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The Woods Hole bottom-trawl resource survey: development of fisheries-independent multispecies monitoring

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Multispecies bottom-trawl resource surveys have been conducted since at least 1885, with substantial development since 1948. The post-World War II development of this survey methodology was similar to the original development, with a focus on the effects of fishing and the nature of ecological interactions. Surveys were initially conducted by individual fisheries laboratories following systematic survey designs, each employing a single vessel and a standard trawl configuration. The data were shown to be useful in monitoring the status of stocks and in simultaneously providing information for addressing technical and ecological interactions. Attempts to design multinational trawl surveys proved difficult, primarily on the point of standardization. This is in marked contrast to other fishery-independent methods of measuring abundance, such as hydroacoustic surveys for pelagic fishes and sighting surveys for cetaceans. Although various attempts have been made at standardization of trawl surveys, the results in the end depend on not only the net, but also the vessel and its configuration. Although the lack of development of a standardized methodology has limited the generality of this approach, long-term single-nation and international multispecies trawl surveys have been used to monitor changes in fish abundance and size and species composition in many areas since at least 1963.

Keywords: demersal fish, ecological interactions, multispecies trawl surveys, technical interactions.

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Introduction

Multispecies trawl surveys became an important research methodology in fisheries research during the latter half of the 20th century. At a 1980 symposium in Ottawa dedicated to reviewing the use of bottom-trawl surveys, Dickie (1981) described the previous secondary role of trawl surveys:

> [i]t has long been accepted that the tool best suited to the estimation of abundance and distribution of fish stocks is the commercial fishery itself. Trawl surveys were originally conceived as sources of biological information which could improve the quality of judgement necessary in interpreting calculations based on commercial data.

Although there had been attempts to develop and use this methodology for estimating fish abundance and distribution even at the end of the 19th century, many questions about the reliability of such sampling were not addressed until after World War II. Subsequently, research-trawl surveys began to be developed, often growing out of exploratory fishing programs that had been a mainstay of many fisheries laboratories. Such surveys in some areas have emphasized sampling all demersal (and even some pelagic) fish species, becoming multispecies surveys. It is this development that has allowed the ecological aspects of the marine fish community to begin to be monitored and examined.

The gradual adoption of trawl survey methodology can be seen by examining several books that attempted to address the scope of fisheries science. Rounsefel and Everhart (1953) discussed the possibilities of obtaining direct estimates of fish abundance from samples with fishing gear, even identifying the possible need to stratify by depth, but expressed hope that underwater photography might help determine the "exact area sampled." Few of the several authors contributing to Michael Graham's comprehensive review of the investigations of sea fisheries in the United Kingdom (1956a) described the use of trawl surveys, and those who did focused on the representativeness of trawl survey samples for length or age composition rather than for abundance (e.g., Graham, 1956b; Parrish, 1956). Trawl surveys were not mentioned by Cushing (1968) or Royce

(1972) in their general texts, but Gulland (1983) described them as an accepted methodology for determining fish abundance.

This shift from fishery-dependent to fishery-independent data collection for measuring abundance occurred in several areas of fisheries research over the 20th century. One example is a beach-seine survey conducted along the southern Norwegian coast since 1919 aimed primarily at the sampling of young-of-the-year demersal fish in the fjords. Other surveys for young fish have been conducted since the early to mid-1960s, one an international survey in the Barents Sea (O. Nakken, personal communication) and another the International Young Herring Survey in the North Sea (Anon., 1976). Another example is hydroacoustics methods adapted from military and commercial fishing operations to monitor abundance of pelagic fish, especially since World War II. This methodology was pursued in a 1973 ICES symposium in Bergen (Margetts, 1977) and again at a joint US–USSR symposium in 1979 in Cambridge, Massachusetts (Suomala, 1981). The International Whaling Commission also held a workshop in Seattle in 1980 (Anon., 1982) to review the adaptation of whalers' searching and sighting procedures to line-transect survey methodology, marking the beginning of a shift to the adoption of multispecies sighting surveys for estimating whale and dolphin abundance. The shift from fishery-dependent to fishery-independent methods of monitoring abundance completely altered fisheries science in most places in the world, and the history of the origin and nature of that transformation needs to be more fully described.

As a contribution to that, this paper describes the development of trawl surveys for measuring fish abundance since World War II. This must be seen in the larger historical context of earlier surveys, especially that by RV "Garland" in Scotland from 1885 to 1895, and the attempt by the ICES Overfishing Committee at the beginning of the 20th century. I described these previously (Smith, 1994), and here need only to emphasize a few points. One is that the RV "Garland" survey showed the applicability of multispecies trawl surveys to multispecies interactions with the demonstration of decreases in exploited and increases in unexploited species (Garstang, 1900). The second is that the Overfishing Committee's attempt to establish an international survey to trace "the fluctuations in abundance of North Sea plaice" to their "natural causes" failed after only a few years. Although useful results were obtained (Garstang 1909), the lack of even a standardized trawl resulted in substantial uncertainties that doomed the survey.

Multispecies trawl surveys were used to measure fish abundance in at least one other place after the ICES international survey ended. Prior to its sinking in 1914, the RV "Endeavor" conducted both exploratory fishing and systematic multispecies trawl surveys on the southwestern Australian shelf (Klaer and Tilzey, 1996). Although some trawl surveys were conducted subsequently in Australia (N. Klaer, personal communication), using trawls for measuring abundance of adult fish was not pursued systematically again until after World War II. The primary focus in 1920–1940 was to establish the representativeness of trawl samples with respect to size or age of fish. Only after 1948 were the precision of trawl survey catch rates evaluated and the ideas of the RV "Garland" systematic spatial and seasonal coverages and multiple species sampling pursued.

The "overall census" of the New England banks

During the first half of the 20th century, research at the US Bureau of Commercial Fisheries (later the National Marine Fisheries Service) Woods Hole Laboratory focused on individual New England fisheries. Successful biologists formed and maintained strong ties with the fishing fleets and focused what little research trawling they did on the "fishing grounds". They collected samples from aboard commercial vessels, both on the fishing grounds and in ports, and investigated the cause of catch fluctuations and effects of so-called "savings gear" (Royce, 1948).

After the RV "Albatross" was decommissioned in 1921, the Woods Hole Laboratory was left without a high-seas research capability, resulting in an increased focus on laboratory work. At-sea work was restricted to commercial fishing vessels. The RV "Albatross" was replaced in 1926 by the RV "Albatross II", a converted Navy tug which Elmer Higgins (1934) would later politely describe to Congress as "not adapted for fishery research". It was subsequently decommissioned in 1933 owing to lack of operating funds. A year later, Higgins, the Chief of the Division of Scientific Inquiry for the Commercial Bureau of Fisheries, argued unsuccessfully to Congressional committees for a purpose-built research vessel (Higgins, 1934).

Instead of a new research vessel, the Bureau, in 1939, began converting an ageing steam trawler, the RV "Harvard", which had been given to the government. This conversion was interrupted by World War II and not completed until 1948 when the "Harvard", lengthened and renamed the MV "Bellefonte" during the war and then renamed the RV "Albatross III", was delivered to the Woods Hole Laboratory. One hundred and eight feet long with room for 12 scientists, this ship would allow the Laboratory to expand its work from the docks and laboratories to the sea. Anticipating receipt of the ship, William Royce pointed to declines in several of the main fisheries and identified several factors that previous research had suggested might be responsible (Royce, 1948). These included seasonally varying availability, potential competition between adults and young fish, strong effects of catches in subsequent years, recruitment varying with wind conditions, and variability due to fluctuations in slope-water eddies surrounding Georges Bank. The complexity of these factors, he concluded, implied that "complete information can be

obtained only by studying the ecology of interrelationships of all of the animals and plants and their environment."

