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ICES Science 1979–1999: The View from a Younger Generation

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Foreword

The six articles in this number of the *ICES Cooperative Research Report* series provide an overview of important developments in key fields of marine science in the ICES Area between 1979 and 1999. They constitute a review of the twenty years of progress since the date of the last article contained in *Study of the Sea*, an anthology of material stemming principally from ICES publications and edited by Edgar M. Thomasson, former ICES Librarian/Information Officer (Fishing News Books, 1981).

The Bureau Working Group on the Planning of the ICES Centenary, through its Chair, Michael M. Sinclair, and John Ramster, asked Pierre Petitgas to coordinate the preparation of this publication. It was mutually agreed that a balanced and unbiased review of recent work conducted under the auspices of ICES would best be undertaken by the younger generation of marine scientists.

These articles present the views of six scientists who are currently engaged in working with ICES and who will, it is warmly hoped, continue to help define and shape its future.

Biological oceanography discoveries, findings, and new concepts: the contribution of ICES publications

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The work of ICES in biological oceanography has a long history and, indeed, was one of the subjects that led to the creation of ICES itself (Mills, 1989). Factors controlling the abundance and distribution of phytoplankton, and later zooplankton and fish eggs and larvae, were of great interest to the marine scientists in the late 1800s and early decades of the 1900s. This interest stemmed from the search for explanations of the causes of fluctuation in the major fish stocks of northern European waters (Hjort, 1914). In the 1980s and 1990s these factors continued to be one of the foci of ICES activity. This overview of the biological oceanographic science that ICES published during the period 1979–1999 will evaluate and compare the major trends in this field within ICES as opposed to the international community at large. A second objective will be to estimate the quantity of work that ICES has done in biological oceanography relative to other fields.

Major concepts and discoveries in biological oceanography during 1979–1999

What were the major concepts and discoveries within all of biological oceanography during 1979–1999? I defined “major concepts and discoveries” as new ideas, approaches, observations, or technical developments that met the following criteria:

- (i) those that took the field into completely new directions which did not exist previously or could only be addressed in the past in qualitative ways;
- (ii) those that led to new major research initiatives and large numbers of publications/symposia within and/or outside ICES and
- (iii) those that had some impact on the way the oceans and its resources are managed and therefore an impact on society at large.

According to these criteria, I identified nine new concepts or discoveries (Table 1). Most of these concepts and discoveries have been made via the collaboration of large numbers of scientists involved in ICES, and ICES has arranged meetings on many of these topics and published papers from them in one form or another. For example, most of the issues have been discussed or addressed in various ICES committees and working groups (e.g., Biological Oceanography, Hydrography/Oceanography, Zooplankton Ecology, Recruitment Processes) as can be seen by the reports presented at ICES Annual Science Conferences.

One discovery that seems to have had a particularly strong impact is the presence and role of the “microbial foodweb”

in pelagic ecosystems. This concept is probably the single most influential new finding in biological oceanographic research of the last thirty years and has been an enormous stimulus to investigations of carbon fluxes, marine snow formation and pelagic-benthic coupling (Jumars, 1993; Valiela, 1995; Jumars and Hay, 1999).

Another major development in biological oceanography during the period 1979–1999 was the growing awareness of the strong coupling between physical and biological processes. Physical processes (e.g., advection, mixing, stratification, tides, upwellings, fronts, storms, etc.) were shown to have major impacts on the structure of entire food webs (Cushing, 1989; Kiørboe, 1997), population abundance and structure in fish (Sinclair, 1988; Jakobsson *et al.*, 1994; Caley *et al.*, 1996) and benthic invertebrates (Connolly and Roughgarden, 1998), fisheries recruitment (Jakobsson *et al.*, 1994; Bakun, 1996; Daan and Fogarty, 2000) and predation processes among individual plankters (Rothschild and Osborn, 1988; Kiørboe, 1997).

The ability to cross disciplines between biological and physical oceanography (Daan and Fogarty, 2000; Tande and Miller, 2000) was particularly important. An excellent example of how this barrier is dissolving is the development and application of three-dimensional (3D) ocean circulation models to address the transport of biological entities (e.g., fish eggs and larvae, copepods) and the visualization of such distributions over time. Developments in remote sensing also facilitated a quantum leap in the understanding of the spatial scale of variations in sea surface temperature and phytoplankton pigment concentrations because they can now be measured routinely. This contributed to the tremendous increase in understanding of the linkages between large-scale climate variability and large-scale biological and hydrographic variability.

Several other oceanographic issues requiring biological expertise became apparent during the period 1979–1999. These issues include the following: global climate change, carbon fluxes, aggregate formation and dynamics, harmful algal blooms and the role of eutrophication, the role of fishing as opposed to environmental variability on the collapses of exploited populations, species invasions and introductions, biodiversity issues and the ecological effects of aquaculture. These topics have arisen partly owing to the direct influence of humans on marine ecosystems, their inhabitants, and the biosphere in general. While these issues are not discoveries or concepts, they have influenced the amount and scope of biological oceanographic research, and how its findings can be applied to anthropogenically related problems. They have also led to new insights into processes affecting plankton distribution and abundance.

Table 1. Major biological oceanographic concepts and discoveries during the period 1979–1999.

	Concept, discovery, or trend	Type
1	Microbial foodweb	Observational
2	Role of physical processes on population abundance/structure (“supply-side ecology”, “retention-dispersion”), pelagic foodweb structure (“diatom-dominated vs. flagellate/microbial-dominated”) and predator–prey interactions	Observational
3	Hydrothermal vents and new mero-/holoplankton species	Observational
4	Iron hypothesis for limiting primary production	Observational
5	Satellite imagery and remote sensing of temperature and phytoplankton pigments across large spatial scales	Technical
6	Impacts of major climatic events on large-scale variations in hydrography, plankton, and fisheries (i.e., NAO in the North Atlantic and El Niño/La Niña in the Pacific)	Observational
7	Coupling of 3D ocean circulation models to plankton distributions	Theoretical-technical
8	Radioisotope applications for detecting foodweb links, eutrophication patterns, decadal–century scale hydrographic variability.	Observational-technical
9	Development and application of individual-based approaches (e.g., models, biochemical measurements, otoliths) for estimating survival and growth probability of individual plankters	Technical

Some of the indirect outputs of this research have been the development of remote-sensing methods to estimate phytoplankton production rates over large areas, and an awareness of the role of long-term natural variability in marine ecosystems and their response to climate change. The state-of-the-art of biological oceanography therefore owes much of its present understanding to attempts to solve these and other types of applied problems.

Other outstanding new findings, concepts, and interpretations during 1979–1999 included the discovery of an entirely new means of primary production associated with hydrothermal vents and entirely new benthic communities in their vicinity.

In another field, improvements in “clean” analytical marine chemistry methodologies (Martin *et al.*, 1991) enabled the role of iron on primary production to be quantified and clarified (Chisholm and Morel, 1991; Mann and Lazier, 1996; Jumars and Hay, 1999). This development has subsequently led to large-scale *in situ* experiments to investigate how iron fertilization in the open ocean might affect primary production and carbon fluxes to the benthos (Mann and Lazier, 1996). Perhaps not unexpectedly it has also led to much debate within the scientific community and general public (Chisholm and Morel, 1991; Mann and Lazier, 1996).

ICES contribution to the major discoveries and trends in biological oceanographic research during 1979–1999

Many of the papers that contributed to the discoveries and concepts in Table 1 have appeared in ICES publications.

ICES has been particularly active in promoting, and publishing, results of investigations describing the coupling of physical and biological processes from small to large scales. This work is partly due to the contributions of the ICES Working Groups on Recruitment Processes, Hydrography,

and Biological Oceanography / Zooplankton Ecology (e.g., ICES, 1993, 1994a), and the ICES/GLOBEC Working Group on Cod and Climate Change as well as the Workshops, Theme Sessions, and ICES Symposia that this Working Group has co-organized and supported (e.g., Jakobsson *et al.*, 1994; ICES, 1994b, 1998a, 1998b, 1999). The general objective of most of these activities has been to quantify the linkages between physical processes, zooplankton and fish with the overall goals of improving fisheries management and our understanding of life in the oceans. One of the major findings of many of these studies is that physical processes and the variability of circulation patterns have major impacts on zooplankton (Tande and Miller, 2000) and the early life history stages of fish (Daan and Fogarty, 2000), which often translate into fluctuations in recruitment independent of reproductive output and spawner biomass (Bakun, 1996; Cushing, 1996).

Scientists within ICES have also been among the first to use 3D ocean circulation models to describe the drift of zooplankton (Bartsch *et al.*, 1989). The new models and technology have contributed to the development of a new emphasis on individual-based approaches (i.e., non-aggregated models in which characteristics of individual organisms are specified) in fisheries oceanography (Heath and Gallego, 1997), which is now an important part of ICES GLOBEC-related activities (ICES, 1998a, 1998b).

The development of individual-based models has also been encouraged by improvements during the last 20 years in methodologies for measuring characteristics of individual plankters, including fish larvae. Potentially this work will contribute to ICES fisheries research and assessment activities. For example, analyses of otolith microstructure and biochemical components now make it possible to assess birth dates, daily and lifetime growth rates, condition, feeding, and metabolic rates of individual larvae (Ferron and Leggett, 1994; Fossum *et al.*, 2000). These developments and the application of new technologies have often been

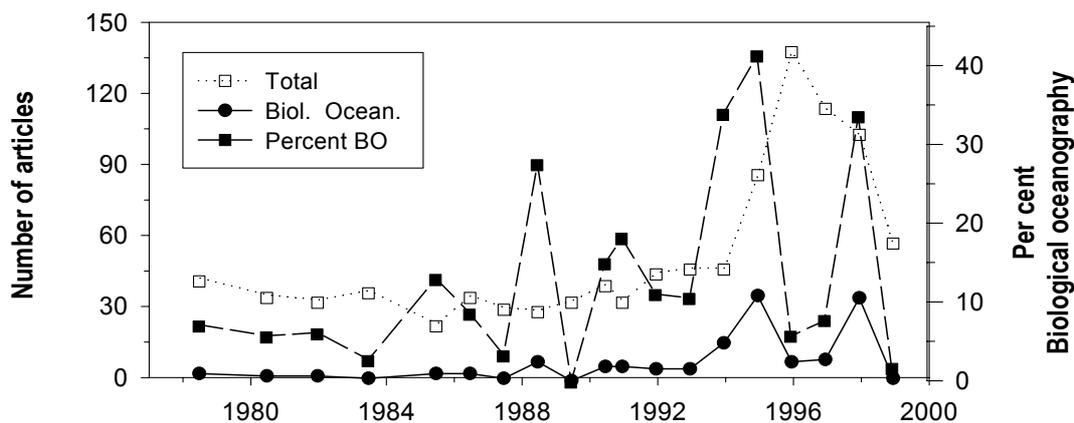


Figure 1. The total number of articles published per year by the *ICES Journal of Marine Science* and the number and proportion of biological oceanography articles published per year in the same journal.

presented at ICES meetings (Clemmesen, 1987; Ueberschär, 1987) and published in either ICES journals (Ueberschär and Clemmesen, 1992; Bergeron, 1995; Bergeron *et al.*, 1997) or elsewhere. The techniques are frequently used to compare growth and condition of larvae and juveniles with hydrographic and biological variability in the sea (Ferron and Leggett, 1994), and these findings contribute to many ICES committee and working group activities (ICES, 1993, 1994a, 1994b).

While these topics have been dominant within ICES biological oceanography, major new areas of biological oceanographic research are nearly invisible in ICES publications. Papers relating to the microbial web (and in particular the roles of ciliates and bacterioplankton), iron regulation of primary production, hydrothermal vent communities, and marine snow formation and its role in carbon flux to the benthos (and more generally biogeochemical cycling of materials) are noticeably rare in the ICES literature. This relative absence could be due to geography: many of these findings involve oceanic areas outside the North Atlantic, and few scientists within the ICES community have routine access to these regions. In addition, these topics have considerably fewer, and less direct links to the main research and advisory role of ICES—the growth, dynamics, and regulation of exploited marine populations—than studies of fish biology or zooplankton and primary production.

ICES-published science in 1979–1999: the contribution from biological oceanography

A more quantitative way to summarize the overall biological oceanographic contribution of ICES is to evaluate the titles of papers and reports published in the *ICES Journal of Marine Science* and in the *ICES Cooperative Research Report* series. For the purposes of such an analysis I will use the term “ICES biological oceanography” to describe that

field of research whose objective is to describe how the abundance and distribution of plankton (including fish eggs and larvae) vary with environmental conditions and species interactions (e.g., predation).

The following are examples of what will be included under the “ICES biological oceanography” umbrella: plankton distributions in relation to hydrography, plankton feeding, growth, and mortality rates, long-term trends in plankton abundance (e.g., from various monitoring studies), ichthyoplankton abundance, distribution, and growth, and development of methods and techniques used to describe plankton distributions and growth rates (e.g., improvements in primary-production methodology, plankton sampling devices). Examples of topics that have been excluded are the following: benthic ecology (except for the meroplanktonic stages), harmful algal blooms, species invasions and the effects of aquaculture activities on the environment.

During 1979–1999 ICES published a total of 33 volumes of proceedings of ICES Symposia, 153 *ICES Cooperative Research Report(s)*, and 1012 research articles and notes in its *ICES Journal of Marine Science*. Thirteen symposium proceedings titles (39%), 20 report titles (13%), and 15% of the *Journal* articles had titles related to “ICES biological oceanography” according to the criteria above. On average during the period 1979–1999, the *Journal* published 53 articles per year (standard deviation = 33), of which 13 articles (standard deviation = 12), i.e., 25%, were related to biological oceanography (Figure 1).

The topics of the “ICES biological oceanography” articles published in the *Journal* can be grouped into broad subject categories. The most frequent topics were related to recruitment and ichthyoplankton including statistical analyses of effects of oceanographic variables on recruitment (Figure 2). The second most frequent topic was plankton distributions (e.g., in relation to hydrographic variability).

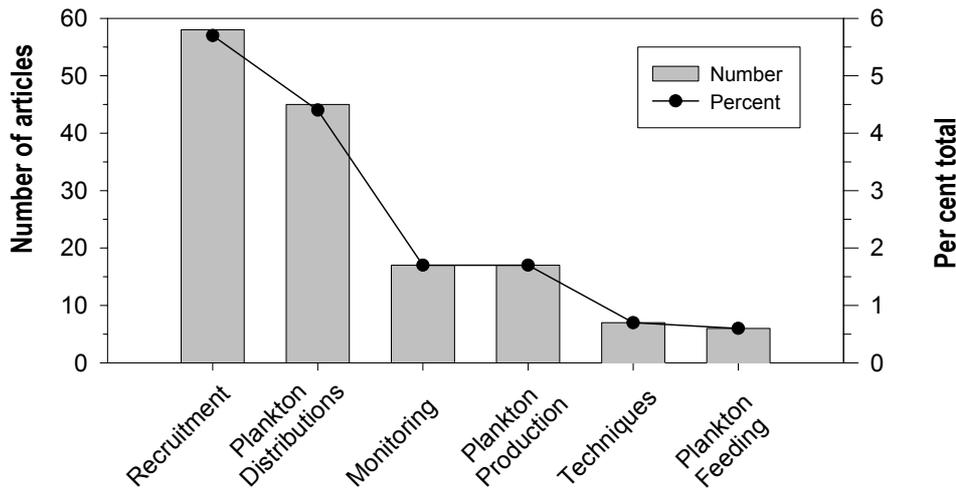


Figure 2. The total and proportion of articles within six different subject areas of biological oceanography that have been published by the ICES Journal of Marine Science during 1979–1999(4).

Several topics within biological oceanography *per se* are not represented in ICES publications and some of these were noted above. In addition to these, zooplankton behaviour (e.g., prey, predator, and mate detection), top-down control of zooplankton populations, and primary production/phytoplankton ecology are under-represented. These fields have been active in the last 20 years and have been published in other journals (Mauchline, 1998). In general the biological oceanographic material published under ICES auspices is only a small fraction of that which is published annually in all journals combined. Several of the major oceanographic and marine ecological journals increased the number of pages published per year during 1979–1999 (Figure 3) and, in addition, some new journals became established within the field during this period (e.g., *Fisheries Oceanography*, *Journal of Marine Systems*, *Aquatic Microbial Ecology*). The increase in total marine science output was probably partly due to an absolute increase in the biological oceanographic component during these years.

The *ICES Journal of Marine Science* increased its publication output to a substantial degree during the same period (ca. 5–6-fold; Figure 3). The increase occurred even though the *Journal* did not publish material in some major areas of biological oceanography. This observation suggests that the share (or at least diversity) of articles on this topic published in the *Journal* could perhaps be increased if investigators in the field chose to publish in it.

In addition to its published literature ICES produces a large number of annual reports based on the biological oceanographic activities of its committees and working/study groups. These reports are influential within ICES and the general biological oceanography community because they represent the latest and evolving perspectives of many experts within biological oceanography. As such, these reports

can be an important vehicle for communicating preliminary, yet authoritative, consensus ideas and research plans to the wider biological oceanographic community. However, the reports are not formally published and are therefore part of the grey literature. For this reason, although they provide great value to the ICES and general biological oceanographic communities, they have been excluded from this review.

Conclusions

ICES has played a major role in the field of biological oceanographic research since its inception in 1902. This role involves publishing research articles, reports, and proceedings of conferences and symposia, and organizing working groups, committees, and workshops to carry out and coordinate research and advisory activities at the international level. In the last quarter of the century biological oceanographic articles represented about 15% of all those published in the *ICES Journal of Marine Science*, and this fraction increased in the 1990s compared with the late 1970s and early 1980s. Most of these papers are related to fisheries recruitment and plankton distributions, and large areas of biological oceanographic research are under-represented. Hence biological oceanography as viewed from the pages of ICES publications is focused on certain key components of biological oceanography and is not, therefore, representative of the field as a whole. This situation will likely continue for as long as ICES continues to be one of the major suppliers of fisheries management information to regulatory authorities. However, ICES could publish larger, and more diverse, amounts of biological oceanographic information in future, particularly as ICES implements its Strategic Plan (initial version: ICES, 2000), which emphasizes multi-

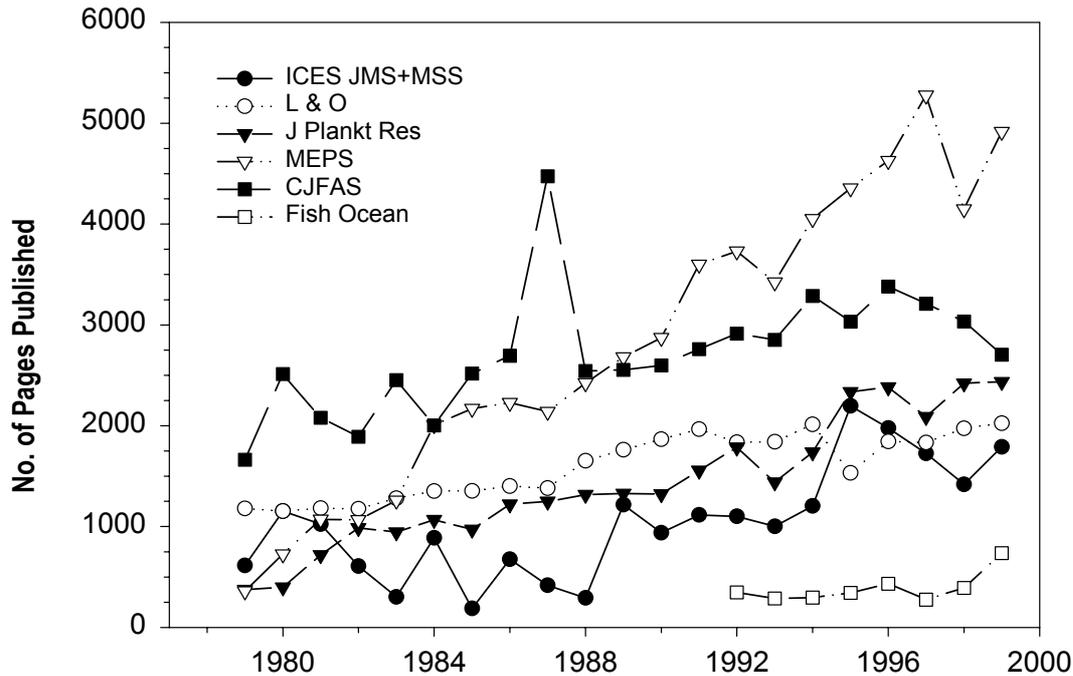


Figure 3. The total number of pages published per year by different biological oceanography and marine ecological journals during 1979–1999. Abbreviations: ICES JMS: *ICES Journal of Marine Science*; ICES MSS: *ICES Marine Science Symposia*; L & O: *Limnology and Oceanography*; J Plankt Res: *Journal of Plankton Research*; MEPS: *Marine Ecology Progress Series*; CJFAS: *Canadian Journal of Fisheries and Aquatic Sciences*; Fish Ocean: *Fisheries Oceanography*.

disciplinary and broader-based approaches to fisheries and ecosystem management.

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Ecosystem effects of fishing activities

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The scientific basis of fisheries management was founded in the study of the exploited populations. It was never surprising that these were the primary units of concern since they are targeted by fishers, sold at auction, and known to buyers, and were the groups in which the effects of fishing were most clearly recognized. Although the effects of trawling in the North Sea had been a topic of debate in English, Scottish, and Welsh governing circles at various times since the fourteenth century, such concerns were largely neglected until the end of the nineteenth century when major advances in the management of living resources began to be made by scientists working on quantitative stock assessment (Ramster, 2000). However, by the last quarter of the twentieth century as fishing intensity increased and a wider range of species were targeted, gears became larger and more destructive, and the wider effects of fishing on the ecosystem became more of a concern.

In the 20 years since 1979, ICES has played a central role in promoting interest in and research on the ecosystem effects of fishing activities. The early ICES Working Groups on the “Ecosystem Effects of Fishing”, chaired by Henrik Gislason and subsequently Steve Hall, were the meeting place for researchers interested in the study of fishing effects and became a stimulus for further research (e.g., ICES, 1992, 1996). Prior to their formation, relatively little was known about the ecosystem effects of fishing in the Northeast Atlantic, and many leading scientists in this field, such as N. Daan, S. J. de Groot, H. Gislason, S. Hall, H. Heessen, M. J. Kaiser, H. J. Lindeboom, and J. Rice developed their interests within the ICES Working Groups and subsequently published some of the most widely cited books, reviews, and conference volumes on this subject, e.g., Jennings and Kaiser, 1998; Lindeboom and de Groot, 1998; Hall, 1999; Kaiser and de Groot, 2000; and Hollingworth, 2000. The discussions and publications of these groups were to change the emphasis of research in many fisheries laboratories. Now it seems quite normal to open an issue of the *ICES Journal of Marine Science* and to read several papers on seabirds or the effects of trawling on the seabed: something that was inconceivable only 20 years ago.

The effects of trawling on the seabed worried fishers as early as the fourteenth century, but sustained and vocal concern about the ecosystem effects of fishing is a recent phenomenon. Part of this lack of concern stemmed from the fact that few effects were apparent in the ICES Area until the 1980s, and these paled into insignificance beside the collapses of herring and mackerel stocks, the gadoid outburst, and other events that dominated the lives of assessment scientists. Beam trawling had begun in the 1970s, and industrial fishing was most intensive in the 1980s. Early papers had considered these issues (e.g., Cole, 1971), but few labo-

ratories had programmes of work that related to them. From the scientists’ viewpoint the lack of clear necessity kept ecosystem approaches from advancing in a field where the main concern was the mechanics of short-term management.

At the 1975 ICES Århus Symposium on “North Sea Fish Stocks—Recent Changes and Their Causes”, there was little reference to the effects of fishing, other than those on the dynamics of exploited species (Hempel, 1978) although, at this time, there was already wide-ranging interest in the relative roles of natural and anthropogenic factors in governing fluctuations of North Sea fish stocks. By 1999, times had changed dramatically and ICES (with SCOR) organized a meeting in Montpellier on the “Ecosystem Effects of Fishing”, co-convened by M. Sinclair and H. Gislason (Hollingworth, 2000). The perspective was international, and seabirds, genetic selection, and trawling effects on the seabed dominated the proceedings. It is extraordinary that in less than 20 years we are approaching a time when ecosystem management has become a matter of real importance to ICES scientists. This is reflected in the changing concerns of bodies like OSPAR and the EC, with fisheries increasingly seen as a conservation issue. Moreover, interest in ecosystem effects was often driven by the involvement of pressure groups responding to individual issues such as “industrial fisheries” or “porpoise by-catches” (e.g., Greenpeace, 1996). ICES research has often provided a scientific perspective on problems in these emotive areas.

The history of the study of fishing effects in the ICES Area is well reflected in the publications of ICES, and many of these publications have acted as stimuli for further research. The *ICES Journal of Marine Science* reflects the development of the field. From 1979 to 1988 there were almost no published papers that dealt directly with ecosystem effects. Then, from the early 1990s, they started to appear. One key publication appeared in the *ICES Journal of Marine Science*, Volume 49, in 1992: papers from the “Mini-Symposium on the Benthic Ecology of the North Sea”, where issues such as the direct effects of beam trawling were considered in detail for the first time, and their potential role in governing the ecology of the North Sea was drawn to the attention of a wider audience (Bergman and Hup, 1992). These ideas were developed in subsequent papers such as Witbaard and Klein’s examination of trawling effects on the large and slow-growing bivalve mollusc *Arctica islandica* (Witbaard and Klein, 1994). However, the landmark in the study of fishing effects was the 1995 ICES Symposium on “Changes in the North Sea Ecosystem and Their Causes: Århus 1975 Revisited” (Daan and Richardson, 1996). Unlike the Århus Symposium some 20 years earlier, there was a clear focus on the effects of fishing on

non-target species and communities. Although concern over the mortality of non-target species really began with a paper by Brander (1981), where he described the virtual disappearance of common skate from the Irish Sea, the 1995 meeting made it clear that such effects were widespread and affected many other species (Heessen and Daan, 1996; Walker and Heessen, 1996). This Symposium set a trend that was to be reflected in subsequent issues of the *Journal* and would culminate in the previously mentioned ICES/SCOR Symposium on the “Ecosystem Effects of Fishing”, held in Montpellier in 1999 (Hollingworth, 2000).

Following the publication of the papers given at the 1995 Symposium there followed a similar conference on seabirds. This dealt with many “fishing effects” issues, including seabirds as monitors of the marine environment, changes in breeding success with food supply, and the role of seabirds as consumers of fishery discards (Reid, 1997). Other related publications in this period included *ICES Cooperative Research Report(s)* on the “Ecosystem Effects of Fishing Activities” (ICES, 1995) and “Fish–Seabird Interactions” (ICES, 1996), as well as the widely read annual reports of the ICES Working Group on the Ecosystem Effects of Fishing Activities.

Even today the science of the effects of fishing is in its infancy. While there is a good understanding of fishing effects, there are relatively few applications to management, although this is likely to change rapidly with the formation of the ICES Advisory Committee on Ecosystems. Knowledge of fishing effects has been gained by the addition of new research programmes in many fisheries laboratories, and these have looked beyond pure stock assessment to the role of fisheries in the ecosystem. At present, the main role of this science is to provide the basis for advice, but ICES will doubtless play a key role in the first attempts to implement ecosystem-based fishery management.

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Fisheries technology

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Technology for finding and catching fish developed rapidly after World War II. Fishing boats became bigger and more powerful, the hydraulic deck machinery could handle heavier fishing gears, and underwater acoustic instruments like the echosounder and sonar became available for detecting fish concentrations anywhere in the water column. Together with instruments for geographic positioning (Loran, Decca) and safe navigation (radar), this technological revolution enabled fishers to locate and catch fish wherever they were distributed and in any season. With unlimited access and no regulations, this led to recruitment and growth overfishing that caused a drastic decline in the abundance of bottom species and the collapse of many pelagic fish stocks in the 1960s and 1970s.

With the escalating quantity of fish landed, concern was raised within the ICES community in the 1950s and 1960s about the fate of the fish stocks (Smith, 1994). This concern led to the development of virtual population dynamic models to explore and predict the development of fish stocks on the basis of catch-at-age statistics. By using such models, fisheries could be regulated through the setting of total allowable catches (TACs). On the technical side, studies of the selectivity of fishing gears showed that the size-at-first-capture for many species was usually much lower than optimal, and in many cases, most of the fish landed had not realized their growth potential. Therefore, minimum landing and mesh sizes and closed-area regulations became common in many fisheries throughout the late 1960s and 1970s.

However, the decline in many gadoid fish stocks continued, and the collapsed clupeoid fish stocks were slow to recover throughout the 1970s. Development of more selective trawl gears continued during the 1980s and 1990s in the belief that technical improvement could contribute to more optimal fishing patterns.

To improve the assessment of fish stocks, fishery-independent estimates of abundance, relative or absolute, were needed. This was the scientific rationale behind a substantial effort to develop fisheries acoustics from a qualitative towards a quantitative method for mapping fish stocks.

Within the ICES community, the development of more optimal fishing gears and of methodology for fish-abundance estimation by using underwater acoustics have been the main activities of the Fisheries Technology Committee, which was called the Fish Capture Committee before 1997. Since the early 1980s this Committee has had two active Working Groups: the Working Group on Fisheries Technology and Fish Behaviour (WGFTFB) and the Working Group on Fisheries Acoustic Science and Technology (WGFAST). Both groups have had a significant influence on the scientific development within their fields (Fernandes

et al., 2001; Walsh *et al.*, 2001), and a common interest of the groups has been studies of fish behaviour based on the realization that fish behaviour determined availability and catchability.

Trawl selectivity

Because it was the main gear for catching gadoids and bottom species within the ICES areas, the bottom trawl became associated with fish-stock decline throughout the 1970s. Therefore, scientific efforts to improve the size selectivity of bottom trawls have been an important topic within the Fisheries Technology Committee.

Trawl selectivity was known to be a function of mesh size, but new studies showed that it was also influenced by the number of meshes in the circumference of the trawl bag, the length of the extension, the length of selvaige ropes relative to trawl bag and extension, twine thickness, catch size, and mesh geometry. In the North Sea, whitefish fishery trawl selectivity can be enhanced by changing the geometry of the meshes in the codend (Figure 1) from rhombic to square (Robertson and Stewart, 1988; Van Marlen, 2000), while in other areas use of such a mesh configuration did not improve selectivity because of clogging by redfish (Isaksen and Valdemarsen, 1986) or catch-size-dependent selectivity (Suuronen *et al.*, 1991). Use of rigid sorting grids (Figure 1) gives a sharper and more efficient selection than mesh selection alone (Larsen and Isaksen, 1993). The Barents Sea whitefish trawl fishery was required by regulation to use grids from 1997 onward. In the relatively fine-meshed shrimp trawls, by-catch has been a substantial problem. To reduce by-catch in shrimp trawls, the Nordmøre grid (Figure 1) was made mandatory in the Barents Sea in 1990 (Isaksen *et al.*, 1992).

Survival

Size- and species-selective fishing function only if the fish survive after escaping physical contact with the gear or the selection device. Experiments based on the collection and caging of fish escaping selection in trawls showed that gadoids like cod and saithe survived, but that the mortality of haddock was substantial for small individuals and low for the larger ones (Soldal *et al.*, 1993, Sangster *et al.*, 1996). Most small herring die when escaping through meshes and selection devices in trawls (Suuronen *et al.*, 1996).

Scientific trawling

With increased demand for knowledge about the factors causing bias and precision in fishery-independent surveys, the "representativity of bottom trawls" as a tool for fish

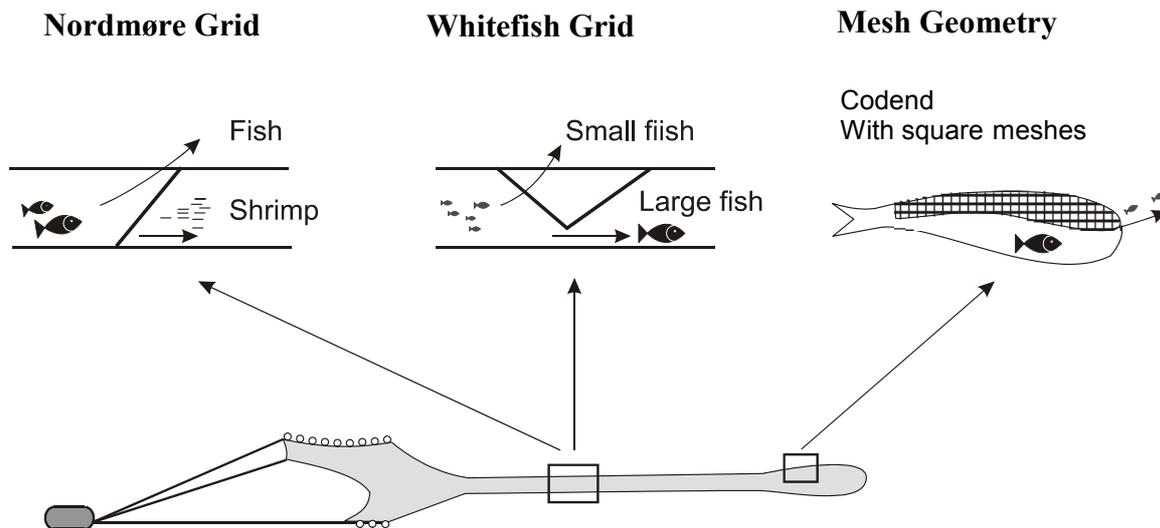


Figure 1. Selection technology developed to enhance species selectivity in shrimp trawl (the Nordmøre grid, see Isaksen *et al.*, 1992), and to improve the size selectivity in whitefish trawls (a whitefish grid, see Larsen and Isaksen, 1993, and a codend with square-meshed panels, see Robertson and Stewart, 1988).

sampling has been investigated. This index has relevance not only to pure bottom-trawl surveys but also to acoustic surveys where sampling by trawl for identification of species and length composition is an integral part of the experimental design. Main and Sangster (1981) observed that cod search towards bottom when approached by a bottom trawl, haddock rise and may escape over the headline in substantial numbers, while whiting (*Merlangius merlangus*) tend to aggregate more in the middle of the trawl opening. Such species-dependent reactions may clearly result in a species composition in the trawl catch that is not representative for the area sampled. Diurnal changes in species and length composition with large fish available during daytime and small fish dominating the catches at night have been reported (Engås and Soldal, 1992). Experiments with collection bags under the fishing line of bottom trawls showed that juvenile gadoids escaped capture in large numbers under the trawl (Engås and Godø, 1989; Walsh, 1989, 1991). Substantial changes in trawl geometry as a function of bottom depth were revealed (Godø and Engås, 1989). Also, to obtain a fixed geometry and sampling width, a technique using a constraining rope about 175 m in front of the trawl doors has been introduced (Engås and Ona, 1991).

Environmental impact of fishing activities

Unaccounted mortality of seabirds during longlining and of cetaceans in gillnets has been documented, and technical solutions like bird-scaring devices and cetacean-scaring pingers have been developed and taken into use in the fisheries. Likewise, the continued “ghost” fishing of lost gillnets has been studied (Kaiser *et al.*, 1996). Much focus has been placed on the physical impact of bottom-trawl gears on the bottom fauna and topography. On sandy bottoms, tracks of heavy beam trawls were shown to have faded completely after 37 hours (Fonteyne, 2000). On other bottom types with more fragile fauna the impact can be more permanent. In the southern North Sea several benthic species have decreased in abundance and even disappeared from certain

regions (Bergman and Van Santbrink, 2000). Some regions of deepwater coral reefs (*Lophelia* sp.) off western Norway have been cleared of life by heavy rock-hopper trawl gears.

Fish behaviour in relation to fishing

Fish entering between the trawl doors tend to be guided by the bridles towards the mouth of the trawl where they turn and try to swim in front of the rolling ground gear (Wardle, 1993). Small fish and species with poor swimming capacity like plaice are less easily herded than larger and faster fish. As fish get exhausted they turn back and enter the trawl bag, but in the elongation at the back in the bag, they turn forward and try to swim along with the moving mesh wall (the optometric response). Gear avoidance seems mainly to be elicited by visual stimuli, and the reactions decrease at night (Glass and Wardle, 1989). Fish finally panic when in the bag and swim towards the meshes in an attempt to escape through them. The selectivity of the trawl bag then becomes apparent, as small fish pass through the meshes while a greater proportion of the larger fish are physically unable to do so.

The capture process of longlining has been studied with the aim of increasing the efficiency of the gear, and developing artificial bait (Løkkeborg, 1994). The rate of release of attractants (amino acids) in the water decreases rapidly with time, but the bait can still be detected up to hundreds of metres by its odour trail that is dispersed by the water current (Løkkeborg and Fernø, 1998).

Fisheries acoustics: from observation to quantification

By taking advantage of the general progress in electronics and computer technology, reliable scientific echosounders and integration units became available about 20 years ago (MacLennan and Simmonds, 1992). The accuracy of a 38

kHz Simrad EK400 echosounder varied within about 7% only over a five-year period (Simmonds, 1990). More modern echosounder and integration units with a higher degree of computerization probably have an even better performance and accuracy. The echo-integration method has been proven experimentally to be linear (Foote, 1983), which means that the acoustically measured density and the real density are equal. Calibration of echo-integration units was a major challenge for many years, but collaboration by research teams participating in the Working Group on Fisheries Acoustic Science and Technology resulted in an accurate solution by the use of a metal sphere with known backscattering properties (Foote *et al.*, 1987). Output from the echo integrator could then be converted to fish density per unit area (ρ_A) by the equation (Dalen and Nakken, 1983):

$$\rho_A = (C_1/\sigma) \cdot M = s_A/\sigma \quad (1)$$

where

σ = fish backscattering strength found by the relation $\sigma = 1/10 \cdot 10^{1/10 \cdot TS}$ where TS = fish target strength
 C_1 = calibration constant of the equipment
 M = echo integration output (mm/nautical mile)
 s_A = area backscattering coefficient ($m^2/(\text{nautical mile})^2$).

Target strength

A fundamental parameter for converting echo-integration recordings to fish density is the target strength of fish. This parameter may vary by two orders of magnitude depending on the orientation, fish size, and swimbladder. Ona (1990) found that the swimbladder volume of herring followed a Boyle's law depth relationship, thereby indicating a certain reduction in backscattering cross-section of herring with increasing depth. In the early 1980s much attention was given to *in situ* target-strength measurements of fish at sea by the split-beam technique. Based on regression of results from several of these measurements, Foote (1987) recommended using $TS = 20 \log L - 67.5$ for the physoclist gadoids and $TS = 20 \log L - 71.9$ for the physostomous clupeoids when conducting acoustic surveys with 38 kHz echosounders.

Survey design

The whole distribution area of a fish stock must be surveyed for a reliable acoustic abundance estimate to be obtained. The design and conduct of acoustic surveys were reviewed and discussed by the Working Group on Fisheries Acoustic Science and Technology and published as an *ICES Cooperative Research Report* (Simmonds *et al.*, 1992). Usually fish stocks are surveyed for exploratory purposes by zigzag transects or systematically by equidistant, parallel transects. A precise estimate of the biomass in an area will be obtained by a stratified random survey or a systematic survey (Simmonds and Fryer, 1996).

Preferably, fish stocks must be surveyed during a limited period to obtain abundance estimates that are as synoptic as possible. In practice this can be difficult to achieve when surveying such widely distributed fish stocks as the North

Sea herring, which may take 3–4 weeks to map even by coordinated surveys with several participants (Bailey and Simmonds, 1990). Acoustic abundance estimates may be significantly biased if the fish are migrating during surveys (MacLennan and Simmonds, 1992).

Post-processing

A significant improvement of the echo-integration method is seen in the computer-based, post-processors (Knudsen, 1990; Weill *et al.*, 1993). With these instruments it is possible to replay the acoustic recordings, do thresholding to separate scatterers, allocate area backscattering strengths to species, identify schools, and correct the recordings for noise and bottom spikes (Figure 2).

Fish behaviour in relation to acoustic surveys

Fish behaviour in the wild has been studied for more than 30 years by the use of small acoustic tags attached to the body of individual fish (Urquhart and Stewart, 1993). Such studies have shown that cod can carry out rather rapid vertical migrations beyond the range of their neutral buoyancy, which is controlled by the secretion/resorption of gas in the swimbladder (Arnold *et al.*, 1994). It is likely that such migrations affect the back-scattering cross-section of the fish through changes in both tilt angle and swimbladder volume (Arnold *et al.*, 1994).

Based on herring purse-seining experience, concern was raised during the 1970s that the noise from conventional fisheries-research vessels drove the fish away from a ship's track to such an extent that fish density recorded from the vessel would be underestimated. Olsen *et al.* (1983) showed that species like cod, herring, and polar cod did indeed avoid an approaching survey vessel and that the density of these species became substantially reduced from the usual state of affairs in the sea when passed over by the vessel. Many studies in both northern and tropical waters confirmed this result (Fréon and Misund, 1999). Now a new generation of diesel-electric powered fisheries-research vessels fulfilling the ICES recommendation (Mitsun, 1995) for maximum noise emissions have been built, and studies suggest that fish do not avoid these relatively quiet ships (Fernandes *et al.*, 2000).

Perspective

On the national level, there has been a tendency for fishing-gear and sonar sections within marine research institutes to have been substantially downsized or even dissolved over the last twenty years. This may have been attributable to the realization that fishing technology has become very effective and that further development could be carried out within the private sector. On the other hand there are many unsolved fishery-resource and environmental issues linked with today's fishing operations. Further research is needed, for example, on the selectivity (of fish size and species) of fishing gears, the unwanted by-catch of other species (birds, marine mammals, other fish species), ghost

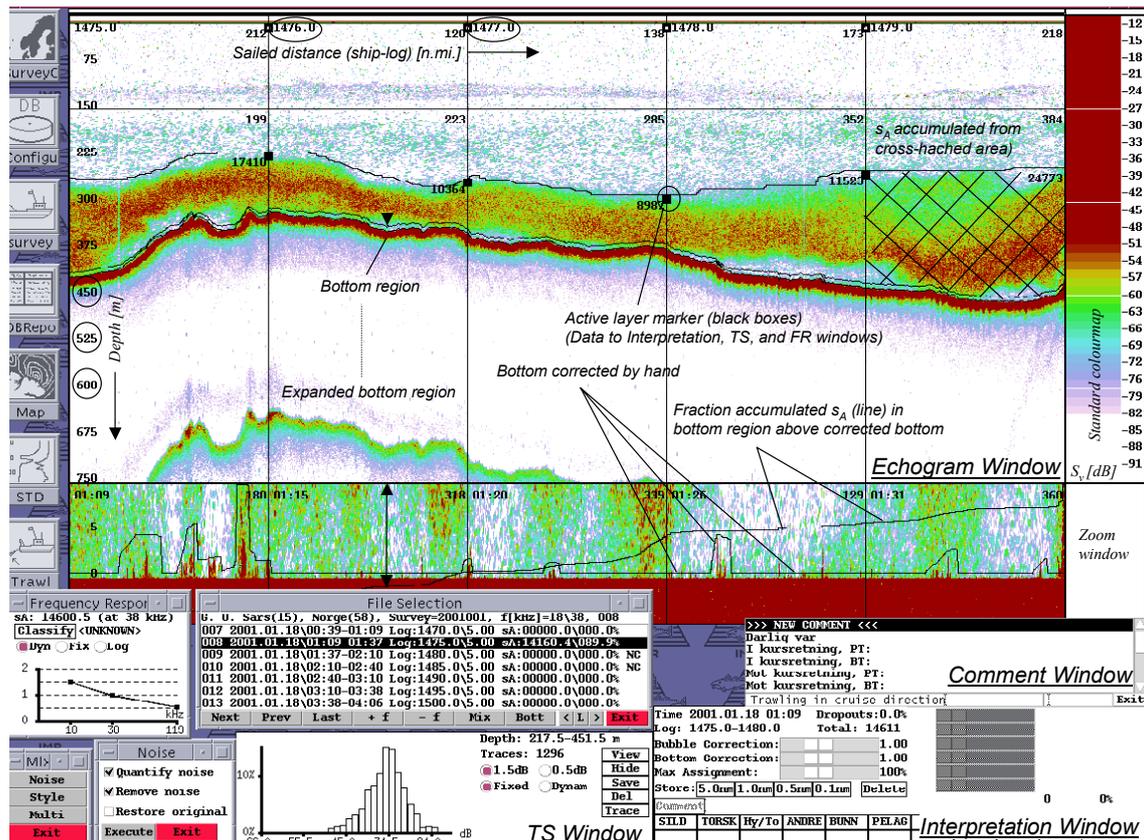


Figure 2. The graphical user interface under the scrutinizing process by using the BEI system (after Korneliussen, 2002, see also Foote *et al.*, 1991).

fishing of lost gears, and on the effects of fishing activities on the bottom fauna. The important studies in these areas should be given continued priority within ICES and national marine research institutes.

Similarly, further development of both fisheries acoustics and scientific trawling should be supported, because of the increasing need for the fishery-independent survey estimates of fish abundance, which can be achieved by combining these techniques. As the reliability of fishery statistics has probably declined substantially during the last decade owing to misreporting and the unsatisfactory control of the quantity of fish caught, absolute abundance estimates by fishery-independent surveys could be vital to the credibility of fish stock assessments in the future.

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Modelling in fisheries assessments

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The advisory role of ICES in fisheries management led to the development of dedicated population models. By the late 1970s, Virtual Population Analysis (VPA) had already been formulated and was used by ICES to provide quantitative assessments of fish stock abundance and fishing mortality. National systems for collecting the necessary catch-at-age data were already established. The 1980s were characterized by the development of procedures for the best application of VPA ideas and the interpretation of its results. The 1990s, on the other hand, saw the opening of a new age. First, the rate of development of the production of operational results decreased. Second, scientific focus shifted from the management of resources to that of ecosystems, as politicians decided that fisheries and environment issues should be integrated. The report of the Delegates Meeting at the ICES Statutory Meeting in 1996 makes this point clear.

During the 1990s though, there was no framework of operational models for responding to the new and more comprehensive demands. The structure of ICES was progressively changed during that period to meet the new challenges. The fish stock assessment Working Groups of the Advisory Committee on Fishery Management (ACFM) were reorganized by regions rather than by stocks as in the past, following a Council Resolution passed at the Statutory Meeting in 1991. The former Science Committees were reorganized into seven new Science Committees on a thematic basis rather than on a species basis via a Council Resolution at the Statutory Meeting in 1997. Then the advisory committees were reorganized and, in particular, a new Advisory Committee on Ecosystems (ACE) was established through a Resolution passed at the Statutory Meeting in 2000. An ACFM Working Group on Comprehensive Fishery Evaluation was established for the period 1995–1999. These progressive changes were intended to bring about a more substantial overview of the uses of the sea and their interactions, without neglecting the provision of the traditional advice on single fish stocks.

Virtual Population Analysis (VPA) of single species

Assessment of the stock

VPA is the standard method used by ICES at present to assess stock size and fishing mortality. The technique is best applied to populations which are structured by one reproductive phase per year and many year classes for which fishing is a major cause of mortality (e.g., the demersal stocks of temperate latitudes). VPA is a cohort analysis that considers the catches of the same year class in successive years. The data required are catch-at-age data from commercial catches (landings are used). The analysis uses two

equations, the survival equation, which states the exponential decay of cohort numbers (N), and the catch equation, which relates catches (C) to cohort numbers. In both equations mortality rates due to fishing (F) and natural mortality (M) intervene. The population can be represented in a matrix form where line i represents age i for all years and column j represents year j for all age groups. VPA will estimate the values for N and F in each matrix cell. First, M is an input in the model and is in general assumed constant over years and ages because of lack of information. Second, values of F for the last line and last column of the matrix must also be input to initialize the computation. Having made these choices, numbers-at-age in each year and fishing mortality are back-calculated for earlier years.

The first papers in this field were presented to ICES by Jones (1964) and Gulland (1965). Pope (1972) showed convergence in the estimates for young age groups (i.e., top left corner of the matrix): the values assumed for terminal F has progressively smaller effects on the estimates for younger age groups as the cumulative of F for the age group gets larger. From this starting point a lot of work went into choosing terminal F and in particular “tuning” the VPA (also termed “calibrating” or “fitting”). Pope and Shepherd (1982) proposed that the exploitation diagram (i.e., the distribution of F over the age groups) could be interpreted using a multiplicative model with a year and an age effect. This was the “separability” assumption, which provided a procedure to estimate terminal F . The idea developed rapidly using other information than catch-at-age data. Converged VPA estimates for the years and age groups of the left corner of the matrix could be compared with other estimates obtained using other information. The possibility of minimizing the difference between converged VPA estimates and other estimates opened the way for various tuning methods.

Both commercial effort and scientific survey data were used to estimate catch per unit effort which provided the tuning data (i.e., estimates of abundance-at-age). The advantage of survey data was that both effort and spatial coverage were more controlled than the data from the commercial fleets. The major disadvantage of scientific surveys was their limited sampling effort, which generated high variability in the estimates.

Various tuning methods were proposed (e.g., Laurec and Shepherd, 1983) and compared by the ICES *ad hoc* Working Group on the Use of Effort Data in Assessments (ICES, 1981). Catchability coefficients were introduced to relate the estimated cohort numbers to the tuning data. Changes in the catchability over time were a major concern. Pope and Shepherd (1985) proposed a method which allowed the es-

timization of a linear trend in catchability. In 1988, the ICES Workshop on Methods of Fish Stock Assessment compared, with a standardized procedure, the many methods developed on both sides of the Atlantic (ICES, 1988). The European fisheries community developed *ad hoc* methods while the North American community developed an integrated statistical approach. In *ad hoc* methods, terminal F was first fitted then the assessment VPA was run. In integrated methods the model parameter values were estimated by a minimization procedure to best-fit observed data values. Integrated methods were of particular interest for short-lived species for which VPA cannot converge. At the meeting of the Working Group on Methods of Fish Stock Assessment in 1991 (ICES, 1995a), a new *ad hoc* method was presented by Shepherd, the Extended Survivors Analysis (XSA), which was later published (Shepherd, 1999). The XSA method performed better than the previous tuning methods because, in particular, tuning estimates of cohort abundance for all ages were treated coherently. Consequently in 1999 the ICES Assessment Working Groups of ACFM used the *ad hoc* XSA method for tuning VPA on demersal stocks while the Integrated Catch Analysis method (Patterson and Melville, 1996) was used for pelagic stocks. More than a hundred stocks were individually assessed in 1999.

Once tuned, the VPA gave estimates for recent years when convergence was not guaranteed, and their precision was investigated using retrospective analysis. After a while, catch data being available for a longer period, the estimates for the recent years could be compared with the converged VPA estimates. Brander (1987) estimated the average prediction error to be 14% in the current year. In 1991, the Working Group on Methods of Fish Stock Assessment conducted retrospective analyses on many stocks with different tuning methods (ICES, 1995a). These showed that patterns in the retrospective analysis were real and that these were stock-specific (e.g., positive or negative bias) but not method-dependent. The major causes were attributed to variation in the catchability in the tuning indices. Remedies were envisaged, and in particular a statistical estimation procedure robust to bias called “shrinkage”. At its meeting in 1993, the Working Group on Methods of Fish Stock Assessment looked at estimates of terminal F (ICES, 1999a) produced by this technique and found it to be an improvement on past methods. It is now used in the Assessment Working Groups of ACFM.

The analysis of “catchability” has received less attention. Mohn (1999) showed that trends in the catchability generated patterns in the retrospective analysis. Factors affecting catchability were density-dependence of the fish spatial distribution, fish behaviour, and changes in fishing gear and strategy. Various solutions were investigated. Somerton *et al.* (1999) considered using experimental knowledge on gear performance. Trends in survey abundance were analysed independently of VPA estimates (Cook, 1997). Monitoring and better understanding of the effort developed by the commercial fleets was also advocated. Retrospective analysis is currently applied in the Assessment Working Groups of ACFM and allows testing for apparent incoherence in the data.

Status of the stock and reference points

In the 1950s and 1960s optimal harvest strategies together with technical measures for mesh sizes were formulated (i.e., F_{\max}) using the age-structured population model of Beverton and Holt. However, as overfishing spread from growth overfishing to recruitment overfishing and to population extinction (e.g., the North Sea herring fishery was closed during the period 1977–1982), the overall objective changed progressively in the 1970s and 1980s to one of advising on sustainable catches. The European Common Fisheries Policy established a system for regulating catches based on annual total allowable catches (TAC) per stock to be partitioned between member countries, but on the socio-economic side, the fishing capacity of fleets increased. The role of scientific advice was merely to limit fishing mortality by providing:

- (i) a reliable assessment of fish stocks for the current year,
- (ii) a reliable statement of where the stock was relative to biological limits of reference which if trespassed would jeopardize the sustainability of the fishery, and
- (iii) a projection for one year ahead with advice on the TAC.

The shift in the goal of scientific advice from optimality to sustainability was evident when the terminology of the precautionary approach came into play in the 1990s. Shepherd (1982) constructed replacement lines which opened the way to defining biological reference points. He pointed out that VPA estimates of F and yield outputs of the age-structured population model (e.g., the yield per recruit or biomass as a function of F) could be coupled so as to give a more comprehensive understanding of the stock dynamics. The inverse of the slope at the origin of the stock-recruitment relationship had the dimension of a biomass per recruit. Thus the slope increased as F increased. Therefore, limits on F known as F_{high} , F_{med} , and F_{low} were defined in relation to levels of fish biomass necessary for the stock to reproduce. This was an improvement in comparison to the value of $F_{0.1}$ set empirically ($F_{0.1}$ was defined as F for which the increase in the yield per recruit was 10 per cent of its value at $F=0$). Ulltang (1996) proposed considering not only biomass and F but also variation in all life history parameters to improve stock assessment.

A Study Group on the Precautionary Approach for Fisheries Management was established in 1996, and met in 1997 and 1998. A list of biological reference points was stated in terms of fishing mortality (e.g., those above) and biomass (e.g., minimum sustainable biomass) (ICES, 1997a). The Assessment Working Groups estimated values for them for each stock. The trajectory of the stock over the years could thus be represented on appropriate graphs showing domains of sustainable fishing. Concern was also expressed concerning whether the reference points should be reviewed at times when, for example, changes in the life history parameters and the ecosystem due to climate regime shifts or changes in fishery technical interactions or predator-prey relationships respectively had been identified (ICES, 1999a).

Catch forecasting and simulation of scenarios

Catch forecasts are currently provided by ACFM using the VPA in a forward mode. The short-term forecast is a prediction for next years' annual TAC. This is done by assuming a specified recruitment level (e.g., from VPA estimates of past recruitment) and a specified fishing mortality (e.g., *F status quo* or *F advised*) then summing weight-at-age over the year classes. For medium-term forecasts the dynamics in the variations of recruitment and fishing mortality must be formulated. Given the lack of reliable models for these dynamics, medium-term projections are provided by simulating scenarios designed to answer "What if?" types of questions (Payne, 1999).

Forecasting recruitment was a major concern, which stayed unresolved. The ability of fish populations to support high fishing mortality suggested a strong regulatory mechanism. However, the stock-recruitment plots were very noisy and rarely gave evidence for or against. The factors affecting recruitment variation were spawning-stock abundance, environment, and predation. The possibility of predicting recruitment using a relationship with the environment was analysed by working groups in 1983 (ICES, 1984) and again in 1999 (ICES, 2000a). Although retrospective relationships between the environment and recruitment were found statistically, and progress was made in understanding the processes affecting recruitment (Fogarty, 2000), confidence in the predictive power of recruitment–environment models remained low. Stock-recruitment models or some estimate of average past recruitment were preferred for forecasting purposes.

Because there is uncertainty at various levels in the VPA (i.e., the catch-at-age data in the model assumptions and in the estimates for recent years), it was thought that management options should be given in terms of probabilities. In 1993 the Working Group on Methods of Fish Stock Assessment considered the issue of risk analysis (ICES, 1999a) for short-term and medium-term projections. Various methods for simulating errors were compared, in particular bootstrap and Monte Carlo. Results were given as the probability that the stock would fall under a specified reference point for a specified management rule.

Management objectives could be very diverse because they could be formulated to meet many criteria such as the sustainability of single stocks, ecosystem integrity, and multiple-fleet viability, respectively. Hence recommendations became complex in comparison with the optimal harvest objectives of the 1960s. During the 1990s research was undertaken in a diversity of directions, as reflected in the establishment of new working groups, e.g., the Working Group on Long-Term Management Measures, which met during the period 1993–1995, and the Comprehensive Fishery Evaluation Working Group which met during the period 1995–1999 (ICES, 1995, 1999). Models of complex dynamic fishery systems were developed for particular fishery situations and ecosystems, such as *Simp* in the Southern North Sea, *Bormicon* in Iceland, and *Flexibest* in the Barents Sea (ICES, 1995, 1999). They took into account mul-

ties and multifleet interactions as well as spatial dynamics and economic considerations. These models provided tools for simulating scenarios and assessing the potential response of stocks to alternative management measures (e.g., closed areas, pluri-annual strategies, multispecies harvest rules). The question remains unanswered as to whether these complex tools are more reliable than simple assessment tools. Clarification of management objectives is clearly a driving element in making these models complex or simple.

Multispecies Virtual Population Analysis (MSVPA)

An important question that had not been tackled since the 1950s concerned multispecies effects on the life history parameters of individual stocks, stemming from the fact that fish populations do not exist independently of each other in the sea. During the second half of the 1970s, field work directed by N. Daan in the Netherlands on the diet of cod, and the development of an ecosystem model for the North Sea by Anderson and Ursin, constituted the first new steps in this field. At the ICES Statutory Meeting in 1979, two papers were presented (Pope, 1979; Helgason and Gislason, 1979) that proposed Multispecies Virtual Population Analysis; a major international research effort on this topic then began in the North Sea under the umbrella of ICES and lasted for more than a decade.

The ICES Multispecies Assessment Working Group was established at the annual meeting in 1983 and worked from 1984 to 1997, producing both methodological developments and new insights into the predation dynamics between demersal fish stocks in the North Sea. Major sampling programmes were organized to collect the necessary stomach content data. Four international surveys per year covering the entire North Sea were coordinated in 1981 and again in 1991, which made these years known as the "Years of the Stomach" (ICES, 1987, 1997b). Additional surveys were conducted during the period 1985–1987. An ICES Symposium on "Multispecies Models Relevant to Management of Living Resources" was organized in 1989 and reviewed a decade of work (Daan and Sissenwine, 1991). Indeed the development of MSVPA and the associated collection of field data form an impressive example of international scientific cooperation over the whole of the North Sea, inspired and coordinated by ICES for more than a decade.

In single-species VPA (SSVPA) the natural mortality (*M*) of fish was assumed to be constant over years and ages, simply on account of lack of information. It was an input in the model, and the reliability of the value used was questionable. The interaction between species modelled in MSVPA being that of predation, the application of MSVPA gave new insights into *M*. *M* was considered to be made up of two additive components, *M*₂ and *M*₁: *M*₂ was the predation mortality while *M*₁ was the mortality due to other sources. *M*₁ played the same role in MSVPA as did *M* in SSVPA. A predation mortality equation relating the species was added to the two SSVPA equations, and the system was solved for estimating *N*, *F*, and *M*₂ (Sparre 1991). The equation derived for *M*₂ was formulated using the concepts

of “suitable prey biomass” and the annual food ration. This required the estimation of “suitability” coefficients for different prey species relative to the predators. As a result, sampling surveys to collect the model-driven data were organized. Respecting SSVPA, MSVPA was solved backwards in time by encapsulating the SSVPA in two loops, one for solving the predation equation until the convergence of M2 in each year, the other until there was a convergence of the suitabilities. The equations in MSVPA were solved year-by-year and not cohort-by-cohort as in SSVPA because in each year, numbers-at-age for all species were required to estimate M2. MSVPA required tuning and a methodology was proposed (ICES, 1992).

The functional form of the predation equation for M2 is of central importance. For the North Sea it was developed as an *ad hoc* empirical equation and therefore its validity for other seas was questionable. In the predation equation three assumptions were made, viz. the “other food”, “the ration”, and the suitability of prey, and these were debated. Because it was only feasible to acquire the relevant data for a limited number of species (i.e., nine) the category “other food” had to be considered in the model. This term was an input in the model as was M1. Various assumptions were proposed for considering how much of the diet “other food” represented. At its meeting in 1985, the Multispecies Assessment Working Group (ICES, 1986) finally adopted the assumption of Helgason and Gislason (1979), which stated that the biomass of “other food” in the sea was constant over the years. The annual food ration was assumed constant over the years and independent of prey biomass and so were the “suitabilities” of prey. Such assumptions led to a particular functional relationship between predator and prey abundance (Sparre, 1991) which contained no switching to other preys at low abundance of a particular prey.

By the late 1980s the abundance of the fish stocks were seen to have changed since the beginning of the decade, and this was a major argument for repeating the stomach sampling programme in 1991. The stomach data collected at sea over the different years were analysed to test for constancy in suitability, and the conclusion was drawn that constancy of the suitabilities was appropriate for the North Sea (Rice *et al.*, 1991; ICES, 1997). Suitability measures what the predator likes to eat (i.e., preference), and what it is able to eat (i.e., vulnerability, accessibility, spatial overlap). The relation between prey suitability for an individual predator and suitability averaged over space and year for the population of predators was analysed. This showed that constancy at population level could be found when suitability varied at the level of the individual (ICES, 1997). The functional form of the predation equation was regarded as *ad hoc*, i.e., not based on a theory of foraging and not easily applicable to other areas. In particular, the Boreal and Baltic ecosystems with fewer species in the foodweb were thought to behave differently from the North Sea ecosystem: important variations in suitability and ration were found between years owing to recruitment variability of prey and, as these variations in suitability and ration could not be compensated by “other food” because of the simplicity of the foodweb, growth was affected (e.g., Magnússon and Pálsson, 1991; Sparholt, 1991). Also, Gislason (1991) showed that the

MSVPA long-term predictions were sensitive to the level of recruitment in the predators.

These findings justified considering more processes than only the predation equation. Populations can be considered as being regulated by competition, predation, and environmental variability. Each factor may influence different life history stages. Therefore complex models are required that incorporate relevant interactions at specific stages. Comprehensive process-orientated models were developed to incorporate more biological processes than the only predation mortality (ICES, 1999b). The Bormicon (BOreal MIgration and CONsumption) model was the first comprehensive one developed in ICES waters to take account of multispecies interactions, their effects on growth and recruitment, the age-structure of the fish, their spatial distributions, and, finally, multiple fleets.

The MSVPA application to the North Sea carried out by the ICES Multispecies Assessment Working Group verified the hypothesis that predation (including cannibalism) structured the dynamics of the fish community. It also gave the major following results (Pope, 1991):

Predation varied with age and year and was more important on the young fish. This resulted in higher estimates of natural mortality rates, M , than previously assumed. Predated fish and fishing catches expressed in biomass units were of similar values.

Increasing the mesh size would have a detrimental effect on the yield per recruit in the long term. This was so because an increase in large predator fish increased predation on younger fish. SSVPA suggested that increasing mesh size increased the yield per recruit, but via MSVPA a different forecast was made because it considered predation interaction between species.

However, SSVPA and MSVPA gave similar short-term forecasts and so MSVPA was not retained by ICES as an assessment tool. The potential importance of multispecies interactions was recognized in the analysis of natural mortality, recruitment, and reference points in particular (Gislason, 1999).

The increasing use of scientific surveys

The importance of scientific sea-going surveys to monitor stocks and ecosystems has increased considerably since 1979. In the 1980s surveys were undertaken with the primary objective of providing abundance estimates of recruits to the fishery in order to provide a TAC as well as to tune the VPA, but they also provided a wide range of information for biological and ecological studies (e.g., spatial distribution, hydrology, age-length keys, maturity, fish diet, occurrence of fish diseases, biodiversity, community structure etc.).

Large-scale international surveys were organized on a routine basis under the auspices of ICES for monitoring programmes for demersal and pelagic fish stocks and also for ichthyoplankton abundance. ICES played the central roles

of coordination, standardization, and data storage. The international bottom-trawl surveys provide a good example of this work. Bottom-trawl surveys in the North Sea had been undertaken since the 1960s but not systematically and on national interests only. In 1974, national surveys started to be coordinated by ICES under the name IYFS (International Young Fish Surveys) to cover the North Sea, Skagerrak, and Kattegat during the first quarter of the year. These surveys provided estimates of recruit abundance for target species. In 1981 and 1991 the temporal coverage of these surveys was extended for the stomach-content sampling programme and four surveys a year took place. During the period 1985–1987, quarterly surveys were also undertaken to study predation interactions. The results of the stomach-content sampling programme changed the purpose of the IYFS from that of the estimation of recruitment indices for target species to the monitoring of target- and non-target fish populations and ecosystems. From 1991 the IYFS was continued under the name the International Bottom Trawl Survey (IBTS) and a Working Group on IBTS was established. During the period 1991–1995, the IBTS was carried out on a quarterly basis, covering the North Sea, Skagerrak, and Kattegat. The IYFS/IBTS database was stored and maintained at the ICES Secretariat from the beginning.

At the ICES Statutory Meeting in 1994 it was decided to coordinate all the surveys being made of the western seaboard of Europe, from Cadiz to Orkney, and since 1997 the IBTS Working Group has been the lead agency in this exercise. Standardized sampling procedures were agreed and applied and in 1996 the IBTS Manual was published (ICES, 1996). Similar coordination occurred for pelagic egg and larval surveys. In 1999 large-scale surveys, coordinated by ICES through its appropriate working groups, were undertaken using standardized procedures, for both demersal and pelagic fish.

At the 1997 ASC the first Scientific Theme Session on the use of surveys was held. Since then a Theme Session has been dedicated each year to the use of surveys. This series of monitoring surveys is now long enough to allow independently of commercial catch statistics the study of trends in the fish stock abundance (Cook, 1997) as well as in the structure of fish assemblages (Rice and Gislason, 1996; Zwanenburg, 2000). The organization of these surveys has brought about a major change in our understanding of fish stocks by providing the spatial and seasonal dimensions of their distributions. A tangible result of all this effort is the production of an “Atlas of North Sea Fishes” from the compilation of data from these surveys (ICES, 1993a).

The spatial analysis of surveys required the use of spatial statistical techniques. ICES played a central role in the development of their application in fisheries by organizing three workshops in 1989, 1990, and 1991, as described in an *ICES Cooperative Research Report* (ICES, 1993b). In these workshops the formal differences between methods and their performance were analysed and compared using test data sets. The problem of estimating survey precision for a systematic survey design and in particular for acoustic surveys was analysed in detail because of the importance of reducing the variance of fish stock survey estimates. For survey designs in which samples are not taken independ-

ently of each other, as in random sampling, classical statistics do not apply. Because covariance structure in geostatistics is explicitly used, the method allows the derivation of the appropriate estimation variance for many types of survey designs. A geostatistical application was demonstrated by Petitgas (1993) for acoustic survey designs made with regularly spaced line transects. Simmonds and Fryer (1996) tested different survey designs using simulations and found that the systematic design performed best, and Petitgas and Lafont (1997) provided software allowing a geostatistical estimation of survey precision. This meant that a solution had been found to the problem of how to compute the precision of fish stock survey abundance estimates for non-random designs.

Ecosystem models and ecosystem objectives in fisheries management

By its direct effects (e.g., change in abundance) and its indirect effects (e.g., energy flow through the ecosystem), fishing potentially modifies the structure and functioning of marine ecosystems. Under the United Nations Code of Conduct for Responsible Fisheries (FAO, 1995), countries agreed to consider the impact of their fishing policy on ecosystems. Sustainability of target species was no longer sufficient; sustainability of ecosystems needed to be considered as well. An ICES/SCOR Symposium was held in 1999 on the “Ecosystem Effects of Fishing” (Hollingworth, 2000; Gislason *et al.*, 2000) in which a theme session was dedicated entirely to the methods available for quantifying ecosystem impacts. While changes in abundance were addressed by single-species models, changes in the energy flow through the ecosystem required the use of trophodynamic models, multispecies models, and indices of community structure. Results from these models of ecosystem structure and productivity were expected to be the basis for incorporating ecosystem objectives in fisheries management.

At its meeting in 1999, the Working Group on Ecosystem Effects of Fisheries (ICES, 2000) reviewed the many models developed in the greater scientific community, envisaged the way in which human impact could be introduced, and emphasized that the reliability of these models should be analysed within appropriate working groups. Metrics and reference points associated with particular ecosystem models are expected to be defined in the future and monitored by, for instance, scientific surveys. A variety of models are available for ecosystem objectives in fisheries management depending on what aspect of the ecosystem is being considered (e.g., the Basin model for habitat suitability, the Size Spectrum Theory for community structure, MSVPA and comprehensive models such as Bormicon for interactions between species and fleets, and Ecopath for energy flow through the foodweb) and depending on the scale at which the model is formulated (e.g., aggregation of species, space and time).

Assuming that the structure of a community of species resulted from trophic interactions, Platt and Denman (1978) proposed a community-level model based on trophodynamic transfer efficiencies. Animals of a given size fed

on animals of smaller size and this resulted in growth. At steady state, the biomass and numbers of individuals pooled across all species decreased log-linearly with size. Fishing mortality was added as additional mortality in the equation of the mass transfer between size classes (Gislason and Lassen, 1997). Because MSVPA formulated trophic interactions, a size-spectrum analysis of MSVPA population estimates would reveal the resulting community-level pattern and provide another test for the assumption that predation effectively structured the fish community in the North Sea. Rice and Gislason (1996) computed the spectrum for MSVPA estimates and survey abundances independently and demonstrated that the assumption was appropriate for the demersal fish community of the North Sea. The size-spectrum metrics were considered to be particularly informative by the Working Group on Ecosystem Effects of Fishing Activities (ICES, 1994) as the slope could indicate changes in the community structure under fishing pressure. Rice and Gislason (1996) demonstrated for the North Sea that the slope in the biomass size spectrum was related to fishing pressure, whereas the slope in the diversity spectrum remained unaffected. These findings were generalized to other exploited ecosystems (Zwanenburg, 2000; Bianchi *et al.*, 2000).

The European Regional Seas Ecosystem Model (ERSEM) was developed outside the ICES umbrella as a modular, dynamic-system model of the carbon pathway through the North Sea ecosystem from nutrients to fish and higher predators (Baretta *et al.*, 1995). ERSEM used the 10 ICES Areas to achieve a sufficient spatial resolution. The boxes were divided in two vertical layers to account for the development of a seasonal thermocline. A hydrodynamic circulation model was used to estimate horizontal and vertical exchange rates of dissolved and suspended constituents between the boxes. The model was modular in its construction, with each module dealing with a collection of functional groups. The modules were linked to allow the exchange of carbon and nutrients between the boxes. Size and age structures were represented in the fish groups (Bryant *et al.*, 1995), while the other biological components (e.g., zooplankton, benthos) were represented as unstructured populations. If applied within ICES in the context of fisheries, this model could show the deleterious effects on the structure and productivity of the marine ecosystem attributable to human activities, such as the unbalanced nutrient ratios in river discharges, heavy fishing mortality on the fish community, and the effects of fishing gears on the benthos.

Concluding remarks

The present overview cites ICES literature almost exclusively. Within its Working Groups, Theme Sessions at annual meetings (now Annual Science Conferences), and Symposia, the scientists working within ICES have been able to synthesize and incorporate results and developments from outside that community (e.g., integrated methods for calibrating VPA, ecosystem models) to provide the best means of promoting its advisory role in fisheries policy.

ICES was founded in 1902 as a scientific organization with the broad goal of understanding the physical and biological interactions in the sea as a means of ensuring the continu-

ance of the commercial fisheries. Over the decades it became more and more concerned with providing independent scientific advice for fisheries management. This advisory role orientated the development of models within ICES, as the complexity of a model is necessarily related to the question being posed for it to answer. Models were developed that required basic biological data and basic underpinning science to encapsulate biological processes at appropriate space and time scales in a way that enabled the formulation of simple and robust *ad hoc* models for fisheries management. A recurrent activity of the Working Groups was to identify those procedures that were most reliable and that could be used to provide the advice. The other need for medium- and long-term projections of the effects of human activity on the ocean was a driving force for developing process-oriented models capable of reproducing the dynamics of the system.

With the increasing capacities of computers, the most recent trend has been to develop process-oriented complex models across the whole spectrum of activity, whether this is in fisheries oceanography (e.g., integrated models of hydrodynamics and larval survival in predator-prey fields), fisheries management (e.g., comprehensive fishery system models including multispecies and fleet dynamics), ecosystem modelling (e.g., ERSEM), or mariculture (e.g., integrated models of hydrodynamics, production, and growth bioenergetics of molluscs, respectively). These models require both a thorough understanding of the science involved and complementary large-scale data-collection programmes. They provide a way to synthesize coherently the knowledge dispersed in different disciplines. Even though fisheries science collaborates closely with pure academic research in these fields the limitations of our knowledge will continue to hold back the formulation of practical models. ICES is expected to continue to play an important role in this formulation process.

Because the advisory role of ICES has been extended to ecosystems, because fisheries management objectives include ecosystem objectives, and because recruitment dynamics is of central importance, the development of fisheries oceanography, fisheries management, and ecosystem models as modules of one another is the obvious road to be followed. The Advisory Committee on Ecosystems (ACE) was established in 2000, and it is expected that the reliability of coupled, complex-dynamic models will be scrutinized by relevant ICES Working Groups in the future in order to establish the procedures needed to produce the wide-ranging and robust scientific advice required by society these days.

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Environment and contaminants

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Scientific studies of the marine environment have played a major role in ICES since its foundation in 1902. Whereas early activities largely focused on the effects of the physical environment on exploited fish stocks, it was increasingly realized that there was also a need for studies on other environmental aspects, particularly those related to the effects of human activities on the marine environment and its living resources other than overfishing.

One of the first major environmental concerns in ICES was created by the finding of elevated concentrations of anthropogenic contaminants in seawater and marine organisms in the ICES Area. As a consequence, systematic ICES research, monitoring, and intercalibration programmes with respect to the measurement of contaminants in biota, water, and sediments were launched and coordinated by ICES Working Groups. The next step was to initiate scientific ICES activities aimed at the measurement of the biological effects of those contaminants identified in the sea.

The issue of marine pollution was given high priority and the Council decided in 1971 to establish an Advisory Committee to provide scientific information and advice on marine pollution and its effect on living resources. This Committee, the ICES Advisory Committee on Marine Pollution (ACMP) began its work in 1972 and was a major driving force for 20 years with respect to the development of ICES science on marine pollution.

While the first years of ACMP's activities were dominated by providing advice on contaminants and their biological effects, it was soon apparent that other issues related to effects of anthropogenic activities had to be dealt with by ICES because of their impact on the marine environment and its living resources. In order to meet these requirements the remit of ACMP had to be broadened to cover such topics as the environmental effects of mariculture, the effects of eutrophication and harmful algal blooms, the effects of marine sand and gravel extractions, benthos and marine mammal issues, and the ecosystem effects of fishing.

Taking into account the increasing need to provide more ecosystem-based, multidisciplinary advice on environmental issues, the Council decided in 1992 to replace the ACMP with a new committee, the ICES Advisory Committee on the Marine Environment (ACME), which would be responsible for providing advice on all aspects of the marine environment, from chemical and physical oceanography to ecology and fishery–environment interactions. The annual reports of these Committees published in the *ICES Cooperative Research Report* series are an excellent record of the progress made in ICES environmental science in the period 1979–1999.

This review aims to highlight some facets of ICES environmental science partly using the deliberations of ACMP and ACME for guidance. Only information appearing in one or other of the ICES publications has been considered in comparing and assessing the scientific output on selected environmental issues. It is not the intention to provide a thorough and completely balanced overview of ICES environmental science over the last twenty years but rather the views of one observer of the programmes of work carried out under its auspices.

Some aspects of ICES environmental science

The areas of work that will be considered are those of contaminants and their biological effects, the environmental effects of mariculture, eutrophication, and harmful algal blooms, and the introductions and transfers of marine organisms. The information used was extracted from the ICES publication series only, viz. *ICES Cooperative Research Report(s)* (ICES CRR), *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer / ICES Marine Science Symposia* (ICES MSS), *Journal du Conseil / ICES Journal of Marine Science* (ICES JMS), *ICES Techniques in Marine Environmental Sciences* (ICES TIMES), and *ICES Identification Leaflets for Diseases and Parasites of Fish and Shellfish* (ICES ILD). Many of the results derived from environmental studies initiated and/or coordinated by ICES have been published elsewhere. However, it is not within the remit of the present contribution to include this information.

Even more condensed summaries of the main environmental issues dealt with in ICES are to be found in the 1991 ACMP Report (ICES, 1991a) and the 1999 ACME Report (ICES, 2000), which contain overview lists of ICES advice provided by topic for the years 1980–1991 and 1988–1999 respectively.

Chemical analysis of contaminants

Systematic work in ICES on marine contaminants started already in 1967/1968, when the ICES Working Group on Pollution in the North Sea and the ICES Working Group on Pollution of the Baltic Sea were established for the purpose of assembling data on harmful substances being discharged to both seas (ICES, 1969, 1970). A major subsequent development was the establishment of the ICES Coordinated Monitoring Programme (CMP) in 1974, in which scientists in each of the ICES Member States analysed a range of metals, PCBs and organochlorine pesticide residues in marine fish and shellfish species. Annual reports of the results were published in the *ICES CRR* series (e.g., ICES, 1980c, 1984a).

During the period 1979–1999, a number of ICES-coordinated studies on contaminant levels in seawater, sediments, and living resources of the North Atlantic (e.g., ICES, 1980b, 1988b, 1991b; Rowlatt and Davies, 1995) were carried out. These were accompanied by a variety of ICES intercalibration/intercomparison exercises, e.g., on the analysis of trace metals in seawater, metals and organochlorine compounds in fish and shellfish, petroleum hydrocarbon in marine media, trace metals in suspended particulate matter, and polycyclic aromatic hydrocarbons (PAHs) in marine media. An overview of the intercalibration/intercomparison exercises on chemical analyses coordinated by ICES during the period 1972–1993 is provided in the 1994 ACME Report (ICES, 1994a).

ICES has also been providing regular advice on the guidelines and techniques for contaminant monitoring, largely at the request of OSPARCOM and HELCOM. These have either been published in the annual ACMP/ACME reports or in the *ICES TIMES* series (e.g., Harms, 1987; Ehrhardt *et al.*, 1991; Smedes and de Boer, 1998).

Special reports on marine contaminants published in the *ICES CRR* series 1979–1999 are focused on:

Measurements of trace metals in sea water (Topping *et al.*, 1980);

The design of scientific studies in relation to oil spills, considering physical and chemical characteristics and short-term and long-term biological effects (ICES, 1981b);

Water quality and transport of materials in coastal and estuarine waters (Pearce, 1983); Contaminant fluxes through the coastal zone (Bewers *et al.*, 1985);

A review of the contaminants in Baltic sediments (Perttilä and Brüggemann, 1992).

Quantitative approach: In total 32 (= 20%) of the *ICES CRRs* published during 1979–1999 were explicitly on results of and guidelines on chemical contaminant measurements, of which 75% (= 23) were published in 1979–1989, reflecting the intensive effort ICES dedicated to this issue at that time. In contrast to the numerous reports published in the *ICES CRR* series, only 11 scientific papers (= 1.1% of all papers) on contaminant-related issues were published in the *ICES Journal of Marine Science* in the period 1979–1999, three in 1979–1989 (Behrens and Duedall, 1981a,b; Yeats and Dalziel, 1987), and eight in 1990–1999 (Misra *et al.*, 1991; Balls *et al.*, 1993; Fryer and Nicholson, 1993; Macdonald and Bewers, 1996; Pedersen, 1996; Føyn and Sværen, 1997; Stange and Klungsoyr, 1997; Scholten *et al.*, 1998). Only two out of 33 *ICES MSS* were dedicated to contaminants, the first of these on sediment and pollution interchange in shallow seas (Postma, 1981), and the other on contaminant fluxes through the coastal zone (Kullenberg, 1986). The *ICES TIMES* series published 14 papers (= 51.2%) providing methodological guidelines for contaminant analysis and associated methods (Ehrhardt, 1987; Harms, 1987; Rantala and Loring, 1987; Vijverberg and Cofino, 1987; Yeats, 1987; Grøn, 1990; Loring and Rantala, 1990; Yeats and Brüggemann, 1990; Ehrhardt *et al.*, 1991;

Uthe *et al.*, 1991a,b; Nichol森 and Fryer, 1996; Nichol森 *et al.*, 1998; Smedes and de Boer, 1998).

Biological effects of contaminants, including fish diseases

The 1979 ICES Workshop on “The Biological Effects of Marine Pollution and the Problems of Monitoring” held in Beaufort, North Carolina, USA, was a major milestone for ICES activities with respect to the study of biological effects of contaminants. The aim of the Workshop was to examine possible approaches to monitoring biological effects and to identify techniques, which could be recommended for immediate use. Some 50 techniques were identified at the workshop to be appropriate to biological monitoring, via the fields of biochemistry, physiology, pathobiology, behaviour, genetics, ecology and bioassay (ICES, 1980a; McIntyre and Pearce, 1980).

Based on the review of the results of the Beaufort Workshop the ACMP considered at its meeting in 1980 that there was a firm basis for biological-effects monitoring and that biological techniques should be included in existing monitoring programmes. These should encompass a suite of biological-effects techniques, supported by chemical-residue analysis and the appropriate hydrographic observations (ICES, 1981a). As a first step to accomplish this strategy, it was proposed that certain aspects of fish pathology might be particularly amenable to cooperative monitoring. Therefore, ICES Member Countries were asked to make observations on grossly visible fish diseases for a joint assessment. This was the beginning of ICES-coordinated fish-disease studies and also the beginning of a structured disease data submission to ICES, since Member Countries were requested to report their results annually and to submit data to the ICES Secretariat using special data-reporting formats.

The results of this first ICES wild-fish disease survey were reviewed by ACMP at its 1982 meeting (ICES, 1983). The report covered the occurrence mainly of tumours, fin rot, and the skeletal anomalies of 12 fish species and many thousands of individual specimens from the Baltic, North, and Irish Seas and off the east coast of Canada and the USA, and revealed considerable spatial differences in the prevalence of certain grossly visible diseases. In the discussion that followed, the ACMP noted that there still was uncertainty in many cases about whether there was a cause-and-effect relationship between pollution and disease and suggested that additional information on diseased fish and on the body-burdens of contaminants should be sought to investigate this relationship.

Whenever results of studies on the link between fish diseases and marine pollution were presented at meetings of ICES Working Groups or Science Committees or at annual ICES Statutory Meetings or Science Conferences, their conclusions were debated controversially and some heated discussions occurred. This was most evident in the 1980s when the discussions in ICES on the quality of the marine environment and the extent to which man impacts it were polarized and often of a political nature rather than being based on scientific knowledge. Since fish diseases were the

first biological marker proposed for biological-effects monitoring at that time, the discussion in ICES on possible adverse effects of contaminants on marine life centred around this issue. Information on fundamental discussions within ICES on this issue can be found in the reports of ACMP and ACME (e.g., ICES, 1983, 1987, 1996).

All further ICES activities of later years regarding the monitoring of wild-fish diseases were coordinated by the ICES Working Group on Pathology and Diseases of Marine Organisms (WGPDMO). These included the organization of three practical, sea-going workshops aiming at an intercalibration and standardization of methodologies for fish disease surveys (1984: North Sea; 1988: Kattegat; 1994: Baltic Sea, with the Baltic Marine Biologists as co-sponsor) (Dethlefsen *et al.*, 1986; ICES, 1989; Lang and Møllgaard, 1999) and the publication of a Training Guide for the identification of common diseases and parasites of fish in the North Atlantic (Bucke *et al.*, 1996) in the *ICES TIMES* series.

Whilst the results of the first two workshops were published in the *ICES CRR* series as practical guidelines on methodologies for fish disease surveys (Dethlefsen *et al.*, 1986; ICES, 1989), the results of the BMB/ICES sea-going workshop on fish diseases in the Baltic Sea were published in the *ICES JMS* as a series of scientific articles, focusing on diseases and parasites of Baltic flounder (*Platichthys flesus*), cod (*Gadus morhua*), herring (*Clupea harengus*), and sprat (*Sprattus sprattus*) (Bogovski *et al.*, 1999a,b; Drevs *et al.*, 1999; Grygiel, 1999; Køie, 1999; Lang *et al.*, 1999; Møllgaard and Lang, 1999; Wiklund *et al.*, 1999). In addition, information on the workshop rationale and objectives and the major conclusions drawn based on the practical work carried out on board are provided in an introductory chapter (Lang and Møllgaard, 1999). These papers reflect the current status of wild-fish disease monitoring activities in the Baltic Sea from both methodological and scientific points-of-view. They provide guidelines for practical work including fish sampling, the selection of target species and diseases useful for monitoring purposes in the Baltic Sea, disease diagnosis, and current techniques for the statistical analysis of epidemiological data.

Further steps in the coordination and standardization of fish-disease surveys were the implementation of the ICES fish-disease database as part of the ICES Environmental Data Centre and the establishment of standard procedures for submission, validation, and statistical analysis of disease data submitted to the ICES Secretariat by Member Countries as results of their national monitoring programmes. The ICES fish-disease database comprises information from studies on the occurrence of externally visible diseases and macroscopic liver lesions in the common dab (*Limanda limanda*) and the European flounder (*Platichthys flesus*) from the North Sea and adjacent areas, including the Baltic Sea, Irish Sea, and English Channel. From 1981 onwards in part, data are held on length, sex, and health status of almost 500 000 individual specimens, as well as information on sampling characteristics (Wosniok *et al.*, 1999; Lang and Wosniok, 2000). In 1998 ACME reviewed a comprehensive report providing results from a statistical analysis on temporal and spatial trends in the prevalence of diseases of dab

(lymphocystis, epidermal hyperplasia/papilloma, skin ulcerations) and flounder (lymphocystis, skin ulcerations) from the North Sea and Baltic Sea for the period 1981–1997 (Wosniok *et al.*, 1999). Subsequent work was dedicated to a more holistic data analysis; combining the fish-disease data with other data maintained in ICES databanks (oceanography, nutrients, contaminants, and stock assessment data) in order to try to explain the causes of the observed spatial and temporal variation in the disease prevalence recorded (Lang and Wosniok, 2000).

Other major ICES activities related to fish diseases were the 1980 ICES Special Meeting on Diseases of Commercially Important Marine Fish and Shellfish (Stewart, 1983), the 1993 ICES Workshop on the Distribution and Sources of Pathogens in Marine Mammals (ICES, 1994a), and the 1996 ICES Special Meeting on the Use of Liver Pathology of Flatfish for Monitoring Biological Effects of Contaminants (ICES, 1997).

More general aspects of the biological effects of contaminants have been dealt with successfully by the ICES Working Group on Biological Effects of Contaminants (WGBEC) that was established at the 1984 ICES Statutory Meeting as the Study Group on Biological Effects Techniques and became an official Working Group in 1987. A major achievement of WGBEC was the development of an integrated marine environmental monitoring strategy based on the need for closer integration of chemical and biological monitoring techniques (ICES, 1995b), an approach that replaced the traditional purely chemical monitoring in many national and international monitoring programmes. Furthermore, WGBEC developed a suite of biological-effects techniques and quality-assurance procedures to be used in biological-effects monitoring and published in the *ICES TIMES* series. WGBEC also organized the 1990 ICES/IOC Workshop on the Biological Effects of Contaminants in the North Sea, held in Bremerhaven, Germany (ICES, 1991a, 1992b). Although this workshop was a significant step forward in ICES regarding the assessment of the techniques available at that time for the detection of biological effects of contaminants, the scientific results of this workshop were not in fact published.

Other ICES activities regarding the effects of contaminants were first, the “Mini-Symposium on Ecosystem Modelling as a Tool to Predict Pollution-Associated Risks for the Marine Environment”, which highlighted the development of management strategies for marine ecosystems and the role of ecological risk modelling as important tools in the assessment and prognosis of ecological effects of pollution (Everts *et al.*, 1993; Hommen *et al.*, 1993; Schobben and Scholten, 1993) and second, the publication of a report on contaminants and their effects in marine mammals, prepared in collaboration between ICES and IOC at the request of the United Nations Environment Programme (UNEP) (ICES, 1988a).

Quantitative approach: In the *ICES CRR* series, three reports (= 2%) were published directly related to biological effects of contaminants, including wild-fish diseases, (ICES, 1981b; Dethlefsen *et al.*, 1986; ICES, 1986). Two *ICES MSS* were explicitly (McIntyre and Pearce, 1980) or partly

(Stewart, 1983) dedicated to biological effects and pollution-associated fish diseases. Eight articles in the *ICES JMS* addressed the relationship between fish diseases and contaminants (Möller, 1989, 1990; Möller and Anders, 1992; Chang *et al.*, 1998; Bogovski *et al.*, 1999a; Grygiel, 1999; Lang *et al.*, 1999; Møllergaard and Lang, 1999), and 13 papers discussed other aspects regarding biological effects of contaminants, e.g., effects of oil exploitation on benthos, effects of TBT, PAHs, and quantitative approaches for risk assessment (Rees and Eleftheriou, 1989; Vranken *et al.*, 1991; Kingston, 1992; Rees *et al.*, 1992; Everts *et al.*, 1993; Hommen *et al.*, 1993; Schobben and Scholten, 1993; Dethlefsen *et al.*, 1996; Daan and Mulder, 1996; Hall *et al.*, 1996; Briggs *et al.*, 1997; Davies *et al.*, 1998; Bogovski *et al.*, 1999b). In total, these papers comprised 21% of all papers published in the *ICES JMS*. Nine issues (33.3%) in the *ICES TIMES* series provide guidelines for biological effects measurements (Galgani and Payne, 1991; Rees *et al.*, 1991; Thain, 1991; Bucke *et al.*, 1996; Bocquené and Galgani, 1998; Stagg and McIntosh, 1998; Gibbs, 1999; Hylland, 1999; Reichert *et al.*, 1999).

Harmful algal blooms and eutrophication

ICES became involved in the issue of harmful algal blooms at the beginning of the 1980s, when there were reports of an increasing number of algal bloom events in the ICES Area partly harmful to marine organisms and human consumers of seafood. There was a suspicion that these might be linked to anthropogenic eutrophication. The ACMP recommended at its meetings in 1980 and 1981 the monitoring of the occurrence of “red tides” and eutrophication and consideration also of the issue of plankton blooms in relation to their possible impacts on fisheries management and mariculture (ICES, 1981a, 1982a).

In order to coordinate this work, the ICES Working Group on Exceptional Algal Blooms was established in 1984, with the tasks of providing advice to fishery and mariculture managers on monitoring, site selection, prediction, site management, and management options during bloom events. After some restructuring of the ICES Working Groups considering harmful algal blooms, the ICES/IOC Study Group on Harmful Algal Bloom Dynamics was established in 1991. It became a Working Group with the same name in 1994.

Based on the outcome of early ICES studies, it became evident that there was a lack of understanding regarding the dynamics of algal blooms and the key processes leading to harmful algal bloom events, e.g., regarding the role of anthropogenic and natural nutrients. It was also clear that there was a need for more inter- and multidisciplinary collaboration between ICES Working Groups and other organizations. ICES, therefore, intensified its efforts in the 1980s and 1990s, in part as a result of requests from OSPARCOM and HELCOM. This is reflected in an increasing number of ICES reports (e.g., Parker, 1983; ICES, 1986, 1992a), intercalibration exercises and technical guidelines (ICES, 1994a, 1996, 1999; Richardson, 1987; Kirkwood, 1996) and meetings, viz:

1984 ICES Special Meeting on the “Causes, Dynamics, and Effects of Exceptional Marine Blooms and Related Events” (Parker and Tett, 1987);

1988 ICES Workshop on the *Chrysochromulina polyylepis* bloom in the Skagerrak and Kattegat (Skjoldal and Dundas, 1991);

1992 ICES Symposium on “Measurement of Primary Production from the Molecular to the Global Scale” (Li and Maestrini, 1993);

1994 ICES Workshop on Modelling the Population Dynamics of Harmful Algal Blooms (ICES, 1994c).

The work of ICES on this topic in the period 1979–1999 illustrates how complex and complicated marine processes leading to environmental problems can be. This led to the early realization that an understanding of the factors involved and the prediction of effects require a multidisciplinary approach and close collaboration between scientists from various fields of marine science both inside and outside the ICES community. In this context the collaboration of ICES with the IOC can be regarded as particularly fruitful because it resulted in a number of successful joint activities, e.g., the establishment of a database on algal bloom events held at IOC, the annual publication of decadal maps of harmful algal events in the ICES Area as part of the ICES Environmental Status Report (ICES, 1997), and the forthcoming IOC-SCOR GEOHAB Programme (Global Ecology and Oceanography of Harmful Algal Blooms). This programme was implemented to improve the prediction of harmful algal blooms by determining the ecological and oceanographic mechanisms underlying the population dynamics of harmful algae through the integration of biological, chemical, and physical studies supported by extended and improved observation and modelling systems (ICES, 2000). All this joint work bodes well for continued collaboration in the future.

Quantitative approach: Five (= 3.3%) of the reports published in the *ICES CRR* series were directly or indirectly related to harmful algal blooms or eutrophication (ICES, 1990a, 1992a; Kirkwood *et al.*, 1991; Skjoldal and Dundas, 1991; Aminot and Kirkwood, 1995). All of these were published in the period 1990–1995. Three (= 9.1%) *ICES MSS* were published considering these aspects (Parker and Tett, 1987; Li and Maestrini, 1993; Daan and Richardson, 1996). In the *ICES JMS* series, only two papers (= 0.2%) were published directly focusing on harmful algal blooms (Morrison *et al.*, 1991; Raine *et al.*, 1993). The *ICES TIMES* series includes two articles (= 7.4%) on nutrient and primary production techniques (Richardson, 1987; Kirkwood, 1996).

Environmental effects of the introduction and transfer of non-indigenous species

The effects of the introduction of non-indigenous marine species into the ICES Area have been a long-term issue in its environmental work. The ICES Working Group on the Introduction of Non-Indigenous Marine Organisms, now the ICES Working Group on Introductions and Transfers of Marine Organisms, was established in 1969. It met for the

first time in 1970 to consider the principles that might govern the introduction and acclimatization of non-indigenous marine organisms, especially shellfish and anadromous and catadromous fish species (ICES, 1972).

One of the major achievements of this Working Group was the preparation of a Code of Practice on the movement and translocation of non-native species for fisheries enhancement and mariculture purposes, which was adopted by the Council in 1973. A revised version was published in 1979, and this Code of Practice became the standard for international policy for the next 10 years. ICES has published two extended guides to the 1979 Revised Code (ICES, 1984b; Turner, 1988). A second revision of the Code of Practice was adopted in 1990, and the latest issue, the 1994 Code of Practice, was published in 1995 (ICES, 1995a).

The 1994 ICES Code of Practice sets out recommended procedures and practices to diminish the risk of detrimental effects from the intentional introduction and transfer of marine (including brackish water) organisms. It considers the risks associated with the introduction of disease agents, the ecological and environmental effects of species/organisms that may escape the confines of cultivation and become established as wild stocks, and the genetic impact, of the mixing of farmed and wild stocks as well as the release of genetically modified organisms.

The ACMP reviewed the report of this Working Group for the first time at its 1992 meeting (ICES, 1992b). From then on, advice on this issue has been provided on a regular basis by its successor, ACME, since its first meeting in 1993 (ICES, 1994c).

Other major reports published in the period 1979–1999 reflecting the progress made as a result of ICES activities were on the following topics:

Status (1980) of Introductions of Non-Indigenous Marine Species to North Atlantic waters (ICES, 1982b);

Mini-Symposium on “Case Histories of Effects of Transfers and Introductions on Marine Resources” (Sindermann, 1991);

Introductions and Transfers of Aquatic Species (Sindermann *et al.* 1992);

Ballast Water: Ecological and Fisheries Implications (Carlton, 1998);

Status of Introductions of Non-Indigenous Marine Species to North Atlantic Waters 1981–1991 (Munro *et al.*, 1999).

Whilst ICES activities on this topic focused at first on the intentional introductions and transfers there was growing evidence of accidental introductions and transfers of marine organisms occurring and constituting a major threat to the marine environment and the composition of its living communities. This occurred most often through the release of ships' ballast water that included live non-indigenous organisms that could become established in new marine areas. One striking example of this in the early 1990s was the in-

troduction of the western Atlantic ctenophore *Mnemiopsis* sp. to the Black Sea, which was responsible for the collapse of the anchovy fishery (ICES, 1994c; Kideys and Niermann, 1994; Kremer, 1994; Mutlu *et al.*, 1994). Most of the recent ICES activities related to introductions and transfers were consequently focused on this issue in collaboration with, in large part, other international organizations, e.g., the International Maritime Organization (IMO) and the International Oceanographic Commission (IOC) (ICES, 2000), and this issue will certainly continue to be of importance for ICES.

Quantitative approach: Five numbers (= 3.3%) in the ICES CRR series were directly on introductions and transfers and their risks (ICES, 1982b, 1984; Turner, 1988; Carlton, 1998; Munro *et al.*, 1999). One (= 7.7%) ICES MSS on the subject was issued (Sindermann *et al.*, 1992), and 10 articles (1.0%) were published in the ICES JMS (Egidius *et al.*, 1991; Floc'h *et al.*, 1991; Grizel and Héral, 1991; Sindermann, 1991; Greeve, W. 1994; Kideys and Niermann, 1994; Kremer, 1994; Mutlu *et al.*, 1994; Hayes, 1998; McDermott, 1998).

Environmental impact of mariculture

Because of the increasing importance of the finfish and shellfish mariculture industry in ICES Member Countries, the potential environmental effects of mariculture became an issue of concern for ICES in the mid-1980s. In 1985–1986 the Council established the *ad hoc* ICES Study Group on the Environmental Impacts of Mariculture, which became a Working Group in 1987 and was later reconvened as the ICES Working Group on Environmental Interactions of Mariculture. The ACMP reviewed progress in this field for the first time at its meeting in 1986 (ICES, 1987), and the first report of the Study Group was published in 1988 (Rosenthal *et al.*, 1988). Advice was provided by the ACMP and ACME more or less regularly from then on, partly based on requests from OSPARCOM and HELCOM.

The work of ICES in this area has focused in the main on the following topics:

The effects of medication (vaccines, antibiotic and chemotherapeutic agents) on the build-up of residues in sediments and their impact on marine bacteria and on the direct impact on marine planktonic life;

The effects of contaminants used in mariculture (e.g., estrogenic compounds leading to sterility);

The spread of diseases and parasites through stock transfer among countries, and their transfer from wild to farmed fish and vice versa;

The effects on indigenous fauna in terms of competition, species composition and abundance, alteration of the native gene pool by release/escape of cultured organisms, disease transfer;

The use of genetically modified organisms (GMOs) and associated risks;

The effects related to nutrient and organic matter loading; and

Programmes for the monitoring and modelling of the environmental impacts of mariculture.

The late 1980s and the first half of the 1990s was a very active period. A number of ICES Workshops and Sessions were organized, and several ICES reports initiated by the ICES Working Groups and the ICES Mariculture Committee on issues related to the environmental impacts of mariculture were published, viz:

ICES Symposium on the “Ecology and Management Aspects of Extensive Mariculture” (Lockwood, 1991c);

A report on Chemicals Used in Mariculture (ICES 1994b),

1994 ICES Theme Session on Mariculture and Coastal Zone Management;

1995 Workshop on Principles and Practical Measures for Interaction of Mariculture and Fisheries in Coastal Area Planning and Management;

1995 Workshop on Modelling Environmental Interactions in Mariculture;

1995 ICES Theme Session on Mariculture: Understanding Environmental Interactions;

1996 ICES Workshop on the Interactions between Salmon Lice and Salmonids; and

1997 ICES/NASCO Symposium on “Interactions between Salmon Culture and Wild Stocks of Atlantic Salmon: The Scientific and Management Issues” (Hutchinson, 1997).

Quantitative approach: In the *ICES CRR* series, only two (= 1.3%) reports related to environmental effects of mariculture have been published (Rosenthal *et al.*, 1988; ICES, 1994b). Twenty papers (1.9%) were published in the *ICES JMS*, and of these, eighteen in one volume (Egidius *et al.*, 1991; Black *et al.*, 1997; De Casabianca *et al.*, 1997; Boxaspen, 1997; Dawson *et al.*, 1997; Hansen *et al.*, 1997a, 1997b; Isaakson *et al.*, 1997; Jackson *et al.*, 1997; Jacobsen and Gaard, 1997; Jonsson, 1997; McGinnety *et al.*, 1997; McKinnell and Thomson, 1997; McVicar, 1997; Noack *et al.*, 1997; Sægrov *et al.*, 1997; Stokesbury and Lacroix, 1997; Tingley *et al.*, 1997; Youngson *et al.*, 1997; Hansen *et al.*, 1999). Three *ICES MSS* dealt with mariculture issues, of which only one (= 3.0%) directly with ecological effects of mariculture (ICES, 1991c). More than 25 *ICES ILD* (= 50%) have been published so far on diseases/parasites of marine finfish and shellfish, providing brief information on the type of disease, on host species, aetiological agents and associated environmental conditions, geographical distribution, significance and control, impact on the host, and diagnostic methods.

Other environmental issues that have not been considered

ICES environmental science has also contributed to a large extent to progress made regarding other environmental issues not covered in this review. These include, for example, the environmental effects of sand and gravel extraction, the impact of environmental change on benthos communities, the status of marine mammal populations, and the effects of contaminants and diseases and, more recently, the ecosystem effects of fishing on the one hand and marine habitat mapping classification and mapping on the other.

Conclusions

Since the late 1960s environmental issues related to anthropogenic impact on the marine environment have been of increasing importance in the work of ICES. A major achievement during the period up to 1990 was the establishment of coordinated ICES contaminant monitoring programmes. From the beginning these were associated with numerous intercalibration exercises and the development of methodological guidelines, recognizing the need for quality assurance of the data. These activities became less prominent in the 1990s, and they were partly taken up by other international organizations and initiatives.

Another key area of ICES activities during the period 1979–1999 was the development of a basic philosophy, concepts, and strategies for integrated marine environmental monitoring and assessment programmes in relation, for example, to anthropogenic contaminants and their biological effects. The activities of various ICES Working Groups established guidelines for many techniques covering all the steps involved in the studies, from sampling to statistical analysis. These strategies have continuously been improved by ICES and have been adopted in large part by international monitoring organizations such as OSPAR and HELCOM.

Another strength of ICES is that it has established important databases not only in the field of fisheries-related data but also those of oceanographic and environmental (contaminants, biological effects, fish diseases) matters. The importance of these databases will increase in importance in the future when assessments addressing ecosystem management issues will be based on more holistic approaches, utilizing multidisciplinary data such as those stored by ICES.

In the 1990s, in particular, ICES widened the spectrum of environmental issues it dealt with and provided, through its environmental Advisory Committees (ACMP and ACME), advice on an increasing number of topics, ranging from physical oceanography to genetics.

The growing importance of the environmental side of ICES has been underestimated at times. One reason for this may be that it has often not figured prominently at the ICES Statutory Meetings and Annual Science Conferences and not been adequately represented in the scientific publication series of ICES, the *Journal du Conseil* and its successor, the *ICES Journal of Marine Science*.

The quantitative assessment of ICES scientific output regarding environmental issues that has been made here has shown that ICES activities regarding the development of the more technical aspects of environmental science are fairly well documented in the *ICES Cooperative Research Report* and *ICES Techniques in Marine Environmental Sciences* series respectively. However, compared with the more traditional fishery-related themes, only a comparatively small number of scientific papers dealing with environmental aspects have been published in the *ICES Journal*. This is in striking contrast to the excellent work with respect to the initiation, coordination, and conduct of scientific studies that is being done in the various ICES Working Groups and Committees. One reason is that ICES has almost a monopoly as a scientific forum for fishery biology carried out in its geographical area, whilst for environmental issues, such as contaminant chemistry or marine ecotoxicology, there are other organizations and publication series competing with ICES and the *ICES Journal*.

If the intention is to increase the reputation of ICES as a home for environmental science in the future, ways will have to be found as to how this can be achieved. One would be to strengthen further the role of ICES as a truly multidisciplinary and interdisciplinary organization, a strength that other organizations normally do not offer. The different disciplines represented in ICES would need to come closer together in order to facilitate a holistic, more ecosystem-based ICES science in the future. A good example of a multidisciplinary ICES effort, which could serve as a model for the orientation of future environmental science activities within ICES, was the 1995 Symposium on "Changes in the North Sea Ecosystem and Their Causes: Århus 1975 Revisited" (Daan and Richardson, 1996). It brought together scientists from all the different disciplines in ICES and can be considered a major scientific contribution, because it summarized the progress made in the years 1975–1995 in the understanding of the complex interactions between the biotic and abiotic components of marine ecosystems from all points of view.

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Mariculture

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The term “Mariculture” implies some change in the spatial relationships of cultured organisms with their environment. Finfish are generally grown in intensive operations, with density-dependent interactions such as interference competition, parasitism and microbial and viral infections being likely to be more severe (Lively *et al.*, 1995). Confinement implies that fish no longer have access to natural food sources. Therefore processed food must be imported from other marine environments or continental ecosystems (Folke and Kautsky, 1989; Naylor *et al.*, 2000). Spatial relationships of suspension feeding molluscs such as mussels are also modified by mariculture. In many instances they are provided with artificial support devices and raised in the water column. They no longer depend on benthic boundary-layer dynamics for feeding but feed in the water column. Growth nonetheless remains closely linked with the local environmental conditions in the case of suspension feeders and other extensively cultured organisms (Folke and Kautsky, 1989) and, compared with intensively cultured finfish, the consequences on the ecosystem are less drastic. This has had a profound impact on mariculture research since 1979, which is reflected in the contributions to ICES publications and Symposia. ICES has published the papers from three Symposia on aquaculture, respectively held in Nantes in 1989 (*ICES MSS 192*; Lockwood, 1991), Bergen in 1993 (*ICES MSS 201*; Pittman *et al.*, 1995), and Bath in 1997 (*ICES JMS 54 / ICES MSS 205*; Hutchinson, 1997).

ICES Marine Science Symposia, Vol. 192: The Ecology and Management Aspects of Extensive Mariculture

In June 1989 ICES hosted a Symposium on “The Ecology and Management Aspects of Extensive Mariculture” in Nantes (Lockwood, 1991). “Extensive mariculture” was defined as that type of operation where food is provided to the organisms by natural processes, as opposed to “intensive mariculture” where food is supplied by direct human intervention (Troade, 1991). It follows that in extensive aquaculture of organisms with limited mobility, transport mechanisms, i.e., ocean currents and waves, are as important to growth and survival as the potential biological performance of cultured individuals. Not surprisingly the Nantes ICES Symposium covered a large array of topics. In addition to overviews by J.-P. Troade (1991) and P. A. Larkin (1991) providing analyses of differences and commonalities between extensive mariculture and fisheries, thematic sessions and workshops were held on distribution of larvae and eggs, carrying capacity, stock enhancement, epidemiology and genetics and finally, bio-economics and resource allocation. One way to look at the potential impact of *ICES MSS 192* is to examine reports of some of the Symposium’s workshops and analyse how research rec-

ommendations were echoed in subsequent meetings or research programmes.

Distribution – In this session 2D models of the horizontal structure (fronts and gyres) in the English Channel (Salomon, 1991), and of the effect of wind-induced turbulence on vertical distribution of larvae (Sundby, 1991), as well as data on scallop larvae distribution (Tremblay and Sinclair, 1991), were presented. The workshop report stressed the implications of permanent, as opposed to transient, gyres on larval distribution and the need for research on baroclinic 3D models accounting for spatial changes, vertical shear, and vertical distribution of larvae. Some of these points were addressed in the OPEN (Ocean Productivity Enhancement Network) programme with studies of the vertical distribution of larvae with respect to water column structure (Pearce *et al.*, 1996; Pearce *et al.*, 1998) and of the differential behaviour of larvae according to stock (Manuel and O’Dor, 1997; Manuel *et al.*, 1997), as just two of the aspects covered. The workshop report also stressed the need for better information on the distribution of spawning beds and settlement areas. Again the OPEN programme included studies of behavioural mechanisms in substrate selection by larvae (Harvey *et al.*, 1995a; Harvey *et al.*, 1995b) and of cohesive (Stokesbury and Himmelman, 1995) and dispersive (Barbeau and Caswell, 1999; Carsen *et al.*, 1995; Hatcher *et al.*, 1996) mechanisms within scallop beds.

Carrying capacity – The Symposium was held some 15–20 years after the loss of about 35 000 t of scallop production in Mutsu Bay, Japan (Aoyama, 1989) and the demise of the Portuguese oyster (*Crassostrea angulata*) culture industry in the Bay of Marennes-Oléron (40 000 t annual production) and its replacement by the Japanese oyster, *C. gigas* (Héral, 1991). In both cases density-dependent processes were suspected. With growing evidence that phytoplankton depletion and food regulation of individual growth are common in natural bivalve beds (Peterson, 1982; Wildish and Kristmanson, 1984), it was reasonable to expect that in extensive bivalve culture, where populations rely only on natural food sources but densities may be increased dramatically, density-dependence would materialize. Appropriate carrying-capacity models were needed.

In the carrying-capacity workshop, Bacher (1991) used a box model of oyster and other bivalve trophic relationships in the Bay of Marennes-Oléron to show that local trophic dynamics of suspension feeders were dominated by oysters, interspecific competition being negligible. Héral (1991) reviewed models of trophic relationships between plankton and bivalve suspension feeders and concluded that existing models were unbalanced, with the emphasis being put either on physics or biology. Clearly, better interdisciplinary integration was needed.

Diverging views were expressed in the workshop report about the practicality of models. While some felt that existing models were too premature to be used for prediction and management, others held that models provided valuable guidance even if it was rudimentary. It was recommended that the performance and sensitivity of models be studied in different systems. As "Scope for Growth" (SFG) is abundantly used in carrying-capacity studies, the workshop expressed the need for a critical review of some of the terms of SFG and a reassessment of its methodology.

Three noteworthy initiatives on the carrying-capacity theme occurred in the years following the Symposium. First, NATO sponsored a workshop on bivalve filter feeders that was held in 1992 in Renesse. Papers by Grant *et al.* (1993) and by Herman (1993) addressed directly the role of models in the assessment of carrying capacity of bivalves and their role in estuarine ecosystems. Grant *et al.* (1993), for instance, considered the case of suspension-cultured mussels within an embayment. Their model included tidal transport of zooplankton, phytoplankton, and seston in and out of the system as well as the bio-energetics of mussels and plankton. Herman's (1993) contribution included the effect of boundary-layer transport on phytoplankton availability and its uptake by benthic suspension feeders. Both contributions answered Héral's (1991) plea for better integration of bio-energetics and transport mechanisms in suspension-feeder aquaculture research.

The second major initiative to follow the Nantes Symposium (see Volume 219(1–2) of the *Journal of Experimental Marine Biology and Ecology* and Volume 31(4) of *Aquatic Ecology*) was the TROPHEE programme (TROPHic capacity of Estuarine Ecosystems) in which methodological issues in energy absorption measurement were addressed by Iglesias *et al.* (1998). The final workshop also hosted contributions by Grant and Bacher (1998) and Bacher *et al.* (1998), among others, which explicitly addressed the comparison of model performance in different systems.

The third consequence of Nantes, was a meeting organized by ICES in St Andrews, New Brunswick, in 1999 on "Environmental Effects of Mariculture". Most of the papers presented there have been published in the *ICES Journal of Marine Science* (Wildish and Héral, 2001) and others (carrying and holding capacity) in the *Canadian Journal of Fisheries and Aquatic Sciences*. In addition to transport mechanisms and the bio-energetics of average individuals, a third axis of integration in carrying-capacity models, the topic of individual variability and its potential effect on yield (Gangnery *et al.*, 2001), was addressed.

The carrying-capacity workshop issued further points for research. It was suggested that models with appropriate small-scale spatial resolution be designed and that interaction between cultivation arrays and the environment be taken into account. An explicit study of the effect of mussel lines on the flow field and its management consequences is provided in a special section of Volume 17(1) of the *Journal of Shellfisheries Research* (Boyd and Heasman, 1998; Grant *et al.*, 1998; Heasman *et al.*, 1998). Although the small-scale modelling approach was challenged in the Re-

nesse workshop because of the computing burden involved, small-scale processes do need to be taken into account.

A final suggestion of the carrying-capacity working group was that models and concepts used in other disciplines might be useful in dealing with carrying capacity *per se*. One such model may be the Self-Thinning (ST) model (Yoda *et al.*, 1963). The ST theory was used by Fréchette *et al.* (1996) to assess Mussel Optimal Stocking Density (OSD) on individual ropes and to invalidate experiments on stock comparisons because biomass-density patterns showed that mortality on the ropes was attributable to ST, not to stock effects. A further application of ST theory was the assessment of OSD for scallops cultured within spat collector bags for one year, which amounts to performing a stocking experiment without controlled population-density treatments (Fréchette *et al.*, 2000).

Stock enhancement – The session on stock enhancement included, in addition to other papers, contributions reporting ongoing work on European lobster and cod. Tagging studies showed that juvenile lobster were more sedentary and grew faster than thought, compared with other studies (Latrouite and Lorec, 1991). Bannister and Howard (1991) reported that although tagging studies potentially allowed the estimation of the costs and benefits of restocking, such studies had uncertainties as to the net effect of restocking because of the possibility that wild recruits and sown recruits might compete. Cod restocking in the Masfjorden, Norway, was studied intensively, with papers on the comparative diet of wild and cultured young (Nordeide and Salvanes, 1991), on the structure of the pelagic food web (Fosså, 1991), and on the effect of increased advection from the sea into the fjords as a positive factor for the carrying capacity of young cod (Giske *et al.*, 1991; Kaartvedt, 1991).

The workshop report on stock enhancement suggested that progress with release techniques and in the management of fisheries, as well as better knowledge about threats to gene pools and carrying capacity, were required (see Hutchinson, 1997, for *ICES JMS 54 / ICES MSS 205*). The need for better studies of the hydrodynamic control of the distribution and recruitment of pectinids was also stressed (see discussion of the OPEN programme above). The workshop fully endorsed Peterman's (1991) views on the need for rigorously designed assessment of enhancement programmes with the inclusion of bio-economic aspects. It was pointed out that causes of recruitment bottlenecks in lobster restocking programmes were poorly known. The issue was addressed in meetings held in Îles de la Madeleine, Québec (Gendron, 1998) and in Bergen (Howell *et al.*, 1999), where it was reported that yield increases were detectable only in cases of extremely severe depletion of wild stocks.

Epidemiology and genetics – Stewart (1991) noted that common to all successful enterprises is the virtual freedom from disease in the early stages of their development but that conditions favourable to mariculture are also those favourable to disease outbreaks. The workshop report presented a series of recommendations, many of which amounted to restating those issued during an ICES Special Meeting held in Copenhagen in 1980 (Stewart, 1983). A significant change in philosophy was obvious, however,

with the emphasis being placed on good practice rather than curative treatments.

Svåsand *et al.* (1991) and Jørstad *et al.* (1991) showed that rare alleles had potential as markers for assessing the success of restocking operations. This led to a workshop recommendation about the importance of cataloguing and categorizing the genetics of wild populations. Studies of this kind were reported during the ICES Symposium held in Bath in 1997. It was found that genetic distance increased with geographic distance between sites, and since these differences presumably were adaptive, management initiatives should be taken to protect genetic diversity (see Section IV of *ICES MSS 192*).

The workshop group recommended that cultured animals be labelled with genetic markers (rare alleles) and expressed concern about the possibility that sexually active sterile males may displace wild males and thus decrease population fecundity. Both topics were addressed during the ICES Symposium held in Bath in 1997 (see Section IV of *ICES MSS 192*). Finally, the workshop report stated that special attention should be devoted to the fact that all stocks do not have equal sensitivity to pathogens, thus warning against transferring healthy pathogen carriers into sites inhabited by sensitive populations.

***ICES Marine Science Symposia, Vol. 201:* Mass Rearing of Juvenile Fish**

ICES held a Symposium on “Mass Rearing of Juvenile Fish”, in Bergen, in June 1993 (Pittman *et al.*, 1995). Attention was paid to nutrition—endogenous and exogenous—and to other aspects of ontogeny, notably swimbladder abnormalities and skeletal development. Other contributions focused on environmental interactions, behavioural ecology, and various aspects of larval culture. Providing growers with high-quality juveniles is a critical aspect in aquaculture success. The Bergen Symposium, however, did not address grow-out and adult life issues, and therefore relating it to issues raised in the Nantes and Bath Symposia is not really possible.

***ICES Journal of Marine Science, Vol. 54* *(ICES Marine Science Symposia, Vol. 205):* Interactions between Salmon Culture and Wild Stocks of Atlantic Salmon: The Scientific and Management Issues**

Atlantic salmon culture began in the early 1970s in Norway and the early 1980s on the Pacific coast of North America, and has been so successful that in Norway in 1988, for instance, caged individuals outnumbered wild migrating salmon by two orders of magnitude (Gausen and Moen, 1991). Caged stocks are subject to escapes because of equipment breakage inflicted by predators, wear of equipment, and bad weather. In a single event in Norway, losses were as numerous as the total migrating population in Norwegian rivers (Gausen and Moen, 1991). The escape of cultured salmon raised concern about the effects of escapees on wild salmon populations. In 1997, ICES held a Symposium jointly with NASCO (North Atlantic Salmon Conservation

Organization) in Bath (Hutchinson, 1997) to address this question. The Symposium focused on genetic interactions, ecological interactions, disease and parasite interactions, genetic problems and practical solutions, and management implications.

Papers by Danielsdottir *et al.* (1997), Bourke *et al.* (1997), and Nilsson (1997) focused on mapping the stock structure of Atlantic salmon in Iceland and Northern Europe. A number of papers addressed some of the sources of concern summarized in Gausen and Moen (1991) and in the Nantes workshop report on genetics. The general trend was that farmed individuals and hybrids were poorer performers than wild individuals, both in correlative studies (Berejikian *et al.*, 1997; Jonsson, 1997; McGinnity *et al.*, 1997) and in experimental studies (Fleming and Einum, 1997). Papers by Lacroix *et al.* (1997) and by Berejikian *et al.* (1997) addressed behavioural and biochemical aspects of the spawning success of escapees. Studies by Lacroix *et al.* (1997) and Carr *et al.* (1997) showed that escapees do migrate into rivers, and Sægrov *et al.* (1997) estimated that 81% of eggs in a Norwegian river were produced by escapees. Therefore this set of studies provided strong support to the concerns expressed by Gausen and Moen (1991).

McVicar (1997) reviewed the interactions between farmed and wild salmon from the viewpoint of disease transmission and pointed out that the severity of disease transmission, notably sea lice, from farmed to wild stocks, had not yet been quantified. Introduction of exotic pathogens in areas where local stocks have no innate resistance was also pointed out as a source of concern. The available evidence suggests that sea-lice abundance decreases with distance from farms, although more complex patterns are possible (Boxaspen, 1997; McVicar, 1997; Youngson *et al.*, 1997). This idea, taken with the spatial distribution of catches of homing salmon in Iceland (Isaksson *et al.*, 1997) for instance, appears to have provided the basis for the management recommendation to segregate spatially wild salmon from those produced in farms or ranches. To achieve this goal, establishing ranching stations inland and distant from each other, and avoiding estuarine harvesting, were pointed out as possible ways forward (Isaksson *et al.*, 1997). These points echo a strategy proposed by Ackefors *et al.* (1991) to minimize interactions between wild and enhanced fisheries in the Baltic.

Conclusion

Spatial relationships are central to aquaculture management. In the case of sessile suspension feeders, for instance, feeding pressure on resources may result in spatial segregation between resources—phytoplankton—and consumers. To alleviate the resulting growth hindrance, transport mechanisms must be taken into account. To achieve this, carrying-capacity models of suspension feeders have included bioenergetics and physics in an increasingly integrated manner. Recent efforts have pointed toward including the additional aspect of “individual variability” in these models. In the case of salmon, however, potential problems arise from parasitic and inter-group competitive interactions. One possible strategy for minimizing such interactions is to promote spatial segregation between protagonists. Not surprisingly

the spatial relationships between cultured organisms and the ecosystem they are part of, are different in the case of sessile compared with mobile organisms, and the Nantes ICES Symposium clearly highlighted large areas of the two distinct research agendas that needed to be followed.

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