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A Framework for Identifying Fisheries Management Problems Associated with the Influence of Environmental Factors on Distribution and Migration of Marine Species

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Abstract

This paper provides a framework within which to evaluate the nature, and importance to the work of NAFO Scientific Council, of the infleunce of environmental factors on distribution and migration of marine species. The framework is organized on three levels involving increasingly larger numbers of fish, larger spatial and temporal scales, and greater problem complexity. Of most general importance at the population level is the influence of environment on location, timing and degree of aggregation, with major effects on fishing success, managerial planning and stock assessment. At the stock level, problems concern distribution in relation to oceanographic structure and the factors resulting in stock formation. An understanding of these is of great importance in the definition of management units. Concerns at the species level relate to zoogeography and the effect of ocean climate and large-scale man-made influences. New knowledge at this level, by providing a basis for interpretation of resource trends, would give a foundation for longer-term planning. Environmentally-induced variability in availability of fish to commercial and research gear stands out as a significant problem in many aspects of stock assessment and fisheries management and particularly deserves the Council's attention.

Introduction

The Scientific Council of NAFO, at its Annual Meeting in September 1983, reconfirmed its interest in relating environmental factors to the dynamics of exploited fish populations. The Council recognized the value of having specific goals to focus research efforts on important problem areas. It chose to concentrate its work "on the influence of environmental factors on the distribution, movements and migrations of marine species in the Northwest Atlantic" (NAFO, 1983). While this narrows the field of consideration substantially, a broad subject area still remains. The purpose of this paper is to provide a framework within which to evaluate the nature of the problems and their importance to the work of the Council.

A definition of "importance" is perhaps the first task. The Council has a broad mandate, but its primary practical task is to provide advice on the management of fisheries. Thus, the question of environmental effects on distribution, movements and migration of marine species is looked at in relation to the practical problems encountered in fish stock assessment, control of fisheries exploitation, and longer-term prognosis.

The next job is to circumscribe "environment". The Scientific Council's intent, as much as to focus attention on practical problems, is to identify problems of common interest to physical oceanographers and fisheries biologists. Thus, for present purposes, environment is defined as physical oceanographic conditions. Nonetheless, reference is made to "climatic" effects on distributions. This is a convenience, and underlying this usage is the perception that climatic effects on distributions very largely are transmitted through physical oceanographic conditions.

While on the topic of definitions, clarity in use of the words "movements" and "migration" will be of value. Movement is considered to be a characteristic of individual fish and to be of a haphazard nature. Migration is a systematic movement of groups of fish and migration patterns are characteristic of stocks. In the present context, migrations of the exploitable stock are the most relevant.

In choosing distribution, movements and migration as the subjects for consideration, the Council deliberately excluded the effects of environment on fish production. The influence of environment on recruitment, through study of population dynamics at egg and larval stages, has been the subject of other recent initiatives by the Council (i.e. Flemish Cap Project and Georges Bank Larval Herring Program) but has proved to be a problem which is not easily dealt with. The effect of environment on population parameters at later life history stages which affect production has, however, received less attention. A number of recent studies have considered large-scale relationships (in a geographic sense) between fish production and environmental parameters (Sutcliffe *et al*., 1976, 1977, 1983). If these highly integrated views of the effects of environmental factors are looked at from the perspective of explaining the geographic distribution of production, they become relevant to the present topic. Similarly, the effect of environment on species distributions may stem from environmental influences on recruitment. Thus, the effect of environment on distribution and production, when dealing at the species level, can become one and the same question. Consideration of the effects of environment on production is included, therefore, where this is necessary to address distributional questions.

To provide further structure to these considerations, environmental effects are viewed at different levels of organizaton —population level, stock level, and species level. The standard definition of species has received common usage among marine scientists generally, and there is no need to define it here. However, the terms "population" and "stock" have received quite diverse usage, and it is considered necessary to define these as used in the present paper.

A stock of fish is defined here as a group of fish of the same species forming a semi-isolated, self-reproducing production unit. They tend to occupy geographic areas which are characterized by small-scale oceanographic or topographic features (e.g. fishing banks). A population of fish is defined in this paper as a group of fish (from a few to a large aggregation) of the same species occupying a well-defined, usually small, geographic area characterized by localized oceanographic features; they may or may not be of the same stock.

Having thus defined population, stock and species, it follows that environmental effects on a localized scale (local currents, weather, location of oceanographic fronts) will influence fish at the population level, whereas larger-scale effects (large-scale current patterns such as gyres, large-scale run-off, and areas of upwelling) will be influential at the stock level. At the species level, events will be influenced by broad oceanographic and climatic changes on a regional or even a global scale. It is within this organizational framework that an identification of problems associated with the influence of environmental factors on distribution, movement and migration of marine species is attempted.

Definition of Problem Areas

Environment affects the behavior of individual fish. In discussing the effects of environmental factors at stock or species level, it is the net effects of environment on many individual fish which is being addressed. In other words, what is being classified here is the nature of the problems to be discussed. The overall framework which has been developed for identifying problem areas and assessing their practical importance is given in Table 1.

Population level

Movements and migrations modify distribution, and most problems are discussed under the title of distribution. Indeed, it is difficult to conceive of practical problems in the present context which can conveniently be thought of under the title of movements and migrations.

In the sense of movement as "activity", degree of activity in relation to environment (e.g. temperature) could have significant impact on catchability, particularly to fixed gears such as traps in invertebrate fisheries and to hook and line fisheries. This is not, however, a common type of problem in the NAFO context.

TABLE 1. A classification of fisheries management related problems associated with the influence of environmental factors on the distribution and migration of marine species.

Population level

Direction and speed of migrations

- success of localized fisheries
  - dealing with variability

Location, timing and degree of aggregation

- fishing success
  - forecasting services
- managerial planning
  - dealing with variability
- stock assessment
  - interpreting commercial catch rates
  - interpreting research vessel survey abundance estimates

Stock level

Distributional dynamics in relation to oceanographic structure

- stock delimitation
  - definition of management units

Species level

Zoogeography and ocean "climate" (including large-scale man-made influences)

- stock assessment
  - interpretation of trends
- managerial planning
  - investment decisions (i.e. long-term planning)
- indicator species
  - climatic monitoring

Migration patterns, as stated above, are considered to be characteristic of stocks, resulting in systematic seasonal changes in distribution of the various life history stages. Variation in migration patterns are reflected in the distributional characteristics of fish aggregations. Aspects of migration which perhaps deserve separate treatment relate to the direction and speed of migration. The success of localized, particularly coastal fixed-gear, fisheries is sensitive to fluctuations in precise location of migration routes. It can be hypothesized that transit times are also likely to be instrumental in causing such variations. Ability to predict such variations may have practical value in relation to inshore fixed-gear fisheries and the ability to explain them may provide a useful basis for interpretation of events and for longer-term fisheries management planning.

The fundamental distribution-related issue, at this level, is aggregation as it relates to catchability. The location, timing and degree of aggregation have major impacts on the practice of commercial fisheries, fisheries management, conduct of research, and interpretation of results. Improved understanding of variation in aggregation, resulting from variation in environmental factors, would be of substantial practical import.

Variation in aggregation has a major impact on fishing success and hence on the profitability of fisheries over short time scales. This has, at times, stimulated interest in, or demand for, forecasting services as an aid to fleet deployment. This is not, however, the type of problem (i.e. promoting increased fleet efficiency) which has merited much attention in the scientific community in the last two decades, effort being directed toward control of exploitation rates. It is the secondary effects of such variations on fishing success which have had substantial impacts on fisheries management, both on the general managerial process and on stock assessment *per se*.

In terms of managerial planning, catch quota management and then extensions of fisheries jurisdictions introduced an era of increasingly detailed fisheries controls. Integrated fleet planning is based on a static concept that is centered around "average" conditions, and variations disrupt such detailed fishing plans. Closed area and season regulations illustrate the nature of this type of problem. The Scotian Shelf small-mesh-gear-line (SMGL) provides a good example. The defined season and area is designed to allow satisfactory conduct of directed fisheries (with small-mesh gear) for silver hake and squid, while preventing significant by-catch of other species, particularly cod and haddock. Variation in the timing and/or location of aggregation of any of these species will have an impact on the efficacy of this regulation. If haddock are concentrated in deeper water than usual or if these concentrations persist later in the year than usual, by-catch problems could result in fisheries closures. On the other hand, if silver hake disperse over the shelf early, or in greater proportion, fulfilment of allocations may be prevented. Of course, the degree, as well as location and timing, of aggregation will also affect fishing success. Decisions by the licensing authority on the amount of fishing effort to licence, and by the fishing nation on the number of ships to deploy and for how long, are predicated on expectations of fishing success. Variations from this will, at least, create inefficiences and could create difficulties in intergovernmental relations.

In addition to the technical aspects of management, just discussed, there is also an important "philosophical" element to be considered. In particular, if fishing conditions vary greatly from regulatory expectations, the credibility of the regulation, the regulators and the management process comes into question by the fishing industry. Of particular concern to the Council is, of course, the credibility of the stock assessment and advisory process.

From a practical stock assessment viewpoint, interpretation of commercial catch rates play an intergral, sometimes key, role in determination of stock status. A substantial variance around catch-rate versus stock size relationships is common. While factors other than environmental ones are no doubt at play, it is likely that a better understanding of the role of environmental factors on aggregation, and hence catch rates, would aid greatly in data interpretation. Understanding factors affecting (i.e. biasing) data for the most recent year is of greatest practical importance.

In the NAFO Area, a strong research emphasis has been placed on the development of research vessel surveys, particularly stratified-random bottom trawl surveys, to obtain fishery independent estimates of stock size and to provide quantitative estimates of recruitment (see e.g. Doubleday, 1981). Although relationships between research vessel abundance indices and stock size are less subject to bias, as a result of the standardized survey design, than those between commercial catch rates and stock size, they are plagued by very high variances. Again, variation in environment, while not the only factor at play, is likely to be one of the most important.

In the case of commercial catch rates, the most comprehensive data are acquired from the large-vessel mobile fleets. For these fleet sectors, the precise location and timing of aggregation will tend to have a secondary impact on catch rate, while the degree of aggregation (and timing in the sense of duration) is of major impact. For smaller, less mobile vessels and for fixed gears, location of aggregations assumes a greater importance in determining catch rates.

Variation in the degree of aggregation will not introduce the same biases in stratified-random research-vessel abundance estimates as in commercial catch rates because of the randomization of research vessel fishing effort. This variation will, however, be reflected in increased statistical variance of abundance estimates. Variation in the time of aggregation, in this context, is confounded with degree of aggregation, as surveys are conducted synoptically. Stratified-random bottom-trawl surveys are designed to cover the entire area of significant distribution of a stock, but variation in location of aggregations is important knowledge in deciding on stratification schemes, and improved stratification will reduce statistical variance of abundance estimates. Of greater impact in this context are factors which affect vertical distribution rather than location in a geographic sense. Environmental factors which change the proportion of a fish population within the part of the water column sampled by survey gear (i.e. change the availability of fish to the gear) will have a substantial influence on the level of abundance estimates, because only a portion of the population will be subject to estimation. The effect of variation in vertical distribution on variance of abundance estimates will depend on the circumstances, but it is conceivable that variance estimates will not be greatly affected. The distributional characteristics of that part of the population available to the gear may be much the same as those of the total population when all of it is available to the gear.

Stock level

Fisheries management on the basis of total allowable catch (TAC) limitations by species and management area is a practical recognition of stocks as semi-isolated, self-reproducing production units. Questions concerning the definition of stocks and the degree of stock mixing, in relation to the suitability and practicality of management areas for control of exploitation on stocks, can fruitfully be considered in the context of environmental influences.

The concept of relating species tolerances to environmental factors such as depth, temperature and salinity in the context of distribution of these environmental factors, and inferring stock separations from these distributions, has largely fallen into disuse. Emphasis has been placed on modern applications of tagging, biochemical and parasitological techniques. The influence of environment during early life-history stages on meristic and morphometric characters does, of course, provide a classic method of stock separation which is also still much in use. While these currently used methods may be more efficacious in describing the stock separations which do occur, they nonetheless do little or nothing to explain why they occur and provide no capacity to predict the consequence of environmental change.

A recent study (Iles and Sinclair, 1982) has indicated that the number of genetically distinct herring stocks is determined by the number of distinct, geographically stable larval retention areas. The authors used the stratification parameter of Simpson and Hunter (1974) to define temperature fronts demarking the transition between vertically well-mixed and stratified waters, and they associated larval distributions with well-mixed areas. Their theory allowed hypotheses to be erected concerning not only the location but also the size of herring stocks, as a relationship was proposed between absolute population size and size of retention area. This modern approach to explaining stock formation as a resultant of oceanographic structure, which promises the potential of explanatory and predictive ability, deserves attention.

The above is an example concerning stock formation of one species throughout its range, but there are situations where particular areas appear important in stock formation for several species. One is the Western Bank area in Div. 4W which serves as a primary spawning area for several important gadoids: pollock in winter, cod in early spring, haddock in late spring and silver hake in summer. In presenting the preliminary results of extensive egg and larval surveys in the area, O'Boyle *et al.* (1984) have implied that larval retention mechanisms in the area may be responsible for the popularity of the location.

Considerations such as this will not directly influence ability to conduct a particular stock assessment in any specific year. Nonetheless, in developing an understanding of the relationship between oceanographic structure and stock formation, a basis for explaining distributional and migratory characteristics and their variations will be provided. This will allow not only improvement in definition of fisheries management units in the present context but perhaps also the development of new approaches less rigorously tied to the simple unit stock management concept.

Species level

The study of distributional characteristics of species in relation to environmental factors is an aspect of zoogeography which has some important implications to fisheries management. Of primary interest are large-scale oceanographic, or "climatic", events which significantly modify the distribution of fishable concentrations of a species through changing the capacity of an area to produce significant quantities of that species.

There are important practical fisheries issues which need to be addressed through the study of climatic effects on species distributions, and these climatic effects can concern not only boundary conditions but distribution of production through the species range. A classic example of the relationship between climatic factors and fish production, the West Greenland cod, is well known to fisheries research workers in the NAFO Area and has most recently been treated by Cushing (1982). The work of Sutcliffe *et al.* (1976, 1977, 1983), which hypothesizes links between environmental parameters and the distribution of fish production, was mentioned in the Introduction. A superficial review of most recent cod stock assessments adds some support to such hypotheses by suggesting that more southern stocks have recovered more fully (or even "over-recovered") from the low stock sizes of the mid-1970's in relation to historical levels than have more northern stocks, which tend still to be below calculated historical levels. This perception may not withstand detailed scrutiny, and, even if generally true, the event may be attributable to factors other than environmental. Nonetheless, the suggestion of a possible shift in cod production to the south is an intriguing question of obvious practical importance.

So far, the impact of environmental factors on distribution of marine species has been discussed, but to end the list, another topic, the use of distributional information as an indicator of environmental variation or "climatic trends" is raised. This archaic approach is based on the maxim that distributional changes of species will prove to be sensitive indicators of environmental change. Events can than be interpreted in relation to changes observed during direct environmental monitoring. In terms of direct long-term marine environmental monitoring for the purposes of fisheries research, primary questions are what to monitor, where and how often. Changes in species distributions are reflections of the integrated effects of environmental change, and systematic monitoring of range variations could provide a cost-effective supplement to an environmental monitoring program. Potential for success in developing such an approach would be enhanced if indicator species could be identified (i.e. those for which the mechanism of response to environmental factors is known).

Practical Importance of Problems

In this section, an attempt is made to evaluate the practical importance of the three broad problem areas defined above. Practical importance, in the context of this paper, is primarily defined as importance to the provision of scientific advice on stock status, the implementation of such advice in the form of TACs, closed areas and seasons, etc., or the conduct of fishing operations (success of fishing). Importance to more general considerations, such as social and economic planning, are also given some attention, however.

Population level

Effects on the stock assessment and advisory process. As stated above, the success of coastal fixed-gear fisheries is critically dependent on the timing of migrations and the location of migration routes of not only the target species but prey species as well. Because of this critical dependence, catches in these fisheries fluctuate widely. An example of this type of fishery is the inshore cod-trap fishery along the Newfoundland coast. Catches fluctuate greatly in this fishery from year to year because of annual fluctuations in the availability of cod in the inshore areas, even when total cod populations and inshore fishing effort are similar between years. Factors such as the abundance of capelin, the extent of their inshore migration, and the prevailing environmental conditions, chiefly temperature, all act to produce a high degree of variability in inshore catches. This causes great difficulties for inshore fishermen in planning fishing activities in advance of the season.

If fisheries scientists could understand the mechanisms which govern the influence of environmental factors on availability of fish to fixed gear, they would be able to explain events occurring in the inshore fishery in a given year and, thus, counteract the familiar criticism that stock assessments are incorrect because catches are less or more than implied by the assessments. In addition, such knowledge could improve ability to utilize inshore fishery data in assessing populaton abundance. In the case of inshore fisheries, however, there are often other limitations to development of abundance indices from data on fishing success. The inshore cod fishery in Div. 2J+3KL illustrates well the difficulties of obtaining accurate measures of fishing effort. Year-to-year variation in effort cannot presently be measured and, although longer-term trends are documented in terms of "catch per man", this index is subject to various sources of bias. Thus, inshore fishing success is not currently used in any statistical calculations on stock status of cod in Div. 2J+3KL, and, indeed, there are very few cases where inshore fisheries data are utilized for this purpose. Thus, utilization of new knowledge of the effects of enviroment on availability to inshore fisheries would appear to be contingent on coincident improvement of inshore fishing effort measures.

Variation in aggregation has an obvious impact on commercial fishing success by its effect on the level of catch-per-unit-effort (CPUE). Less obvious is the effect of variation in aggregation on the process by which stocks are assessed and advice provided to fisheries managers on quantities of fish to be removed. In many instances in the NAFO area, sequential population analyses (SPA) used for stock assessments are "tuned" by using either commercial or research survey indices of abundance. One of the underlying assumptions in using such indices is that the catchability of the fish by the gear does not change significantly from year to year. Variations in, say, temperature or current patterns may affect the degree of aggregation of fish in a given area sufficiently to significantly influence catch rates. Therefore, in evaluating a relationship between two time series (i.e. regression of SPA biomass on CPUE or SPA population numbers on research vessel estimates of population numbers), in which the last point is very much different from expectations based on other recent points and ancilliary information, one is faced with the dilemma of whether the difference represents a real difference in stock abundance or merely a bias in research and/or commercial fishery abundance index due to greater or lesser aggregation of fish in that year. If the latter is the case, a biased estimate of stock abundance in the last year would result, leading to scientific advice for suboptimal yields from the fishery. A knowledge of the manner in which environmental conditions affect the degree of aggregation of fish could aid greatly in interpretation of such results.

Almost without exception, analytical assessments depend on regressions between commercial or research vessel stock-size indices and SPA results. Less frequently, recruitment is predicted from regression of research vessel survey indices versus SPA year-class size indices. Analysis of historical records of assessment results by Rivard (1981) indicated that current data and analytical methods yield a relative error of 24%, on the average, for estimates of stock size in the current year. Although, in his particular analysis using data for cod in Div. 4TVn, Rivard concluded that improved knowledge of factors affecting mean weight-at-age would improve accuracy of catch projections more than improving research surveys, this stock is a special case. On the one hand, this survey showed less variation in estimates for cod than that shown by other stratified-random surveys for cod or other species (Koeller, 1981), but variation in commercial mean weight-at-age has been greater than that demonstrated for other stocks. Other cases should be analysed to give a more general perception of the importance, to the determination of current stock size, of correcting abundance estimates for environmental factors. It seems clear enough that the accuracy of catch projections leaves something to be desired, and hence there is scope for substantial benefits to be accrued if significant improvement can be effected.

Effects on regulation and on conduct of fishing. From the point of view of the fishing fleets, environmental variations can, as is well known, greatly affect fishing success in any particular season. Fishermen are, on the whole, well aware of variations in fishing success on the grounds which they frequent and no doubt give this some weight in their fishing strategy, both short and long-term. While they may well wish to know why these variations occur, it is doubtful whether this knowledge would affect their planning, unless it provided them with a predictive ability. Historically, fishing success centered around the ability of fishermen to concentrate on high density aggregrations of fish. While this remains an important element of fishing, comprehensive governmental control of total catches has introduced some new elements. For mobile fleets at least, high catch rates increase the speed with which allocations are taken but need not confer a direct benefit in terms of total volume caught. Indeed, there could be losses in terms of reduced fish quality and from the costs of lying idle for part of the year when all allocations are taken. Thus, for mobile fleets, while foreknowledge is no doubt an advantage, benefits from predicting variability in annual density (other than that arising from stock abundance trends which are predicted through the stock assessment process) are not as clearly obvious as they once appeared to be.

In the case of highly specialized fisheries, particularly fixed-gear coastal fisheries, the benefits of predictability are more obvious. If it were known, for example, that the cod-trap fishery in Div. 2J+3KL would be a failure in a given year due to adverse oceanographic conditions, important savings could be made by not investing in gear, or by investing in alternate gears such as gillnets or longlines which are more likely to yield economic returns. Also, associated shore-based processing facilities could direct attention to alternate sources of supply. Coastal fixed-gear fisheries are important throughout much of the NAFO Area, primarily for cod and herring. Fixed-gear fisheries for mackerel and haddock are only of local importance. Thus, a forecasting service could be of practical importance, particularly for the large-scale fixed-gear fishery for cod in the northern part of the NAFO Area. Feasibility would depend on identifying factors which are relatively inexpensive to monitor while giving predictive ability over a geographic area sufficiently large to encompass a major proportion of the fishery.

The trends toward increasing management intervention over the last 10 years has created another set of problems where the effect of environment on variability in catchability coefficient (q) is important to deciding on management strategies. The basic approach to fisheries management in the NAFO Area has been to control exploitation rate at a fixed "optimal" level. Choosing TAC regulation as the primary control relegates catchability problems to a secondary consideration, as was pointed out to ICNAF at an early stage (ICNAF, 1973): "The main advantage of catch quotas is that accuracy [in control of fishing mortality (F)] is independent of variations in the catchability coefficient. But the setting of catch quotas is sensitive to fluctuations in recruitment. Fishing effort quotas are not sensitive to fluctuations in recruitment, but they are sensitive to variations in catchability." In that (substantial) part of the NAFO Area controlled by Canada, direct, although crude, fishing-effort controls are imposed through the licensing system for both domestic and foreign fleets. In this context, variation in catchability has some importance. The catch allocation process, particularly among fleet sectors which are restricted to area and season of operation, can also exacerbate problems caused by annual variations in the relationship between fishing effort and fishing mortality.

In the case of foreign fleets, Canadian regulatory control uses fishing effort limitation as a fail-safe mechanism for the primary control of F through catch limitation. This is dependent for its success, as are national fleet deployment strategies, on low variance in q. The extent to which variation in q presents a problem to the present approach could be quite readily evaluated by retrospective analysis of consistency in catch and effort allocations. The practical importance of such problems could then be assessed and hence the importance of investigating environmental influences on q evaluated.

Fleet sectors that are restricted as to area and season of operation are typically coastal small boat fleets. These tend to be particularly vulnerable to minor variations in migration routes and locations of fish concentrations. Basically, when the scale of management unit is reduced by suballocation to small fishery sectors operating in a localized area in a short season, the importance of annual variability in distribution of stock density is amplified. Success of a "deterministic" approach to resource allocation is dependent on the amount of variance in the system being small or predictable. A management approach incorporating more flexibility in allocations from year to year could prove more effective when working on a regulatory scale which is small in relation to the stock area being managed. This can, however, also be a problem on a large scale, and the inshore cod-trap fishery in Div. 2J+3KL again provides a good example. Management concerns in relation to this kind of allocation problem relate to equity among competing fisheries sectors and to full resource utilization, but, in the case of such a large-scale problem as Div. 2J+3KL cod, many other factors such as seasonal/spatial distribution of supply, product quality, and marketing become relevant. These arguments confirm that development of a predictive ability for the effects of environment on availability of cod to inshore gears in the northern part of the NAFO Area could be cost-effective.

Other regulatory measures which require consideration are closed areas and seasons. Biological reasons for instituting such closures are to protect juveniles or spawning adults from directed fishing or to control by-catch. Examples of each are the closure of areas of the Bay of Fundy to purse seiners in order to reduce their catches of juvenile herring, closures of parts of Browns Bank and Subarea 5 to protect spawning haddock, and the SMGL on the Scotian Shelf to reduce by-catches in small-mesh fisheries. Inevitably such regulations are compromises that are aimed at attaining their objectives while not greatly impairing performance of directed fisheries. Presumably, the criterion is that the expected benefits outweigh the immediate costs. To date, closed areas and seasons have been fixed from year to year and reflect average distribution patterns. Extreme variations in distribution could make this kind of regulation impractical. In the case where the species, or life-history stage of the species, to be protected is contained within relatively small seasonal or spatial boundaries, there is not likely to be severe impairment of fisheries for other species (or life-history stages of the same species) in the much larger area outside it. This is so at least in the context of full resource utilization, although fishing efficiency could be reduced. The question then relates to whether a sufficient proportion of the protected entity occurs within the closure sufficiently often to meet objectives. In the case where the closure is large in relation to the period or area open to fishing, it is convenient to reverse conceptualization of the issue and consider openings rather than closures. Such openings have come to be referred to as fishing "windows". Window regulations restrict directed fishing to relatively small areas or short seasons, and hence emphasis tends to be on impairment of directed fisheries, because relatively small changes in environmental conditions could produce major shifts of biomass into or out of a small geographic area. Conversely, the likelihood of a high proportion of a by-catch species being distributed within the window is not great.

In the present NAFO context, the Scotian Shelf SMGL (which, in practice, defines an area and season along the shelf edge where fishing by small-mesh gear is allowed) is the only regulation of the window type. Although a Canadian regulation, it was inherited from ICNAF and affects the fisheries of several countries. Consequently, it has been the subject of cooperative international research since its inception in 1977. It is located adjacent to spawning areas for several major gadoid stocks (O'Boyle *et al*., 1984) and to a haddock nursery area (McCracken, 1965). The relative importance of problems created for fisheries management by environmentally-induced distributional variation could usefully be assessed using the SMGL problems as an example.

Stock level

The importance of managing on a unit stock basis is so thoroughly engrained in the philosophy of fisheries biologists that it perhaps receives less thought than it deserves. The importance of conducting assessments on a unit stock basis is a different, although related, question which tends to be more thoroughly examined. The importance of both of these will vary depending on the species being considered. Management areas in use today are very largely permutations and combinations of areas defined about 1950 (which bear relation to areas defined as early as 1930), before much of what we now know about stock structure was elucidated. Therefore, one could perhaps be forgiven for wondering whether exact boundaries are critical for management purposes.

In the case of cod and haddock, there has been considerable success in managing for stock recovery in recent years. It was stock separation knowledge for these species which most influenced the location of statistical (subsequently management) boundaries. On the other hand, the multistock composition of herring within presently used management units, the concentration of herring fisheries on mixed stock aggregations sometimes with components from separate management units, and the almost uniformly poor response of herring populations to 10 years of management efforts, provide bases for doubt that their management is scaled and packaged appropriately in relation to stock structure. Furthermore, there is no clear concept of what constitutes a redfish stock, the management approach being based on discontinuities in commercial fishery distributions. The same remarks can be made for essentially all deepwater groundfish and many of the major invertebrate species.

Understanding the factors responsible for such stock formation (or rather, for restriction in gene flow), which involves the influence of environment on all life-history stages, requires more than the application of present stock separation techniques (tagging, biochemistry, etc.). It requires also an understanding of how physical environmental factors are involved in stock boundary determination. This may have little practical value for the well-studied cod and haddock, but it could allow development of new approaches to management of other species for which present management arrangements are not producing demonstrably satisfactory results.

Species level

In this section, environment is discussed in relation to species distribution. In this context, a knowledge of the association between oceanographic systems and stock units would be the basis of predictive ability in relation to climatic change. It is the recruitment process which is most sensitive to environmental change. Thus, response to climatic change will be most immediately and obviously reflected in recruitment trends to geographically marginal stocks.

Environmental factors can be expected, therefore, to have the greatest effect on the distribution and abundance of species at the extremes of their ranges. Species may exist in high (low) abundance at these extremes for varying periods of time, but, with large-scale climatic changes, abundance levels may decline (increase) dramatically for a subsequent period, only to return to former levels with another climatic change. For example, cod were abundant at West Greenland during 1845–1851 and from 1920 to the mid-1960's but were very scarce during the intervening period. They have been declining from the late 1960's and are at present again very scarce. Also, some species at the extremes of their range show wide fluctuations in recruitment as a matter of course (e.g. herring along the east coast of Newfoundland), with the majority of year-classes being very poor in relation to the occasional large year-class. This, of course, leads to long periods of declining resource abundance that are followed by sudden upswings. Similarly, squid exhibit marked fluctuations in abundance, periods of high abundance usually being followed by periods of low abundance, and these fluctuations appear to be more extreme in the northern part of the species range. It is highly likely that such fluctuations are influenced by environmental factors, and, indeed, this has been well documented for cod off West Greenland (Hansen and Hermann, 1965).

An understanding of these changes at the species level, and the role of the environment in determining abundance levels at the extremes of areas of distribution, may enable fisheries biologists to predict periods of high and low abundance in these areas. Knowledge of the impending decline of a resource in an area due to changing environment may dictate a different fishing strategy than if the resource were declining due to fishing pressure.

So far, natural environmental factors and their effects on species distributions have been discussed, but there are man-made influences which also deserve mention. Nutrient flux onto the Labrador Shelf from Hudson Strait has been proposed as a determinant of fish distributions along the Shelf (Sutcliffe *et al.*, 1983). The amount of freshwater outflow from Hudson Bay, through its effect on mixing and the availability of nutrients in surface layers, was suggested as a mechanism that controls production, including fish production. To quote Sutcliffe *et al.* (1983), "the apparent importance of the freshwater discharge indicates possible effects on the fisheries production along the Labrador Shelf by large hydroelectric development schemes on the watersheds adjacent to Hudson Bay".

Runoff regulation for hydropower in the Gulf of St. Lawrence river system caused significant changes in the physics and dynamics of waters of the St. Lawrence Estuary and the Gulf (Neu, 1976), and the oceanographic effects of variation in runoff have been traced as far as the Gulf of Maine (Sutcliffe *et al.*, 1976). Neu (1976) estimated that spring and summer runoff at the entrance to the Gulf of St. Lawrence (of the St. Lawrence river system) has been reduced by 30-50% by hydrodevelopment. Substantial biological effects have been postulated as arising from such variations from the Gulf of St. Lawrence (Sutcliffe, 1973) to as far afield as the Gulf of Maine (Sutcliffe *et al.*, 1977). The effects of freshwater runoff on the marine environment in the Gulf of St. Lawrence has most recently been reviewed by Bugden *et al.* (1982), and recommendations for further research have been formulated.

The harnessing of tidal power in the Bay of Fundy, which has one of the highest tides in the world, has been under periodic consideration since the 1920's. This has been brought closer to reality with the recent completion of a pilot barrage. Numerical models have predicted that the proposed barrage across the mouth of Minas Basin in the inner Bay of Fundy would increase the range of tides at Boston, Massachusetts, by 30 cm and over Georges Bank by up to 5 cm (Greenberg, 1979). This wide-scale effect would probably have substantial effects on many of the fisheries resources of the area.

The impacts of distributional changes of species tend to be of a large and longer-term nature. There are specific practical fisheries assessment and management problems with which knowledge of environmental effects on this scale would aid in dealing. It would aid the assessment of cod in Div. 2J+3KL if there was an awareness that expectations of recruitment should be 500 million fish or more at age 4, as occurred in the 1960–71 period or 100–400 million fish, as was the case in 1973–81 (Gavaris *et al.*, MS 1984). It would have been of benefit to ICNAF scientists to have known the respective role of climate and fishing in the decline of recruitment to West Greenland cod, and advice may have been more clear-cut. The greatest benefits of this kind of knowledge, however, lie in guidance on long-term expectations and the use of these in investment decisions. The cod stock in Div. 2J+3KL, for example, is so large that projections of future yield of cod in the whole Canadian zone are dominated by it. Longer-term expectations for this one stock are pivotal in development of Canadian economic and social policy in relation to its Atlantic marine fisheries (Kirby, 1982).

Conclusions

The framework developed here for identifying fisheries management problems is organized on three levels which involve increasingly larger numbers of fish, larger spatial and temporal scales, and greater problem complexity (Table 1). At the population level, environmental factors affect the direction and speed of fish migrations which influence the success of localized fisheries. Of more general importance, however, is the influence of environment on the location, timing and degree of aggregation of marine species. This has a major effect on fishing success, managerial planning and the stock assessment process. In particular, environmentally-induced variation in commercial (and research vessel) catch rates can be sufficiently large to mask the relationship between catch rate and stock size, which leads to many stock assessment and managerial difficulties. At the stock level, problems concern distribution in relation to oceanographic structure and the factors resulting in stock formation. An understanding of these would be of great importance in the definition of management units. Concerns at the species level relate to zoogeography and the effects of ocean "climate" and large-scale man-made influences such as power dams. New knowledge at this level, by providing a basis for interpretation of resource trends, would aid the stock assessment process and give a foundation for longer-term investment planning.

Thus, this paper has concentrated on defining broad problem areas and evaluating the practical importance of these problems to fisheries management in the Northwest Atlantic, using examples only to illustrate specific points. There is no attempt to develop an exhaustive list of specific problems within these areas nor to address the tractability to solution of any of the problems discussed. Development of methods to address the problems has been left to others, hopefully to teams including both biologists and oceanographers who are experts in this particular field.

Nonetheless, the following brief general comments on program planning are made. ICNAF (more recently NAFO) selected what is undoubtedly the most important problem to fisheries management — definition of the factors controlling recruitment, when sponsoring the Flemish Cap Project and the Georges Bank Larval Herring Program. These projects are at their final stages, and, although they have generated a great deal of useful science, it does not appear that they are going to resolve the "recruitment problem". (A full review of the results of these projects will be dealt with in a special session of the Scientific Council in September 1986.) Because this is an intractable problem, it continues to be identified as the major fisheries research problem on a world-wide basis (see IOC, 1984). The Intergovernmental Oceanographic Commission (IOC) is currently sponsoring an International Recruitment Project-oriented Program, and the Scientific Council of NAFO is presently in communication with IOC regarding sponsorship of a squid recruitment project initiative in the NAFO Area (NAFO, 1984). Thus, with regard to the recruitment problem, NAFO is in a review and reconsideration phase, and this is an opportune time to consider the relative value of initiatives in other problem areas.

This review of environmental effects on the distribution of marine fishes has identified a number of problem areas of substantial importance to the work of the Scientific Council. In particular, environmentally-induced variability in availability of fish to commercial and research gear stands out as a significant problem in many aspects of stock assessment and fisheries management. This would appear to deserve the Council's attention.

It is necessary to explore further the nature and importance of availability problems and their amenability to solution. Much of this could be accomplished through analysis of data that are already collected. While a coordinated approach to any field programs which might subsequently be proposed is no doubt desirable, this topic would seem to lend itself to smaller-scale research initiatives than have been mounted in the past in relation to recruitment studies. The logistic problems in mounting, say, an international cooperative multiship, multiyear research project, such as the Flemish Cap Project or the Georges Bank Larval Herring Program, are daunting indeed. A topic which allows the Scientific Council to encourage coordinated studies by various groups of biologists and oceanographers throughout the NAFO Area would be less organizationally demanding.

In summary, there are problems concerning the effect of environment on fish distributions which are of practical importance to the work of the Council. Pursuing these may not conflict greatly with pursuit of solutions to the recruitment problem, at least in the short term, because, in part, different scientists would be involved but also because major NAFO initiatives concerning recruitment studies appear to have more or less run their course. Focusing attention on, say, environmentally-induced variability in availability to fishing gears has the attraction of being able to be addressed by smaller-scale coordinated efforts than has been the case with recruitment studies.

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