To address the concerns he had outlined, Royce proposed using the "Albatross III" for several purposes, one of which was an "overall census" of the fish. Although most of Royce's research program was standard fare for fisheries science, his overall census was something new. He described his ideas using the analogy of census takers and actuarial scientists, with a goal "to write a life-insurance policy on a haddock at age three, paid up at age six." By this, Royce apparently did not mean the analogy to demography in examining age composition that Hjort (1914) had used. Instead, his focus was "proper sampling methods" based on uniform sampling in each depth zone. Trawl surveys with a similar goal to Royce's surveys were also begun in 1948 in Newfoundland (Pitt *et al.*, 1981). These were conducted along fixed transect lines stretching across the banks. The systematic use of trawl surveys was simultaneously being developed by the US Bureau of Commercial Fisheries in Alaska (Ellson *et al.*, 1949). Both of these were growing out of exploratory fishing operations, but apparently did not include Royce's concept of a census.

Royce envisioned the comparison over years of these census data with the commercial catch data collected in the ports, and their combination with temperature and other oceanographic data. Royce sampled more than 200 stations during July–November 1948, with nearly 1000 sampled by 1951. However, before he was able to begin the analyses, he was transferred to the Bureau's Hawaii Laboratory.

When Royce began his overall census in 1948, the treaty establishing the International Commission for the Northwest Atlantic Fisheries (ICNAF) was just being signed. Drawing on the agreements achieved in the 1937 London Fisheries Convention, ICNAF and many other international conventions were developed following World War II. The 1937 agreement had been intended to apply to the entire North Atlantic, but after the war the ocean was divided at 42°W (Anon., 1948). The so-called Permanent Commission was established to regulate fisheries in the east, and ICNAF was established for the west. The Permanent Commission relied for its scientific advice on ICES, whereas ICNAF established its own Standing Committee on Research and Statistics (STACRES) composed of national scientists.

The focus of management in both the Permanent Commission and ICNAF in the 1950s was on selecting an optimum mesh size, utilizing the methods of computing the effects of changing mesh size perfected by Beverton and Holt (1957). In 1951, ICNAF scientists proposed a long-term research plan with no mention of bottom-trawl surveys (Anon., 1951). The following year, Herbert Graham, who replaced Royce as Director of the Woods Hole Laboratory, noted differences between Royce's overall census data and commercial data, and offered the opinion that the latter "appears to be a more reliable method of determining concentrations of fish of commercial sizes because of the more representative sample obtained."

Graham's concerns were supported by the results of Clyde Taylor's analysis of the variability of the three years of overall census data. Using methods developed since the mid-1930s to analyze the performance of plankton sampling gear, Taylor (1953) demonstrated that fish were not distributed at random, with more samples than expected being larger than average. He showed that the catches of several species, including haddock, followed a negative binomial distribution and that the number of species caught followed a logarithmic distribution. The former conclusion implied that precision of the estimate of mean catch per tow, and hence abundance, would depend on the mean catch rate and the degree of aggregation. Graham (1953) concluded from this analysis that "[e]stimates of density based on the observed mean are, then, subject to so much error as to be of little use."

The same year that Graham announced the end of Royce's overall census, ICNAF scientists were rethinking their initial research direction and produced a revised research program (Anon., 1953) that included the use of trawl surveys to address questions of ecological interactions:

> From the relative numbers of different species of fishes caught in the experimental fishing surveys, and from studies of their food, it can be determined what role each species plays in its ecological system as predator, competitor or prey.

The overall census was not resurrected with this development in ICNAF, and because of severe budget cuts, the Woods Hole Laboratory was forced to lend the RV "Albatross III" to the nearby Woods Hole Oceanographic Institution for a few years where it was used in oceanographic studies supported by the US Navy.

