Chapter 30
Climate and Fisheries: The Past, The Future, and The Need for Coalescence

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Abstract In this chapter we review the history of fisheries science with respect to climate impacts on fisheries and prognosticate the future of this type of research. Our review of the development of climate and fisheries research reveals that advances in our discipline emerge from the coalescence of four factors: shifts in fisheries economics and policy; developments in theoretical ecology; innovations in small-scale field and laboratory studies; and progress in large-scale fisheries statistics and modeling. Major advances have occurred when scientists interacted in multidisciplinary forums. We find that efforts to understand the impact of climate on the annual production and distribution of fish have produced a primary level of understanding of the processes underlying stock structure, production, and distribution of fish species. We find that ecosystem-based approaches to management have been advocated to a greater or lesser degree throughout the last century. In the future, we expect that advances in scientific understanding and improved computing power will allow scientists to explore the complex nature of environmental interactions occurring at different spatial and temporal scales. New field programs will develop to support the development of spatially explicit models of fish that include complex interactions within and between species, and fish behavior. Field sampling programs will benefit from continuing innovations in technology that improve collection of information on the abundance, distribution of fish, and the environment. New technologies will also be utilized in laboratory studies to rapidly assess the reproductive potential, food habits, and genetic history of fish under different environmental conditions. We expect that interdisciplinary training will continue to serve as a catalyst for new ideas in climate and fisheries. However, as researchers shift their focus from retrospective studies and now-casts to long-term implications of fishing and climate on the ecosystem we expect that training in oceanography, ecological theory, and environmental policy will be needed to provide a foundation for the development of models that depict the trade-offs of nature and human use in a realistic manner. Finally, we challenge fisheries scientists to track the accuracy of long- to medium-term forecasts of future states of nature and the potential impact of climate and fisheries on them.

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30.1 Introduction

The common definition of coalescence is the coming together of different units. In the varied disciplines of science, coalescence can take on many different meanings. In genetics, it can mean how lineages merge backwards in time, while in ecology, it has a more forward-looking description of how groups of organisms come together to forge a community. Here we embrace both meanings of coalescence. We look backwards to identify the factors that merged to mold the development of fisheries science as we know it today. We build on this knowledge to prognosticate the new advances in our field. We find that climate and fisheries interactions need the coming together, or merging, of climate scientists, oceanographers, and fisheries scientists in the broadest sense.

A new era of fisheries science emerged over a century ago with the formation of the International Council for the Exploration of the Seas (ICES) in 1902 at a time when European scientists realized the need to coordinate their research and management efforts across international boundaries (Rozwadowski 2002). Around the same time, Johan Hjort (1914) published his work asserting the concept that the dynamics of fish populations were caused by varying recruitment levels rather than large-scale geographic displacements, and pointed at natural fluctuations in populations caused by varying survival rates of young fishes as the probable cause. These products were the result of a "golden age" of fisheries science in Europe and North America, a remarkable proliferation of research and a coalescence of scientific technology and concepts, driven by the economic and political pressures of overfishing and market demand (Smith 1994). Now, near the beginning of a new century when the world faces new challenges of increasing demand for seafood resulting from increasing global population levels, high market value, overfishing, and uncertain climate conditions, more than ever we need to understand the complexity of processes governing population dynamics of marine fishes. Our discussion will trace the historical development of ideas linking climate and fisheries and how the legacy of the past might forge the future of fisheries science. In our long-range vision of the future we think scientists will be able to better forecast ecosystem responses to climate change and shifting demands for seafood because they more fully understand the processes controlling species interactions, and dynamics and the role of climate on these processes. Forecasting tools will allow scientists to inform managers on the impacts of their actions on society and the ecosystem, as well as test scientific concepts. In the short term, we encourage research to understand how animals respond to spatial and temporal changes in environmental conditions in order to construct a foundation for forecasting patterns of ecosystem change due to shifts in climate and the impacts of commercial fishing. Because of unknown future technological advances, it is imprudent to predict future developments much beyond the span of a career, so with that in mind, we discuss some areas where advances are feasible within the coming decades.

30.1.1 A Brief History of Climate and Fisheries Studies: Where We Have Been

There have been three major approaches for scientists studying climate and fisheries: (1) small-scale field observations and laboratory experimentation, (2) large-scale analysis and modeling of survey and commercial harvest data, and (3) development of theory. While these approaches are conducted at different scales and are often pursued independently, when they interface, significant advances occur. Several factors may serve as catalysts at the interface of scientific approaches (Fig. 30.1). The first catalyst is interdisciplinary coalescence and training (Wooster 1988). Individuals trained in more than one discipline communicate more effectively and often introduce new concepts and techniques to different branches of fisheries science. The second catalyst is the initiation of advances in science resulting from changes in marine policies, which directs public interest and the flow of resources for research. For example, considerable research has been generated by social pressure to stop overfishing and understand climate change. However, a change in economic and political pressure can also shift resources away from research, sometimes before answers are reached (Smith 1994). This occurred in the 1930–1940s when the declining economic market for fish and lack of interest by authorities ended the golden age of Norwegian fisheries research (Solhaug and Saetersdal 1972). The third catalyst is a shift in procedures, including methodology driven by technology (computing power, satellites, molecular biology) that opens new insights, and philosophy that results in new ways of viewing how science should be done. These catalysts accelerate paradigm shifts in research. Our brief review of the past

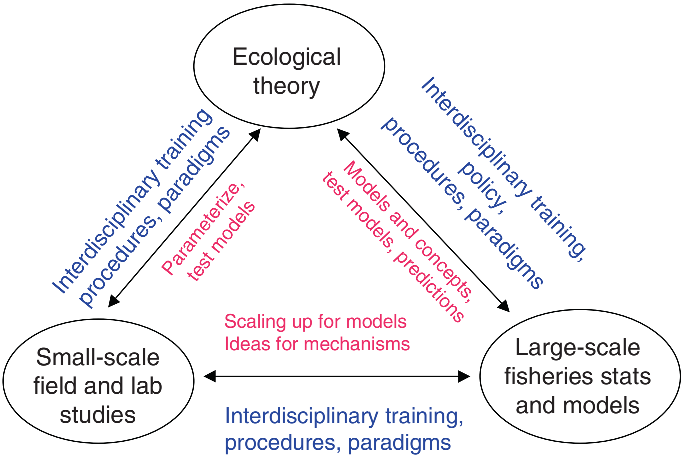

Fig. 30.1 Representation of three major approaches (circled corners) in fisheries science, with catalysts (blue letters) that stimulate interactions between approaches, and feedback mechanisms (red letters)

reveals that these catalysts have acted in concert to precipitate several new avenues for research.[1]

30.1.2 Climate and Fisheries: The Early Years, Setting the Stage

Early research on fisheries and climate variability focused on local and seasonal changes in availability to the fishery (Fig. 30.2). As early as 1832 a Swede named Nilsson reported that the collapse of the Bohlusan herring fishery was due to poor local conditions (Smith 1994). Later, A. Ljungman in 1880 attributed changes in the Bohsulan fishery to changes in weather and solar activity. Due to the importance of fisheries in the Norwegian economy, the modern era of fisheries research

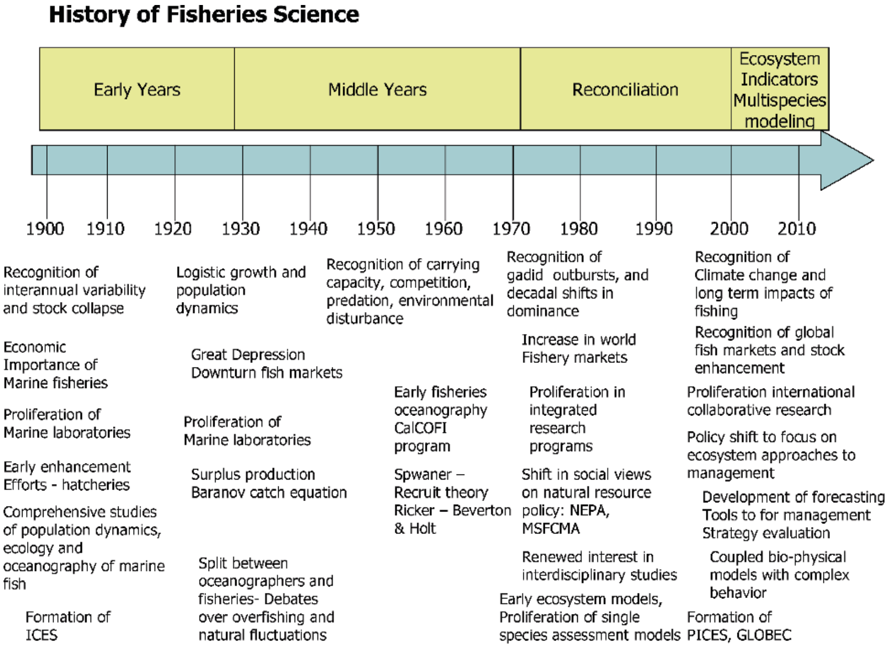

Fig. 30.2 Time line of major events influencing fisheries science (see text for more additional references)

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[1] We recognize that our brief review of the history of fisheries science will inevitably omit some of the classic papers written in the twentieth century. For example, although we cite mainly temperate and subarctic studies, we recognize that many major advancements in fisheries oceanography were accomplished by biologists studying reef fishes (e.g., Sale 1991). Our purpose was not to be comprehensive in our review but to demonstrate the events that resulted in the major advances in fisheries science with respect to climate impacts.

began in Norway in 1864 when the Norwegian government asked G.O. Sars to examine why catches of cod around the Lofoten Islands fluctuated (Smith 1994). Soon afterwards, a number of factors came together in the late nineteenth century to initiate a proliferation of marine laboratories and fisheries research programs not only in Norway, but in Russia, Scotland, Canada, England, Germany, Denmark, the Netherlands, and the United States. One of these factors, the HMS *Challenger* expedition in 1872–1876, clearly had an impact on emphasizing a more global view of marine biology and oceanography and set a precedent for scientific surveys (Kesteven 1972).

In the United States the US Fish Commission was founded in 1871 to address industry conflicts, largely due to the efforts of Spencer Baird (Smith 1994). Partly because of public antagonism towards legislation that regulated harvests, augmentation programs were developed to offset fisheries harvests. Thus, in the 1880s popular programs to propagate cod were started in the United States, Norway, and Canada to enhance cod's declining abundance in the sea. Up to 2.5 billion yolk-sac cod larvae were released annually by American hatcheries and several hundred million were released by Norwegians (Solemdal et al. 1984).

Interest in studying the effectiveness of hatchery releases in enhancing natural populations partly motivated scientific approaches to studying larval survival in the ocean. But as well, large-scale field programs to study fish eggs and larvae in relation to ocean conditions emerged from an interest in the mechanisms behind natural fluctuations in fish populations (Kendall and Duker 1998). In particular, the young Norwegian scientist Johan Hjort along with other Scandinavians, notably C.G. Petersen, F. Nansen, G. Ekman, M. Knudsen, B. Helland-Hansen, and O. Petterson (Solemdal et al. 1984; Smith 1994) initiated studies on hydrographic and fisheries interactions. Around the same time, Baird conceived a research program involving comprehensive studies of population dynamics, ecology, and oceanography of marine fishes (Kendall and Duker 1998). Many of the concepts underlying modern fisheries research came to be developed during this time. These advances were made possible by parallel landmark developments, including the demonstration of racial strains, or local stocks, of herring by Heincke in 1875, and methods for quantitative sampling of plankton by Hensen in the 1880s. A relatively unheralded Danish scientist named C.G.J. Petersen developed techniques for tagging fish, introduced the concept of density dependence in fisheries, and refined methods of demonstrating yearly cohorts. The foundation of the plankton cycle in the ocean was worked out by Hensen and collaborators in Kiel in 1875–1920. Around 1909, Fisheries Oceanography studies started in Japan, and by 1919 Kitihara established that fish aggregate around frontal zones (Uda 1972). These developments contributed to a series of classic and enduring papers by Hjort (1914, 1926), which demonstrated that major fisheries fluctuations were due to irregularities in recruitment of year classes, with the cause of such irregularities occurring early in the life history, which was rooted in hydrographic and planktonic conditions. He also touched on contemporary issues including migrations and mixing of stocks, age and growth, larval drift, variations of quality such as lipid content, and recruitment variations.

The early legacy of ICES, international cooperation in research, information and data exchange, and coordinated transboundary management has been critical to successful fisheries management, and the focus of ICES has been followed in the Pacific by the North Pacific Marine Science Organization (PICES). However, ICES also created barriers to the integration of fisheries and oceanography. After the initial meeting in 1902, two committees were formed: a hydrographic committee and a biological program committee. The biological component was further split into a tagging subcommittee and an overfishing subcommittee. Hjort and his colleagues on the tagging committee became involved in studying fisheries fluctuations due to natural conditions. In our opinion the schism between climate variability and overfishing proponents officially started about then and has been a chasm ever since that has been difficult to bridge.

30.1.3 Climate and Fisheries: The Middle Years

Between the two World Wars and during the Great Depression the economic market for fish products took a downturn and European research on marine fisheries fluctuations reached a low point due to lack of social pressure to capture the interest of politicians (Fig. 30.2). Fisheries research took a new turn that lasted through the 1970s, which focused on developing of the theory of sustainable harvest levels and fisheries harvest models. During this period, scientific investigations by fisheries biologists, mathematical ecologists, and oceanographers developed in parallel rather than in concert.

By the middle of the twentieth century, ecologists had published papers on the importance of carrying capacity, competition for limited resources, the role of predation, and environmental disturbance (Lotka 1925; Volterra 1926; Nicholson 1933; Andrewartha and Birch 1954; MacArthur and Wilson 1967). The well-known concepts of logistic growth (Von Bertalanffy 1938) and allometry were utilized in early models of fish populations. Biologists recognized the importance of considering different sources of mortality when estimating catch (Baranov 1918). During this period, marine fish populations were modeled using surplus production models (Graham 1935; Schaefer 1954; Fox 1970) and Leslie matrix applications that allowed biologists to track the influence of fishing and natural mortality on the whole population. In fact, with the availability of readily available information on year-class strength from fisheries statistics, correlative approaches between fisheries and climate have proliferated from the 1930s to the present day. One major breakthrough was realized through the coalescence of ecological theory and fish population dynamics modeling. Ricker (1954) and Beverton and Holt (1957) adapted the theoretical concepts of carrying capacity, competition, predation, and environmental disturbance into well-known governing equations for the relationship between spawners and recruitment to commercial fisheries.

While most fisheries research was on overfishing to the exclusion of climate as a forcing function, there were bright spots in fisheries oceanography. Reasoning that most of the variability occurred at young life stages, interdisciplinary research teams studied the impact of environmental factors on survival of eggs and larvae

(Sette 1943; Walford 1938). Predation, competition, and the direct and indirect impact of environmental forcing on recruitment and spawning, as well as the impact of fishing on spawning stock biomass and early life history were factors considered in these investigations. An early example of a fisheries oceanography-based program is the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program in the northeast Pacific Ocean. This program has its historical roots in the inspiration of D.S. Jordan and W.F. Thompson to study linkages of natural fluctuations in fisheries with overfishing, and after the collapse of the California sardine the program built on the strengths of scientists at the Scripps Institution of Oceanography, the California Department of Fish and Game, and the National Marine Fisheries Service.

Great debates concerning the role of overfishing versus natural fluctuations were repeated over different stocks in different areas of the world. Among the most famous were the Thompson-Burkenroad debates of the late 1940s (Thompson and Bell 1934; Thompson 1950; Burkenroad 1951).

30.1.4 Climate Variability and Fisheries: A Period of Reconciliation

Several key findings put the climate and fisheries topic back on the menu in the latter part of the twentieth century (Fig. 30.2). The Russell cycle described a 60-year cycle of plankton and fish abundance related to warming and cooling trends in the English Channel (Russell et al. 1971). The dramatic environmental effect of the 1958–1959 El Nino event in the Pacific and collapse of the world's largest fishery, the Peruvian achovetta, were impossible to ignore (Barber et al. 1985). The publication of a landmark paper by Andrew Soutar showed that dramatic large fluctuations occurred in fish populations prior to industrial fisheries (Soutar and Isaacs 1974). Finally, in an influential treatise, Cushing (1975) hypothesized that patterns of fish production were linked to multiple factors including that match–mismatch of the seasonal production cycle and readiness of larvae to feed, larval growth, density-dependence, and the temporal and spatial overlap of predators. By the 1980s, the pioneering concepts of Wooster (1961) and others gave acceptance to fisheries oceanography as a new interdisciplinary research field.

Systematic surveys and time trends in catches revealed that marked outbursts or abrupt collapses in fish stocks occurred throughout the world (Murphy 1961; Skud 1982; Cushing 1984). These findings and a better economic picture renewed interest in process-oriented research. Scientists endeavored to understand the mechanisms underlying these shifts and several hypotheses were resurrected from the past as a result. Among these, advances in physical oceanographic tools resulted in hypotheses regarding the role of interannual variation in wind on ocean currents and the influence of these factors on the transport of larvae to suitable nursery grounds (Nelson et al. 1977; Parrish et al. 1981). Sinclair's (1988) member vagrant hypothesis linked the concepts of larval drift, fidelity to spawning location, and subpopulation structure. New teams of scientists were formed to study recruitment processes (e.g., the MARMAP[2] program in the northwest Atlantic Ocean, Georges Bank GLOBEC[3], W.C. Leggett's research team at MacGill University, Canada's OPEN[4] and NOAA's[5] FOCI[6] programs). Interdisciplinary research teams were not limited to the field, a parallel effort occurred in the evolution of laboratory studies where chemists, physiologists, and behavioral ecologists conducted studies on environmental factors influencing predation and feeding. These studies fostered the development of biochemical indicators for evaluation of fish condition, diet, and predation. Innovative combinations of lab experiments applied to field observations have given insight to survival processes (Blaxter and Hempel 1963; Lasker 1981; Houde 1989). Discovery of increments deposited daily on larval otoliths also provided a major new tool for these studies (Campana and Neilson 1985). Likewise, interdisciplinary collaborations have resulted in the development and application of advanced laboratory techniques to assess stock structure including otolith chemistry and molecular genetics. Physiological studies have provided information on the environmental requirements of fishes, and behavioral studies have provided critical information on the complexity of responses of fishes to environmental conditions.

Theoretical breakthroughs in fisheries science also resulted from the application of ecological theory to the study of exploited aquatic or marine systems. Studies in theoretical ecology provided the foundation for cross-disciplinary research in the study of climate impacts on fish population dynamics. Concepts of trophic cascades (Hairston et al. 1960) and keystone species (Paine 1969) had also taken root in fisheries ecology (e.g., Frank et al. 2005; Kawasaki 1993). In the 1980s, Connell's (1985) work in supply side ecology led to new interest in recruitment, particularly in reef fish systems. In the 1990s, theoretical ecologists focused attention on the role of complexity and hierarchical organization and the role of shifting spatial dimensions in ecosystems (Odum 1992; Levin 1992), which have led to similar studies in marine systems (e.g., Bailey et al. 2005). Pioneering work in population genetics (Wright 1943) expanded into fisheries genetics (e.g., Doherty et al. 1995). Ecologists have explored the role of stock structure, or metapopulation structure, and species diversity as attributes of ecosystems that contribute to overall population stability (Hanski 1991) and likewise fisheries has followed this lead (e.g., Smedbol and Wroblewski 2002). Chesson (1984) introduced the concept of longevity and the storage effect where the reproductive potential of a population can be stored in a few strong year classes. The importance of this concept was recognized as a strategy for preserving reproductive potential in marine organisms when conditions conducive to recruitment success are rare (Leaman and Beamish 1984; Beamish et al. 2006).

In the 1960s and 1970s ecologists endeavored to describe the functional relationships governing species interactions. These concepts were adapted for use in early computer-generated simulation models. Holling (1965) introduced functions to represent interactions of predators to increasing prey density. These early computer

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[2] Marine Resources Monitoring Assessment and Prediction.

[3] Global Ocean Ecosystem Dynamics.

[4] Open Production Enhancement Network.

[5] National Oceanic and Atmospheric Administration.

[6] Fisheries Oceanographic Coordinated Investigations.

simulations included functional relationships between predators and prey and the role of the environment in mediating these relationships (Anderson and Ursin 1977; Laevastu and Larkins 1981).

In the 1970s, Pope (1972) introduced a statistical modeling approach founded on Baranov's (1926) catch equations that tracked the impact of fishing on the individual cohorts within the population. The widespread application of cohort analysis to commercial fish population provided a technique to reconstruct time trends in recruitment, which resulted in numerous correlative studies linking environment and distribution.

In the 1990s, individual-based models (IBMs) provided a basis for tracking environmental forcing on survival during the early life history at fine spatial and temporal scales (Rose et al. 1993; Hermann et al. 1996). In some regions, scientists have coupled these two modeling approaches into a complex marine ecosystem model (e.g., the European Regional Seas Ecosystem Model; Baretta et al. 1995). As our knowledge of the ocean has expanded beyond seasonal effects on local availability, so has the horizon for research expanded beyond the local and seasonal scales of global fisheries dynamics. Fisheries scientists discovered decadal scale variations in fish populations resulting in renewed interest in the mechanisms linking ocean conditions and fish production (Hollowed and Wooster 1992; Beamish and Bullion 1993; Omori and Kawasaki 1995; Hollowed et al. 2001; Steele 2004; Cury and Shannon 2004). At the same time fisheries scientists are realizing that multiple factors including the environment and overfishing interact to cause fluctuations in fish stocks (Fogarty et al. 1991; Stenseth et al. 1999; Rothschild 2007).

Major breakthroughs in fisheries also occurred in response to shifts in societal views regarding the use of natural resources. In the 1970s, fisheries scientists began to recognize the interdependence of ecology, production, and management of our Nation's fisheries (McEvoy 1996; Pascoe 2006). This recognition led to a more formal articulation of the goals of society's use of natural resources (Sanchirico and Hanna 2004). In the United States and Canada, these shifts resulted in increased public demand for environment-friendly policies. The growing scientific evidence of human impacts on managed ecosystems, and subsequent public awareness of these impacts, prompted the US Government to pass the National Environmental Policy Act (NEPA), the Marine Mammal Protection Act, the Fisheries Conservation and Management Act, and the Clean Water Act in the 1970s. These acts established limits to human impacts on marine ecosystems. The new laws challenged fisheries biologists and population dynamics modelers to work together to define limits of impact for use in management of marine resources (Fluharty 2005).

With the passage of the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) in 1996, scientists were faced with defining concepts like sustainability and overfishing (Restrepo 1999). As a result, with all their flaws and deficiencies the concepts central to depicting population growth used in the 1950s were resurrected to define targets such as maximum sustainable yield (MSY) and the biomass associated with MSY (B_{MSY}), and limits such as the fishing mortality associated with the overfishing level (F_{OFL}). Armed with these biological reference points management measures were designed and adopted to prevent overfishing and rebuild depleted stocks (Mace 2001). The emphasis on stock rebuilding and evaluation of the performance of management strategies relative to reference points lead to a renewed interest in simulation modeling. A simulation modeling approach was introduced to evaluate the performance of management strategies when assessed using uncertain observations and variable climate conditions (management strategy evaluations [MSE]; De la Mare, 1996).

At the end of the twentieth century, fisheries scientists and policy makers emerged from a decade of research designed to revise harvest polices to prevent overfishing and rebuild overfished stocks, to refocus their attention on developing tools to forecast the long-term implications of fishing on marine ecosystems (Ecosystem Principles Advisory Panel 1999; DeMaster et al. 2006; Arkema et al. 2006). This shift in focus called for the development of ecosystem approaches to management (EAM) and renewed effort to identify the biological and physical mechanisms underlying fish interactions, distribution and production, and the role of fishing on these processes. At around the same time, a growing awareness of the impact of human-derived changes in climate that are likely to impact physical properties of the ocean (IPCC 2007), ocean acidity, and sea ice extent (Overland and Wang 2007) has led to an elevation of the priority of climate–fisheries interactions. We see this shift in focus as the harbinger of future directions of fisheries science in the coming decades and the catalyst for coalescence of fisheries scientists focused on a common research problem.

30.2 The Next Generation of Fisheries Science

While there has been considerable progress over the last century there remain many opportunities for research in the coming decades. We identify four major research themes in climate–fisheries where we expect progress, including: (1) expansion of theory to include complex processes in recruitment, thereby enabling scientists to better forecast impacts of changing climate and fishing; (2) enhanced recognition of the spatial scale of key processes and the role of climate in adjusting these processes; (3) increased emphasis on behavioral and foraging responses of adult and juvenile fishes to changes in local environmental conditions; and (4) development of modeling tools to assess the performance of management strategies under changing environmental conditions. Research in these four areas will assist efforts to define the role of climate change and interaction with fishing on marine ecosystems.

30.2.1 Complexity in Recruitment

Some argue that the climate–recruitment interactions are too complex to effectively contribute to management of stocks, and correlations of recruitment with environmental factors always fall apart eventually. We perceive recruitment as a complex process (rather than a “problem” with a simple answer), and such a view opens understanding that is critical to effective management of stocks. For example, advocates of ecosystem approaches to management (EAM) hope to forecast performance of management strategies under future states of nature. To perform this analysis, scientists will need to develop realistic forecasts of fish production, distribution, and market demands and constraints. Predicting ecosystem responses to environmental disturbance and fishing requires the integration of complex processes influencing organisms over different time and space scales.

There is no simple factor that is going to dominate recruitment, and factors will shift in importance over space and time as biological players, environmental regimes, and history change. Interacting factors influence important parameters in recruitment, such as larval feeding (Porter et al. 2005). In the future, development of statistical models can help with understanding the interactions between conditions (e.g., Ciannelli et al. 2004). Enhanced understanding of processes, comparative knowledge of population interactions under different conditions, and methods of scaling up to metapopulations should be productive avenues of research. We envision that combining the probabilistic nature of the many lower scale-level interacting factors with the different types of constraining and boundary or higher scale-level factors will lead to better forecasting models. These can be linked to real-time information on current recruitment status (such as current juvenile abundance) and combined with multispecies models with contemporary estimates of spatial distribution and interactions to better define the arc of a year class while continually updating and refining predictions of its recruitment level (Fig. 30.3).

There are many questions to confront in the future. How much do we need to know to forecast and how far ahead? In the early 1900s, scientists were already thinking about forecasts, but believed definitive predictions were premature (Hjort 1914, p. 227). Sette was making formal predictions of the Atlantic mackerel fishery based on incoming year classes as early as 1928 (Smith 1994). But are short-term forecasts and correlations good enough? What is the appropriate scale and how much do we need to know about fine-scale processes, such as larval behavior? With the growing concerns regarding the long-term implications of climate change on marine ecosystems, we expect that the required time frame for forecasting will be extended to decades. We expect that as fisheries scientists shift their focus from prevention of overfishing to assessing the performance of management strategies relative to benchmarks of ecosystem status under different climate scenarios (Fig. 30.2). This shift in focus will increase the need for a mechanistic understanding of processes underlying recruitment to enable scientists to forecast fish reproductive success under different states of nature.

As in other scientific disciplines, we expect that there will be continued debate regarding whether the merits of holistic (e.g., correlative) or reductionist (e.g., individual based) approaches are best. A criticism of a holistic approach is that there is little confidence without understanding mechanisms. A criticism of the reductionist approach is that while it leads to understanding mechanisms, it also can lead down a narrow alley, sometimes without a good perspective of how this path fits into the bigger roadmap. On the other hand, having detailed mechanistic

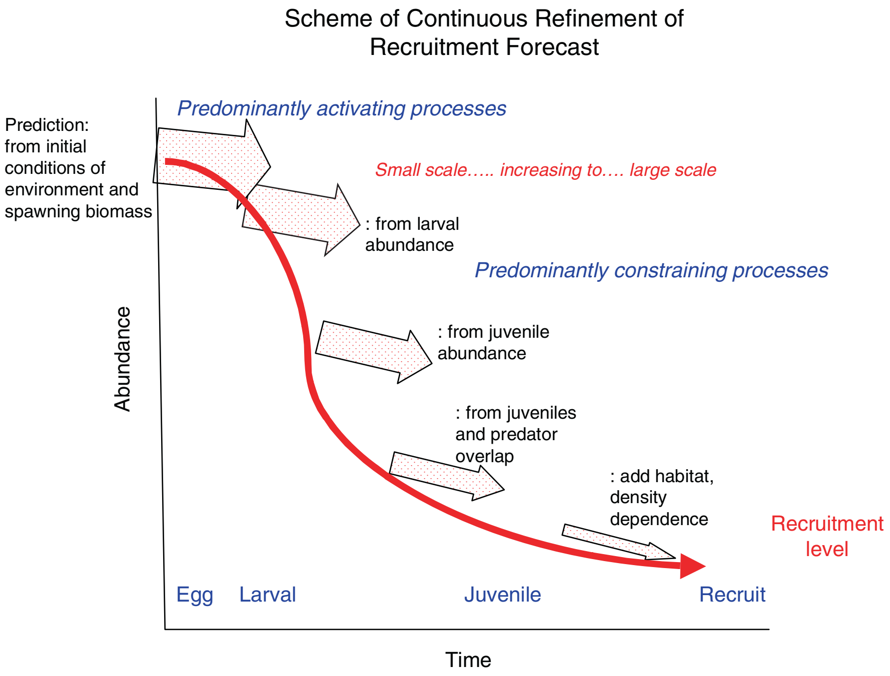

Fig. 30.3 Representation of a scheme for forecasting recruitment, continually refining the forecast with new information on the year class as it develops. The direction of the patterned block arrows reflects the accuracy relative to the true recruitment trajectory (red line) and the width of the block represents precision of the forecast at each stage. We envision a first prediction based on spawning biomass, environmental conditions, and possibly regime state. The forecast gets refined with information on larval and juvenile abundances, abundance and overlap of predators, density-dependence, and habitat availability

knowledge presents far greater opportunities for engineering solutions, in our case a forecast model. We expect that the greatest discoveries will be made through the development of techniques that scale local responses to population-scale events. For example, physiologists have gained great understanding of metabolic pathways, but it takes a more holistic approach to understand what goes wrong in a cancer cell and how to engineer a cure, the objective of integrated systems biology models. In parallel, we have learned much about mechanisms and processes like density-dependence, dispersal, larval feeding, and predation, but an integrated approach is needed to understand how these processes interact to shape a year class. As noted by Levin and Pacala (1997), fisheries scientists should also explore the possibility that there are ecological principles that might govern reproductive potential of marine fish. For example, landscape limits on abundance and recruitment by the amount of available habitat (Rijnsdorp et al. 1992; Bailey et al. 2005), and emergent scaling and power laws (Marquet et al. 2005; Taylor 1961) could be utilized in spatially explicit simulation models.

30.2.2 Spatial Ecology

In the next decade, fisheries biologists are likely to make progress understanding the mechanisms underlying the role of oceanography in governing the boundaries of suitable habitat, and the role of varying habitat volumes on competition between species for limited resources, and the spatial overlap of predators and prey. Fisheries biologists have recognized the role of stock density on habitat use (MacCall 1990). Recent studies demonstrate that shifts in ocean conditions alter the distribution and volume of pelagic ocean habitats and the spatial distribution of suitable habitat and partitioning between competing species (Rooper et al. 2006; Agostini et al. 2006; Hollowed et al. 2007), as well as how changes in the seascape influence predator–prey interactions (Ciannelli and Bailey 2005). Next-generation fisheries forecasts must address the role of climate on the quality and quantity of suitable habitat and its influence on the distribution and abundance of predators and prey. To accomplish this goal, fisheries scientists will need to study landscape effects such as corridors, connectivity, and patch structure and how spatial variation affects ecological processes. In these studies there are combined influences of a fixed landscape, such as bathymetry, coastline morphology and geology, and labile components such as currents and fronts, to form the seascape.

Enhanced near-synoptic sampling of the three-dimensional properties of ocean habitats on a seasonal basis is required to adequately monitor the role of environmental disturbance on the quantity and use of ocean habitats by marine fish and shellfish. We anticipate that progress in data collection will come from technological innovations coupled with data collection partnerships between commercial and recreational fishers, universities, and state and federal agencies responsible for stock assessments. The US National Integrated Ocean Observing System and its regional representatives provide the foundation for storing and distributing information obtained through the partnership (http://www.ocean.us/what_is_ioos). What is currently lacking is the mechanism to coordinate, fund, and standardize the collection of information needed to utilize ships of opportunity as platforms for ocean monitoring. Processing and analyzing the wealth of data also requires considerable resources and development.

Along with environmental monitoring, parallel effort is needed to monitor seasonal patterns of habitat use and the association between fish and their habitats. Meeting this challenge will require studies focused on behavioral ecology. