an optimal sampling protocol for long-term monitoring of fish abundances in the lake. A more complete description of this program can be found in Brandt [1989].

Each whole lake cruise typically collected continuous acoustic data using 2 - 4 frequencies simultaneously and included about 200 bottom and midwater trawl (net) collections, 300 temperature profiles, satellite coverage of surface water temperature and chlorophyll, zooplankton samples and phytoplankton samples. Most of the effort required two or more research vessels.

Lakewide surveys were intended to cover different seasons. During each survey complete day and night acoustic transects were run from nearshore to the deepest part of the lake off 8 - 10 regions of the lake. On all transects, acoustic data were digitally recorded. Transducers for each echo sounder were mounted in tandem in a hydrodynamically stable vehicle and towed alongside the research vessel at a depth of 1 m. Temperature profiles were routinely taken along each transect to map the thermal structure. Bottom trawls, midwater trawls, underwater video profiles and plankton collections were taken to identify the acoustic scattering layers. All acoustic systems were calibrated with tungsten-carbide reference targets [Foote and MacLennan 1983]. Chart recordings and oscilloscopes provided real-time monitoring of fish distributions.

All echogram examples and population estimates in this paper were taken with a 120 kHz echo-squared sounder. Echo integration was used to measure relative fish abundance. Absolute fish abundances and mean target size were measured using the deconvolution of the distribution of echo amplitudes [Ehrenberg et al. 1981; Clay 1983]. Fish densities were measured throughout the water column and summarized into 1 m depth strata and averaged over constant time intervals (e.g. 1 min). Acoustic measures of fish abundance were stratified by water depth and location to help minimize variance for the lakewide population estimate.

Results

During August - September, 1987 the acoustic assessment involved four ships for 16 days. The two independent measures of fish abundance made during that cruise (317,500 and 367,000 metric tonnes) were within 8 % of the mean. Acoustic measures of biomass and numbers of fish make biological sense. Comparisons of acoustic estimates for spring and late summer indicate that numbers of fish increased by a factor of 2.2 over the summer while biomass increased by 1.3 fold over the same time interval. Those results are consistent with expected population dynamics because large numbers of young-of-year fishes were spawned over the summer and mean individual fish weight would be less than for spring.

Large-scale seasonal changes in species composition in different areas of Lake Michigan (Figure 3) suggest lakewide movements of fish that might influence their availability as prey to trout and salmon and their relative effect on lower food levels. Such movements would also affect sampling designs.

Patches of acoustic scattering were clearly correlated with the physical structure. For example, sharp changes in bottom

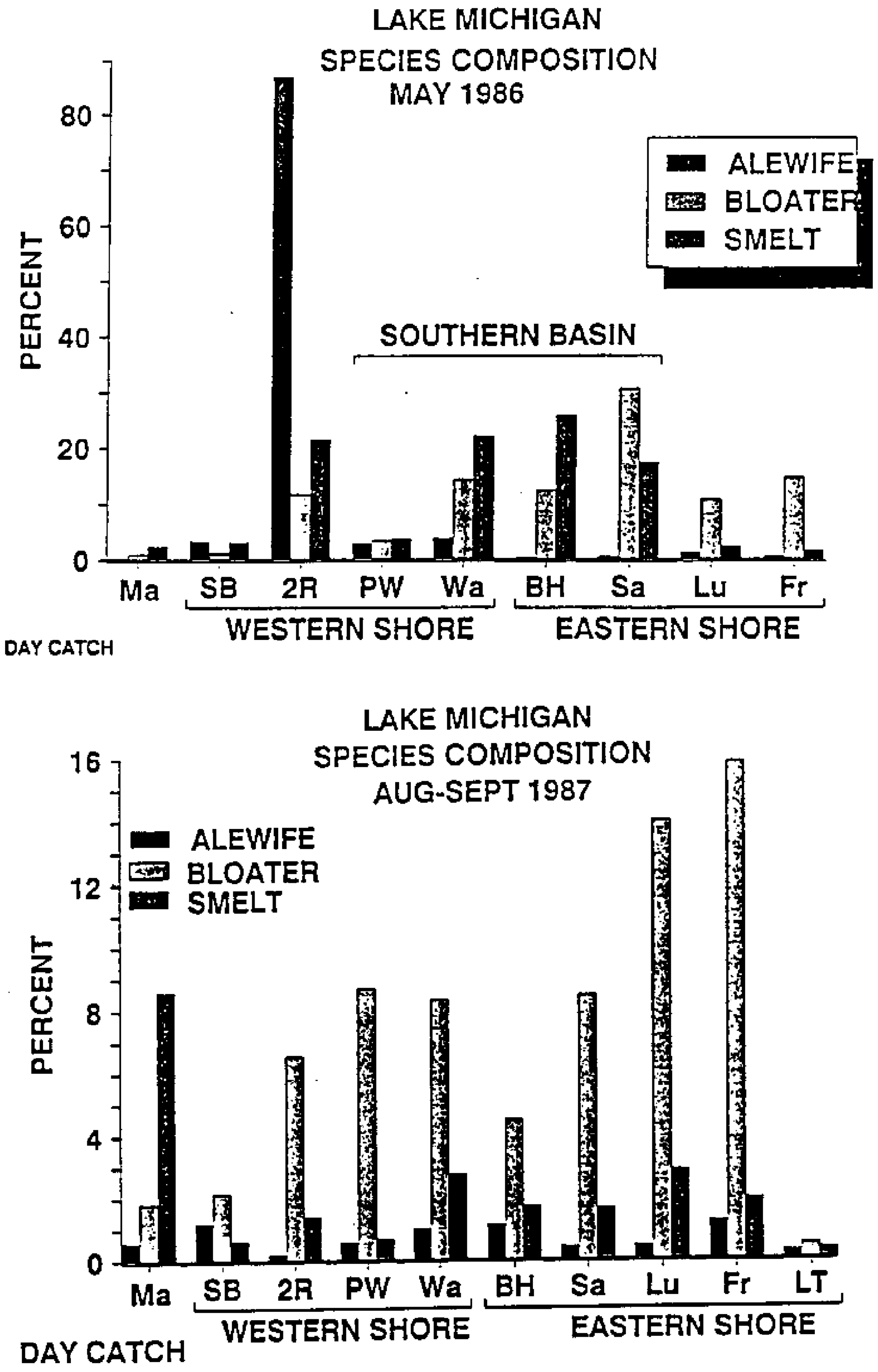


Figure 3. Comparison of species composition of day trawl catches in different areas of Lake Michigan during May and August-September, 1987. Abbreviations represent different ports of the lake.

topography were often characterized by aggregations of fishes (Figure 4). Patchiness in the midwater also showed cohesion with the thermal structure of the water column (Figure 5). Seasonally (Figure 6), fish were generally in layers during periods of thermal stratification (e.g. October) but appeared more dispersed when waters were well-mixed (e.g. April). Within season differences in acoustic scattering patterns were also evident. For example, during October, 1986, fish abundances off one port (Sturgeon Bay) were low (0.33 fish per square meter) compared to those off the two nearby ports of Two Rivers (.99 fish per square meter) and Port Washington (1.00 fish per square meter). During the Sturgeon Bay transect, upwelling extended from nearshore to about the 80 m depth contour and nearshore surface temperatures were less than 7 C. Upwelling in the nearshore areas apparently dispersed fish either out of the area or to regions not accessible using acoustics. In contrast, the other two ports had most fish either nearshore or in a layer associated with the offshore location of the thermocline. Surface temperatures within these areas generally ranged from 11.5 to 12.8 C in the lake and the thermocline was located at 25 - 35 m. Fish at the thermocline were identified as juvenile alewives by underwater video. During day, fish abundances throughout the water column decreased by 92% and most of the fish migrated to the bottom. Fish distributions in Green Bay were also dispersed. Although fish generally occupied the lower portions of the water column during day, distinct diel vertical migrations were not as prevalent as in the lake proper. Species composition in Green Bay was determined by trawling and was similar to that in other areas of the lake but the water column was well-mixed and nearly isothermal at 11.5 - 11.8 C during our survey.

In essence our surveys in Lake Michigan depicted three general habitat types (stratified, mixed and upwelling zones) in which the same species of fish had markedly different distributions.

Although whole-lake measures of fish abundance were obtained from the Lake Michigan study, the research was very labor intensive, largely because of data overload. The latter also restricted the amount of information that could be gleaned from the data in the short-term. Finally, the precision of the species-specific measures of abundance were limited by the precision of the method used to identify species. Knowledge-based systems may provide some solutions to these problems.

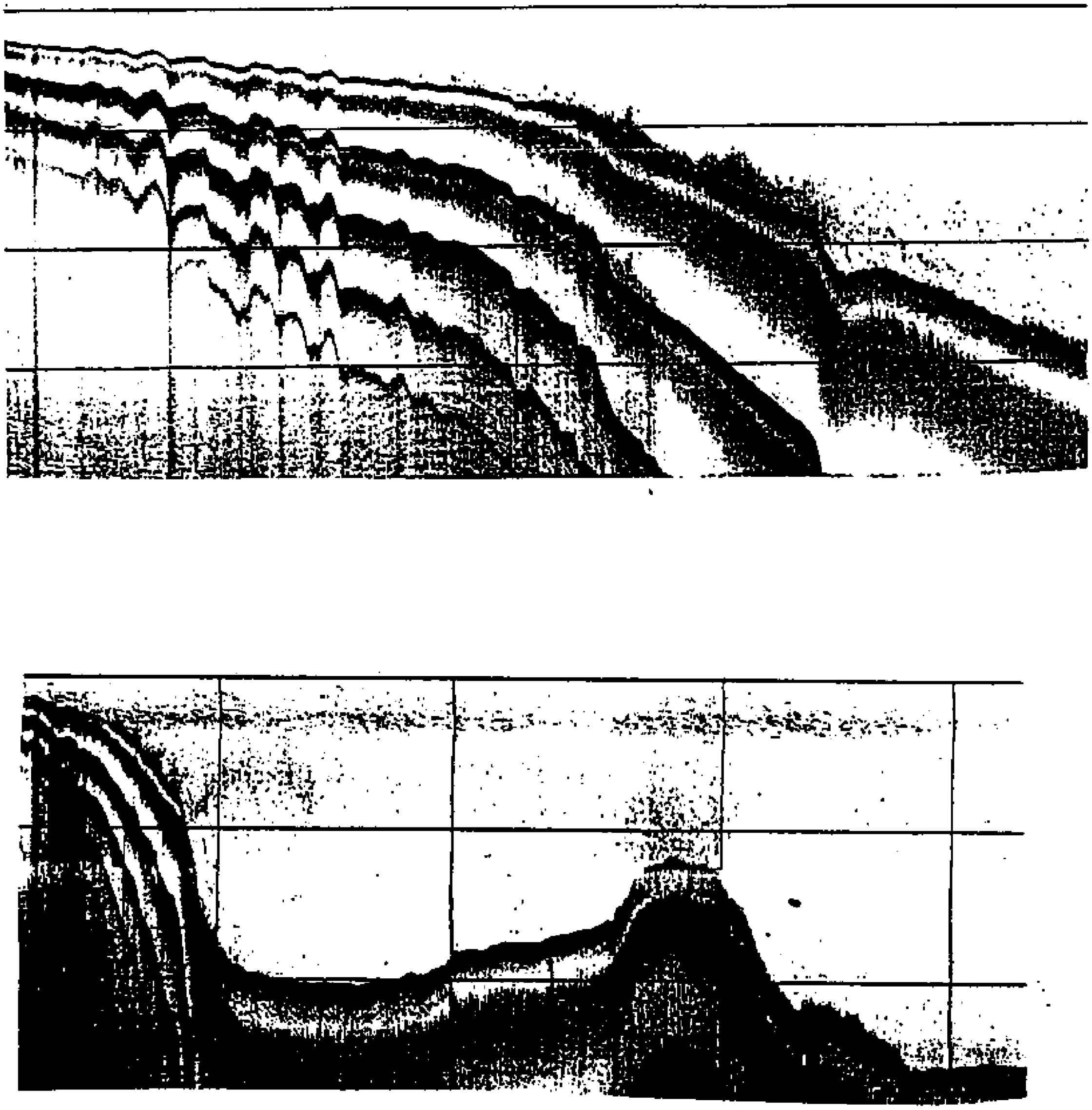


Figure 4. Example of echograms of fish scattering patterns demonstrating the apparent effect of bottom topography on scattering patterns. Data are taken from Lake Michigan during May, 1987. Horizontal lines are at depth intervals of 50 m (first echogram) and 100 m (second echogram).

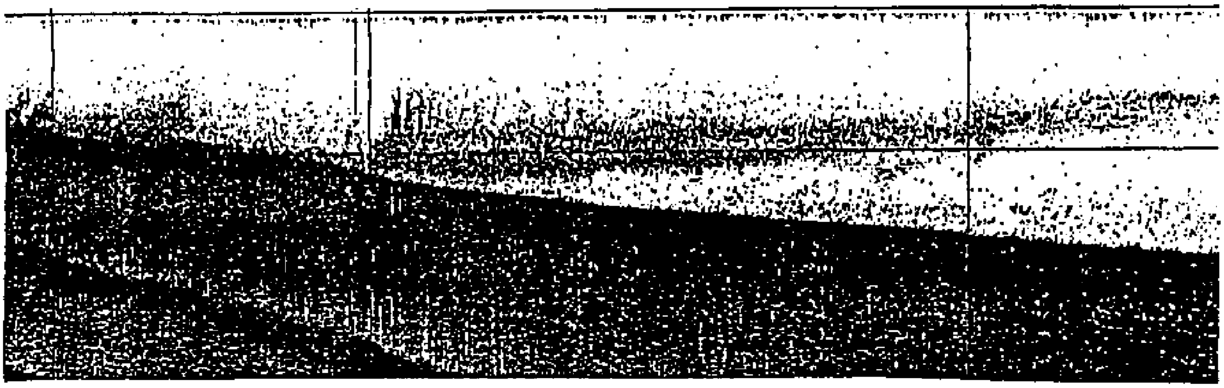


Figure 5. Examples of echograms taken from Lake Michigan during October, 1988 that demonstrate layering of fish that corresponded with the thermal gradient. Horizontal lines indicate 50 m depth intervals.

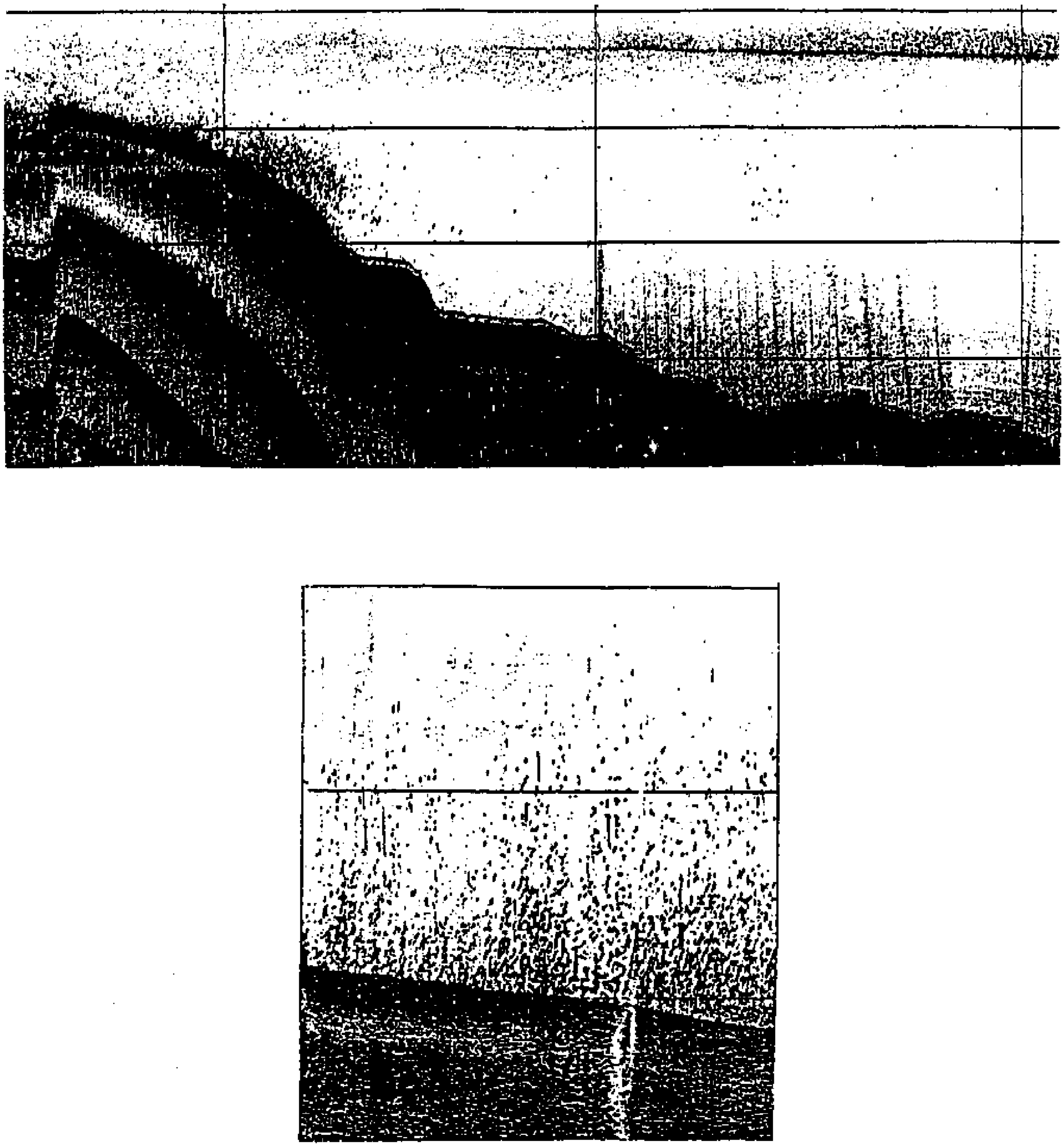


Figure 6. Comparison of echograms taken in Lake Michigan during October, 1986 when the lake was thermally stratified and during April, 1989 when the lake was generally uniformly mixed.

IV. Knowledge-based Applications

Knowledge-based systems have potential applications in future developments of fisheries acoustics by; 1) providing intelligent interfaces to the complex acoustic equipment, 2) increasing our understanding and problem definition of the spatial and temporal patchiness of fish distributions in relation to fish habitat, and 3) optimizing the analyses of acoustic data, through pattern recognition, identification of acoustic targets and decision-making criteria for fish sampling. Knowledge-based systems in this field could help answer such questions as: Is the acoustic sampling intensity sufficient and representative? How should we prioritize the acoustic data for sophisticated signal processing? Are more replicates needed?, Is the acoustic sampling intensity sufficient and representative? Where, when and how often should we sample for target identification? What is the best technique to use?, and What data are noisy? and thus optimize our sampling protocols in real-time and maximize the amount of information extracted from the acoustic during signal processing data. These applications are discussed below.

Intelligent Interfaces to the Equipment

Acoustic systems collect data at rates of approximately 3,000 data points per second in 100 m of water. The information content of each data point or each data set (one pulse equals 3,000 individual samples) will, of course vary greatly. We are only rarely interested in this level of resolution for a population estimate. Only when a series of such data are put together do interesting patterns emerge. The optimal level of data pooling will be dependent on the observed scattering patterns.

There is a strong need for real-time data monitoring to direct the sampling effort and real-time signal processing to estimate fish abundances and sizes. Although microprocessors have evolved rapidly, only limited, standard acoustic analyses are being done in real-time. Full-use of the vast amounts of information generated by these systems is not being made. The most effective use of high-speed computers for acoustic signal processing may be through effective user interface or knowledge-based expert systems [V. Patrick, pers. comm.]. For example, a human observer readily identifies the lake bottom on an echogram, in part because the observer does visual multi-dimensional signal processing. Yet automated bottom detectors frequently fail (in part because they are typically one-dimensional signal processors). A knowledge-based system may work effectively with, or in place of a human observer, as an interface to computer signal processing to specify the location of the bottom boundary to an automated processor so that bottom signals are not counted as fish.

Of course, bottom detection is not the major interest, for the bottom is merely the boundary of what is to be excluded in a fish assessment. Rather, the interest is to have an interactive monitor in which the bioacoustician or fish biologist identifies subsets of interest in the multi-dimensional acoustic record - patches, layers, single fish - and requests acoustically measurable parameters from these subsets. These parameters along with their possible biological interpretations should be displayed in near real time. The development of such an interface would leave the difficult problems of discrimination and decision with the observer or the knowledge-based system and very efficiently pass the computational tasks to the computer [V. Patrick, pers. comm.].

Another type of problem that surfaces frequently in real-time, automated signal processing is noise. If noise is counted as fish, serious bias in fish abundance measures will occur. Acoustic noise generally comes in two forms; 1) Event noise that normally lasts for a short time and is often evident throughout the water column. Such noise happens if the transducer comes out of the water during high seas or if there is sporadic electrical noise in the system. Event noise is recognized on an echogram as a sharp line running throughout the water column (Figure 7). 2) Regular patterns of noise are often caused by acoustical or electronic interference. This noise appears as continuous waves or dots on an echogram (Figure 7). These types of noise are readily identifiable by the human observer, but we do not yet have a system that can digitally distinguish such noise patterns from the signals generated by biological scatterers. Biological scatterers can also produce echo patterns in the form of discrete patches or regular layers (Figure 8). A program that searches for changes or unusual events or regularity in acoustic patterns may help.

Spatial and Temporal Patchiness of Fish Distributions

Fish distributions in aquatic systems are typically patchy. Fish ecologists are keenly interested in the spatial and temporal patchiness in fish distributions and the mechanisms operating to maintain it. Patchiness can loosely be defined as any nonuniform

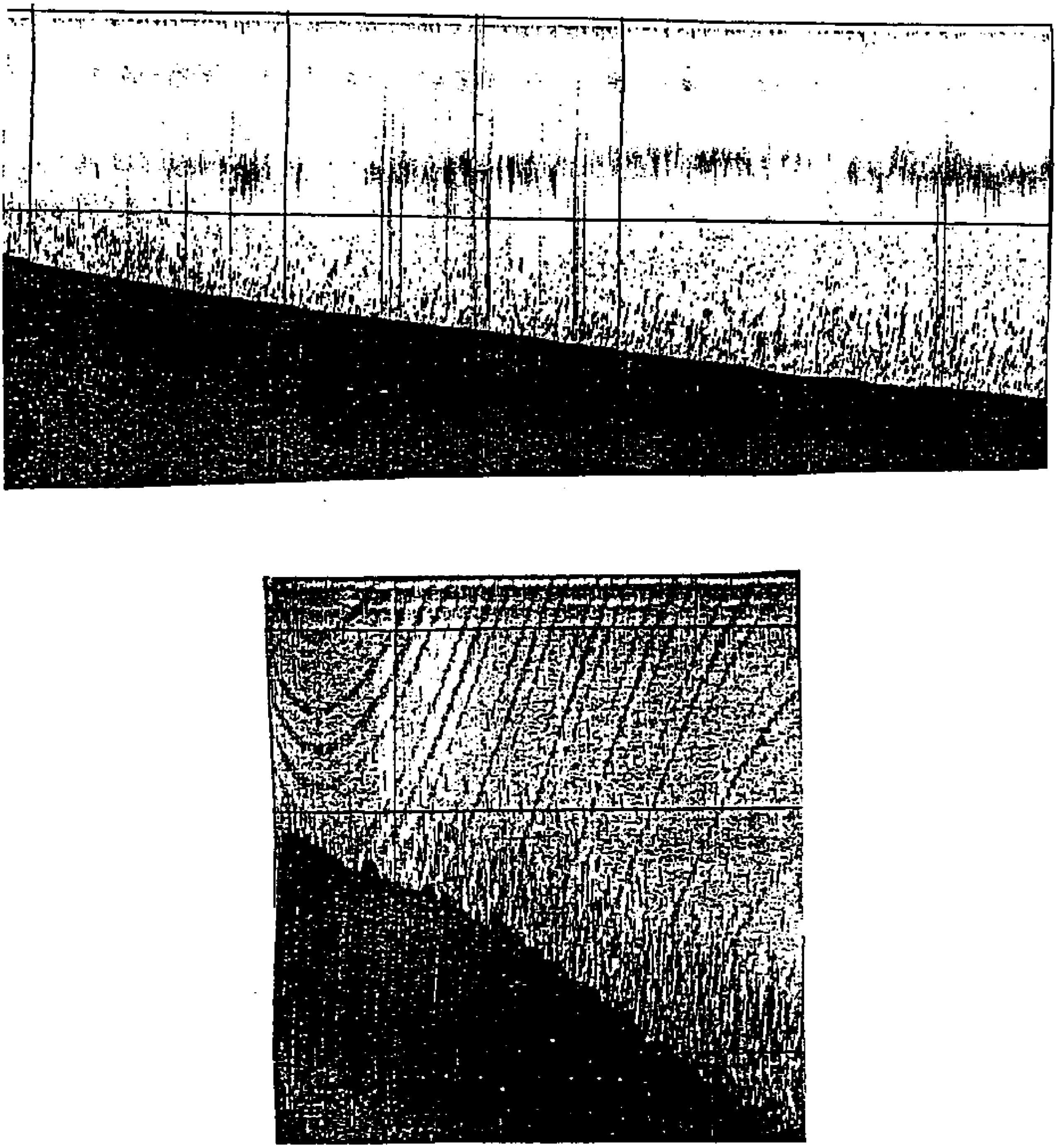


Figure 7. Echograms illustrating the appearance of event noise (upper echogram) and regular electronic interference (lower echogram). Data were collected in Lake Michigan during October, 1988. Horizontal lines are at 50 m depth intervals.

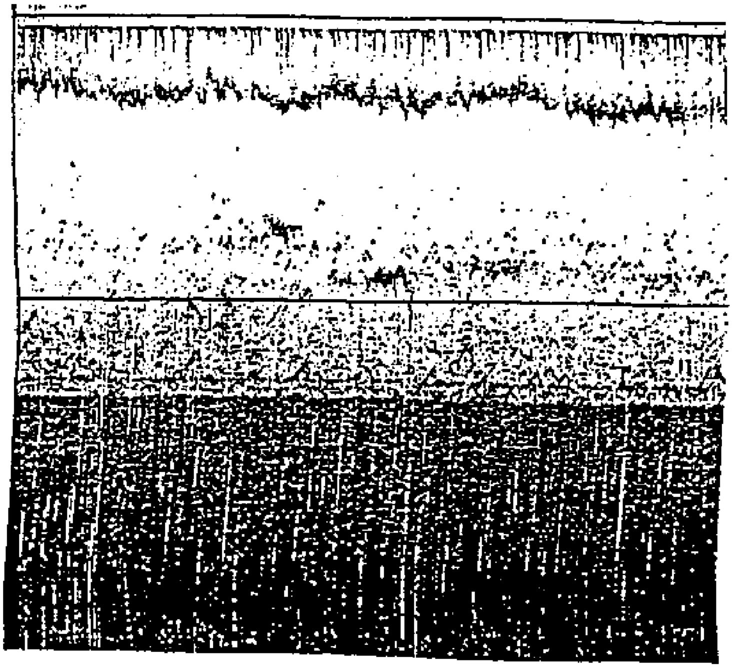
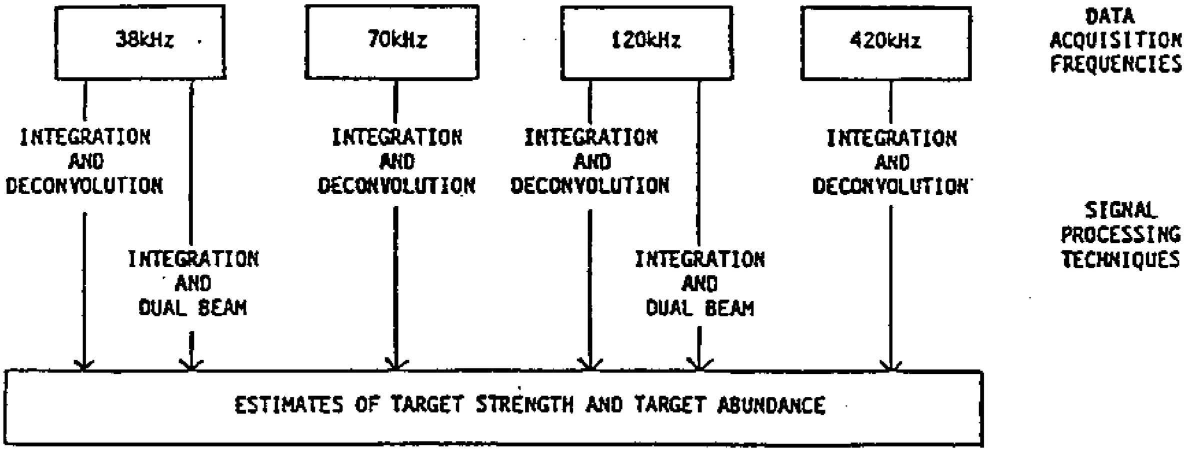


Figure 8. Echogram showing a near-surface plankton scattering layer off Lake Michigan.



pattern in fish distribution across time and/or space [Pickett and White 1985]. Characteristics of patches include patch size, discreteness, uniformity of composition and persistence. However, the degree of patchiness is a function of the spatial and temporal resolution of the observer and must be assessed within the context of the system at hand. For example, zoogeographic patterns of species or communities considered over evolutionary time [e.g. Briggs 1984] provide scales of patchiness in sharp contrast to the microscale patches of plankton that might be encountered by an individual zooplankter searching for prey. Patch structure in this sense is hierarchical [O'Neill et al. 1986].

In pelagic systems, patches may be relatively discrete, and internally homogeneous units with well-defined boundaries (e.g. fish schools) or they may have diffuse edges and be internally heterogeneous with patch of high density embedded in larger regions of lower density (e.g. biological scattering layers). Patch structure is also dynamic and patches can respond to short-term changes in hydrodynamics (e.g. upwelling), schools of fish disperse and reform in response to changes in light intensity and fish stocks congregate annually during spawning migrations.

It is important to differentiate between habitat-derived patchiness and other forms of biological patchiness. Generally, fish have spatial distributions which are associated with specific habitats and biological patchiness may simply reflect spatial heterogeneity in habitat types. Such habitat-derived patchiness that defines the boundaries and centers of distributions of a species via habitat preference mechanisms or physical transport contrasts to biological patchiness that (by definition) occurs within a uniform or homogeneous habitat (necessarily defined from the organisms' perspective). Our ability to distinguish these two patch-forming mechanisms is in part limited by our ability to measure the key factors governing a fishes habitat.

The notions of patchiness and layers in fish distributions are inherently geometric as well as time-varying. When acoustic echos are displayed using either the familiar echogram or in more quantitative contours, one readily visually interprets such time varying geometric structure [V. Patrick, personal communication). However, this structure is not exploited in existing acoustic signal processing equipment.

Examples of echograms show complex patterns of acoustic scattering in which recognizable patch structure is evident in the form of layers or schools (Figures 4-8). Patch structure often correlates with the physical structure of the environment and the type of biological scatterers. Although it is often easy for the human observer to recognize different types of patches on a visual display, we are a long ways from being able to quantitatively recognize patches and define patch structure. In part, the limitation lies in our inability to define what we are looking for, in our inability to define the edge of a patch and in the computers inability to process all of the necessary patch recognition software in real-time.

Arguments for ataxonomic classification [Ulanowicz and Platt 1984] suggest that we consider acoustic patches per se as areas of study and not be restricted by species classification. Acoustic scatterers could be identified by higher-order characteristics such as discriminant analyses of echo statistics, fractal dimension, patch dynamics and variance, level of coherence with physical structure, biomass density/size ratios and multi-dimensional signal processing. The principal of pattern recognition could be applied to define these 'acoustic species' to the level of lowest identifiable unit and these may have biological meaning [e.g. O'Neill et al. 1986]. A knowledge-based system that combines elements of pattern recognition with knowledge of fish behavior may be useful.

Identification of Acoustic Targets

Fish and plankton species cannot be identified with acoustic techniques per se [Clay and Medwin 1977]. The ability of acoustics to measure the abundance of a single species in a multispecies environment will always be limited by the level to which relative species composition can be determined. For example, the relative abundances of alewife, rainbow smelt and bloater in Lake Michigan are not known and these species are approximately the same size. How do we obtain estimates of stock abundance of each of the species in such a system?

One technique is to estimate total abundance of pelagic fishes and then weight that value by the proportion of each species in the environment based on independent target identification procedures such as aimed midwater trawling. The precision and accuracy of these biomass estimates, however, would be directly proportional to that of the 'ground truthing' technique. For example, if trawling suggests that the fish composition in an area is 20% species A (by biomass) and 80% species B, but in fact is 10% species A and 90% species B, our abundance estimate for species A would be 100% too high; our abundance estimate for species B would be 11% too low. The variance about these acoustic estimates would also depend on the variance about the estimate of relative species composition. Most ground truthing techniques are not equally effective at catching different species or different sizes within a species and also have high variance because the underlying fish distribution is unknown. Knowledge-based systems may be useful for optimizing such direct sampling programs by using identification clues (e.g. target size) provided by acoustic signatures [Holliday 1977]. This is useful since the most expensive component of stock assessment is normally the cost of the research vessel time.

A second approach to species identification is to define species-specific distributional patterns and then allocate biomass measures to different species on the basis of the type of habitat from which the measures were taken. In this way consistent patterns in habitat-derived patchiness can be used to identify fish targets if different species or life history stages occupy different habitats. Such habitat-derived patchiness has not been fully used in the design, execution, or statistical treatment of acoustic surveys for stock assessment.

Water temperature is a good example of a pelagic habitat feature that correlates well with fish distributions, has a strong physiological basis and can be measured easily (in contrast to, say, the presence of predators). Fish have specific thermal optima and often regulate body temperatures behaviorally within a small range [Fry 1971; Coutant 1977; Magnuson et al. 1979]. In both marine and freshwater systems, fish and plankton abundances are often highly correlated with thermal gradients [Brandt and Wadley 1981; Owen 1981; Longhurst 1985]. We may be able to use thermal preferences of species to help identify and isolate acoustic targets, particularly if different species have non-overlapping thermal ranges [e.g. Brandt et al. 1980]. If each species of fish was precisely and uniformly always found within a narrow temperature or habitat range, then the problem of species identification would be solved. But this is not the case. Temperature preferences can change with time of day, season or with the age of the fish. Although we can establish general and species-specific rules, the data are messy even for the best behaved fishes. Population maximum may be at the right temperatures but the tailing end of the distributions will be at the 'wrong' temperatures. Deviations are a function of population variance but could also be due to biological interactions. A fish will not stay at its' optimal temperature indefinitely if there is no food available.

The level of variability in fish habitat preferences has rarely been measured in the field nor have acoustic scattering patterns been examined for regularity within and across different bodies of waters or types of fish. Knowledge-based expert systems may be able to optimize the frequency and location of ground truthing\sampling on the basis of specific habitat criteria and prevailing patch structure and may be useful for defining fish patchiness (discussed above). General rules may apply across systems (such as some biological scattering should correlate with physical structure and some fish will have restricted thermal distributions) and refinements may be necessary for each particular system based on the species composition and the nature of the fishes habitat.

A third method to help identify acoustic targets is to use the information contained in each echo. These echo statistics would include measurements of fish size, patchiness, degree of compactness and straightforward measures of the acoustic signature. Echo statistics have been empirically related to individual species using multivariate clustering routines and discriminant analyses [Stanton and Clay 1986; Rose and Leggett 1988] but this field is in its' infancy and the application of artificial intelligence techniques may be appropriate.

V. Conclusions

Underwater acoustics has evolved rapidly to become a much needed tool for fisheries scientists interested in measuring fish abundances and distributions. The advancements in acoustic theory and hardware have outpaced our capability to interpret, evaluate and make full use of the vast amounts of information generated by these systems. Widespread use of this technology is also limited by the need for well-trained experts in the field. The potential of knowledge-based systems to advance the usefulness of this technology has yet to be fully evaluated.

VI. Acknowledgements

This research was funded by the Wisconsin Department of Natural Resources through a grant to the University of Maryland System, Chesapeake Biological Laboratory. Ideas generated in this paper benefited greatly from discussions with Dr. Vincent Patrick of the Chesapeake Biological Laboratory. Contribution No. 2043, Center for Environmental and Estuarine Studies of the University of Maryland System.

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