The Woods Hole bottom-trawl resource survey

Royce's vision was adopted by Robert Edwards, who came to Woods Hole in the early 1950s as an ecologist to study the developing industrial fishery in New England. Edwards had completed his PhD at Harvard and had been strongly influenced by George L. Clarke (R. Edwards, personal communication). Clarke's paper (1946) on Georges Bank entitled "The dynamics of a marine community" had shown how to account for the energy flow across the trophic structure. This paper, elaborated in Clarke's textbook (1954), became Edwards' "initial master plan" at the Woods Hole Laboratory.

The industrial fishery targeted a wide range of species and had rapidly expanded in the early 1950s to fill the gap in fishmeal production left by the demise of the

California sardine fishery. Edwards began his study of this fishery with an intensive port sampling of the landings and, unlike the other biologists at the Woods Hole Laboratory, focused on seasonal and annual fluctuations in catches of a mix of species. He was soon arguing that he was now able "to begin to examine the entire problem of the utilization of a community" (Edwards and Lux, 1958).

Edwards came to Woods Hole with the assurance that the Laboratory was headed toward ecology. This was based in part on the sentiment of Lionel Walford, then Director of Fisheries Research at the Bureau's headquarters in Washington, DC. In 1955, Walford wrote (Walford 1961), "Fisheries researchers . . . have been finding it necessary to rediscover natural history (now called ecology), and to enlarge the scope of their programmes in order to establish a proper balance between the studies of fisheries and of fishes."

Ecological questions were indeed being frequently raised. One question posed in the Woods Hole Laboratory's 1955 annual report (Anon., 1955) was what had happened to the food of haddock when that species' abundance was reduced to one quarter of its previous abundance? The same issue was identified in the 1959 annual report (Anon., 1959a), only this time in the context of Garstang's 1900 suggestion that other species could increase when targeted species are reduced (Garstang, 1900). In the case of Georges Bank, the concern was "whether other species have replaced the haddock in the bottom fish community." This theme was also reflected in the 1959 "Long Range Program" for the Woods Hole Laboratory that was predicated on plans for a replacement for the "Albatross III" (Anon., 1959b):

> Without expanded knowledge of abundance and distribution of commercial and potential commercial species and their ecological associates, efficient exploitation and management cannot be effected. For these reasons it is desired to initiate and maintain a routine groundfish survey.

The Long Range Program discussed the "most efficient means of measuring abundance and distribution" and identified several possible survey designs, with an aim of avoiding the practice of trawling over areas where fish were known to aggregate. These designs included the use of stratified versus random sampling and random versus fixed stations.

The new research vessel, the RV "Albatross IV", was delivered in November 1962 and became available for the first bottom-trawl survey in 1963. The survey design was discussed at some length, with new staff members recently trained in statistics, such as Marvin Grosslein and Richard Hennemuth, providing the leadership (H. Graham, personal communication). Grosslein brought with him from Cornell University the conviction that it was necessary to "randomly pre-select locations in advance of the cruise, as opposed to searching for fish concentrations with echo sounders", and an understanding of the statistical gains to be achieved from stratified survey designs (M. Grosslein, personal communication). This idea was not readily accepted by some of Grosslein's colleagues who argued that surveys had to be designed around the knowledge of habitat and fishing grounds for each species. Most, however, eventually agreed that a single standardized survey could meet their needs, especially because complete sampling of all the fish species caught was an integral part of the design, along with sampling of scales, otoliths, body length, sex and reproductive stage, and stomach contents.

It took considerable discussion, coupled with strong support from Walford at headquarters and Graham and Edwards in Woods Hole, to overcome the resistance to changing the "traditional" way of doing things. However, by early 1964, new depth strata had been defined, and during the second year of the RV "Albatross IV" survey, a table of random numbers as well as the Yankee 36 trawl were on board. The random depth-stratified Woods Hole Laboratory's bottom-trawl resource survey (BTRS) was under way.

Interestingly, although the scientific staff accepted the new survey procedures, the fishermen employed as officers and crew on the RV "Albatross IV" did not. Fishing "at random" was a complete anathema to the practical approach of fishermen. Further, they saw many ways they could improve the old Yankee 36 trawl. It became necessary to take precautions to ensure that the nets, for example, were not "improved" by the fishermen crew when repairs were made (R. Edwards, personal communication).

Initial uses of the trawl survey data

In less than ten years, the Woods Hole Laboratory had moved from rejecting Royce's overall census to embracing the BTRS. The post-World War II shift to fishery-independent measurements of fishery resource abundance was counterpointed by a 1963 ICES-sponsored Symposium on the "Measurement of Abundance of Fish Stocks" held in Madrid (Gulland, 1964). Most of the papers presented focused on fishery-dependent methods, especially improvements on catch per unit of effort that Garstang (1900) had used at the turn of the century. Only a few papers addressed fishery-independent methods. One focused on tagging, another on underwater photography, and two supported use of "echo-abundance" using hydroacoustic methods.

Grosslein had attended that workshop, just as the Woods Hole BTRS was getting started, and recalled (M. Grosslein, personal communication) that no papers addressed one of the concerns that he had heard discussed at the Woods Hole Laboratory in the two years he had been there, namely how to deal with the amount of fish being discarded commercially. The Madrid symposium did not provide any incentive for the Woods Hole BTRS and, in its nearly exclusive focus on fishery-dependent methods, missed stimulating the development of fishery-independent methods.

The Woods Hole BTRS would become a mainstay of the US participation in ICNAF, and by 1966, Graham's staff would write (Graham, 1966):

> One of the major objectives of these surveys is to describe the seasonal distribution and relative abundance of all groundfish available to the trawl in order to get a more complete picture of the structure of the demersal community. These data may be of considerable importance in the long term as an ecological 'benchmark' against which future changes in the composition of groundfish populations may be compared.

The BTRS data for 1964–1967 showed a rapid decrease in the average weight of haddock per trawl haul from 73 to 28 lb (33.1 to 12.7 kg). Graham (1967) argued that these declines showed that the fisheries were heavily exploited and that "we cannot expect any substantial increases from the area in the future." Drawing on his initial experience with the New England industrial fishery, Edwards computed biomass estimates for many of the species caught in the BTRS (Edwards, 1968). To do this, he had to estimate what he termed the availability and vulnerability of each species, given the survey design and the trawl net used. From these estimates of total biomass, he identified the fact that those species most actively fished were declining most rapidly, but even those not fished appeared to be decreasing. He suggested areas and species where US fisheries could be expanded.

Later, the Woods Hole BTRS data would be used to prove that too much fishing was occurring and especially to point at the USSR fleet. This analysis was based on declines in "stratified estimates of catch per tow of haddock by age groups" from 1963 to 1966 (Graham, 1967). For several years, the focus of the Woods Hole Laboratory would be on demonstrating the effects of what was seen as too much fishing, primarily through single-species analysis of declines. However, some attention was also given to the ecological origins of the survey, as reflected in Edwards adoption of Clarke's 1946 energetics model of Georges Bank as his "initial master plan". One place this did emerge was in the development of two-tiered quotas in ICNAF. This complex quota system, where the sum of the species quotas was capped by an aggregate quota, was developed to account for both technical interactions of trawls fishing for a multispecies complex of species, especially that which was taken as by-catch, and ecological interactions (Brown *et al.*, 1976; Clark and Brown, 1977; Hennemuth and Rockwell, 1987). Following this early importance of the trawl survey data for addressing ecological interactions, some work was done to follow up Clarke's energy flow model (e.g., Sissenwine *et al.*, 1984). However, more detailed analyses of the available ecological data proceeded more slowly (Link and Almeida, 2000).

An international annual inventory?

Although the trawl survey indices were being used to measure changes in stock sizes, there were substantial uncertainties that arose because of mismatches between the survey and commercial data. For example, the comparability of US trawl survey and USSR fisheries data in New England began to be addressed in 1967 when joint surveys were first conducted (Grosslein, 1968). These were aimed at establishing a "mutually acceptable index" of relative abundance of fish "free of the potential sources of biases in the available commercial indices." This involved the approach agreed by the ICES Overfishing Committee at the beginning of the century, i.e., calibration of vessels and trawls in field trials. An early result of these field trials was the determination of a high correlation within a field season between relative abundance indices from the small trawl used by the Woods Hole Laboratory scientists and the mammoth trawls used on the USSR survey vessels (Grosslein, 1968). Although the calibration effort over years was ultimately unsuccessful because the USSR fishing power fluctuated greatly from year to year (Griswold and Efanov, 1972), joint studies with other countries began as well.

By 1970, based on the Woods Hole experience, the ICNAF Assessments Subcommittee (Anon., 1970) had agreed that trawl surveys were cost effective, and that integration of the several national surveys would increase their value. During that meeting, Grosslein (1970) outlined several issues related to the question "Should ICNAF coordinate an annual inventory of groundfish stocks with research vessels?" He noted considerable interest from his colleagues in both the short-term and long-term value of an "annual inventory" and argued persuasively:

> There is little doubt that bottom trawl surveys of proper design and sufficient intensity would contribute to a more accurate and far more complete picture of the distribution, abundance and composition of groundfish populations than is now available from commercial statistics alone. In fact, it appears that research vessel surveys may be the only feasible way to obtain data on population structure in many cases...

Grosslein identified several requirements for a truly standardized survey, some of which had been discussed and abandoned in the ICES Overfishing Committee at the turn of the century. Seemingly the simplest of these requirements were consistent stratification schemes and methods of selecting sampling locations so that data from different countries could be easily combined. For example, when Canada began its survey in the early 1970s (Halliday and Kohler, 1971, 1981), Grosslein worked with Canadian scientists to adapt the Woods Hole sampling strata to the areas where they overlapped.

More difficult standardization requirements described by Grosslein included using the same trawl, rigged in the same way, and towed the same length of time at the same speed. The question again arose as to which trawl design would become a standard. Grosslein's conclusion then was essentially that which the ICES Overfishing Committee had come to previously:

> While it is obvious that the survey trawl chosen should have high efficiency for most of the major groundfish species, efficiency may have to be compromised with factors such as size and durability. Further evaluation of this question will be required before a final choice of trawl is made.

Grosslein was asked to pursue this question, and he organized what became known as the "Working Group on Coordinated Groundfish Surveys". The Group met in 1971 at ICES headquarters in Copenhagen, reflecting the fact that many of the same scientists were involved in both ICNAF and ICES at that time. Interesting additional experimental studies bearing on the value and design of such trawl surveys were reported (Anon., 1971), drawing on a 1951 study suggesting large variability in replicate trawl hauls (Barnes and Bagenal, 1951). Another study was an intense trawl survey on Faroe Bank using the UK RV "Cirolana", where each station was sampled twice (Jones and Pope, 1972; Anon., 1972). The sampling was seven times more intense than the BTRS, yet the precision of the abundance indices was not greatly improved. Further, the variability of the catch rates between replicated samples was low. This suggested that increasing survey intensity much beyond that already adopted in Woods Hole would be of relatively little value for statistical precision. The RV "Cirolana" survey also confirmed that the precision of abundance indices and age–length compositions from trawl surveys compared favorably to that obtainable from market samples. These types of studies addressed the statistical precision concerns that had been part of Graham's decision to terminate Royce's overall census and encouraged the Working Group to continue to pursue Grosslein's original question.

When the ICNAF Assessments Subcommittee met in January 1972 at the UN Food and Agriculture Organization in Rome, it was encouraged by the results of the Working Group on Coordinated Groundfish Surveys and recommended that ICNAF should proceed with "coordinated surveys" throughout the Northwest Atlantic (Anon., 1972). In the meeting report, however, only two outstanding questions were identified: 1) how to define fixed stratification schemes in the more northerly areas where both the ice and the fish were known to move, and 2) the desirability of standard data formats and centralized data processing. These issues would not easily be solved; in fact, there was a clear unwillingness by some countries, and an apparent unwillingness by most others, for centralized data processing and analysis.

More important than these questions was that of developing a standardized trawl, a question that was not even discussed. Two considerations had prevented ICNAF scientists from agreeing on a standardized trawl. First, the efficiency of different trawl designs varied with the species mix and bottom type. For example, the small trawl used in the Woods Hole BTRS had relatively small rollers and low headrope height which made it less efficient on complex or "hard" bottom and for off-bottom fish. While it met US objectives, it would not be likely to meet the objectives of other countries, especially in other regions of the Northwest Atlantic. Secondly, once a country had begun a survey, changing the gear to be consistent with other countries would result in the loss of interpretability of data already collected. These practical constraints left ICNAF with the difficult problem of intercalibration of nets as well as ships.

At the May/June 1972 ICNAF Annual Meeting, Grosslein presented the results of a questionnaire about intercalibration of ships that he had circulated after the January 1972 ICNAF meeting in Rome. He wrote that implementing a coordinated survey based on intercalibration would require (Grosslein, 1972):

> a firm basis in inter-calibration experiments of relative fishing power, well defined and carefully controlled survey methods, complete and rapid exchange of data, and a high degree of mutual confidence. Frankly these conditions are not easy to meet. Nevertheless, the importance and cost of research vessel surveys make it desirable to continue seeking ways of pooling our resources more effectively.

ICNAF's attempt to develop a fully standardized survey failed, and even the coordinated survey program that Grosslein and others pursued gradually disappeared in the Northwest Atlantic with the failure of ICNAF to survive the imposition of exclusive economic zones (EEZs) by the US and Canada in January 1977. Surveys were continued under the Northwest Atlantic Fisheries Organization (NAFO) that followed (Doubleday, 1981), but Grosslein's vision was not recovered. What remains today are the parallel surveys conducted by the US (Azarovitz and Sissenwine, 1981) and Canada (Halliday and Koeller, 1981). Attempts have been made to keep the two survey series standardized within themselves as vessels have changed using calibration studies (e.g., Azarovitz *et al.*, 1997), but with no standardization between them and with decreasing overlap in areas surveyed.

Conclusions

The post-World War II development of fishery-independent methods for measuring the abundance of exploited marine animals changed the practice of fisheries science. The development of multispecies trawl surveys was one example of this change. The development of trawl survey methodology was not continuous, with initial attempts at measuring multispecies abun-

dance of adult fish just before and just after the beginning of ICES giving way between World Wars I and II to a focus on measuring single-species year-class strength (Thompson, 1928). The turn-of-the-century ICES interest had failed on the point of standardization, leaving ICES to rely primarily on fishery-dependent data and ill prepared to address the multispecies issues that were arising. For example, ICES scientists analyzed the post-World War I commercial catch rates by focusing on one species, namely plaice. The increases in catch rates were interpreted as demonstrating that there had been too much fishing before the war (Borley *et al.*, 1923). However, Garstang (1926), Petersen (1922), and Baranov (1918) raised ecological questions about this interpretation, emphasizing the effects of the wartime increase in plaice on the plaice food supply. They reiterated the importance of multispecies interactions and identified the possibility that there could be too little as well as too much fishing. Lotka (1925) and Volterra (1928) raised the additional ecological questions about the effects of fishing on predator and prey relationships. These were questions for which fisheries biologists then had no tools to address. Unfortunately, under Russell's (1931) reinforcement of the single-species approach, these were questions for which they found no reason to develop tools.

After World War II, the development of multispecies trawl surveys was stimulated by questions about ecological interactions that were increasingly being raised. Royce's 1948 census and its successor, the Woods Hole BTRS, were both designed to answer questions about the interactions among species in the Northwest Atlantic that were being reduced in abundance by rapidly developing international fisheries. This survey began to provide data that allowed the rapid declines in fish stocks to be demonstrated, and those data were used to devise an innovative international management scheme that accounted for both technical and ecological interactions. Despite these successes, however, the lack of comparability of data from different surveys made it difficult to combine separate data series. Attempts to develop standardized trawl survey methodology within ICNAF in the Northwest Atlantic failed, and this lack of a standardized methodology reduced the effectiveness of multispecies trawl surveys.

Interestingly, ICES took a different approach than ICNAF to fishery-independent measurement of fish abundance. Building from an initial, one-time survey in 1962 to determine the location of juvenile herring, The Netherlands began another herring survey in 1965 aimed at measuring year-class strength (Anon., 1992; N. Daan, personal communication). Other countries joined, and several species, both pelagic and demersal, began to be routinely sampled in what was called the International Young Fish Survey (IYFS, Anon., 1976). In 1976, Great Britain followed up on its earlier RV "Cirolana" experimental survey for adult fish on the Faroe Bank by beginning a multispecies trawl survey in the North Sea (Woolner and Pope, 1983). That survey and the IYFS were merged following the reorganization of ICES working groups focused on herring and gadoids into one group, creating the International Bottom Trawl Survey (IBTS). The area gradually expanded to include the entire North Sea as additional nations joined that effort. Although initially resisted, the need to standardize the survey prevailed and eventually the French "au Grand Ouverture Verticale" trawl was adopted as the standard. This resolved the long-standing issue that had eluded both ICES, at the beginning of the 20th century, and ICNAF, 70 years later. Recognizing the important differences in catch rates among the several national research vessels, IBTS participants also focused on comparative fishing experiments for calibration, taking up where both ICES and ICNAF had struggled (e.g., Pelletier, 1998).

The development of fisheries-independent sampling methods proceeded differently on the two sides of the Atlantic. One question is why did standardization succeed under ICES, but not under ICNAF? An obvious possible explanation is that there was less incentive in the Northwest Atlantic because there were fewer nations adjacent to the fishing grounds. Canada and the US could survey the entire fishing grounds, so including data from additional surveys was perhaps not as vital as it was in the Northeast Atlantic. However, it may also be that the will for standardized surveys across nations waned in ICNAF with the advent of the EEZ. The conditions that Grosslein identified as necessary were in fact difficult to meet without strong motivation.

A second question is why fishery-independent sampling under ICNAF began with bottom-trawl surveys for adults, but under ICES, it began with young fish surveys. One possible factor is the differences in the management approaches pursued by ICES and ICNAF, with the latter shifting from mesh-size limitations to quotas, even two-tiered quotas. In addition, the ICES management-oriented focus on forecasting catches required measures of year-class strength, such as Thompson (1928) had demonstrated in the 1930s. This was given priority to using the trawls for sampling adult age composition, which was well provided by the extensive commercial catch statistics (N. Daan, personal communication). More basically, there may be differences in the way the fisheries were conducted, perhaps in the complexity of the fishing effort, the prevalence of discarding, and the pursuit of a mixture of several species, making fishery-dependent methods more difficult to apply in the Northwest Atlantic. A third possibility is the differences in how the scientific advice for fisheries management was structured, with the management body having greater control over the science under ICNAF.

Although difficulty in the standardization of trawl survey methods had been a major limitation, multispecies bottom-trawl resource surveys have nonetheless become a primary tool for fishery-independent measurements of abundance in many areas. More importantly in the longer term is the consistent multispecies sam-

pling that has allowed many of the questions about multispecies interactions to be addressed (Link and Almeida, 2000). Further, time-series such as those available from the Woods Hole BTRS, if continued, have the potential to detect some of the shifts in ecosystem structure that are expected due to the direct and indirect effects of fishing and to climate change (Hall, 1999).

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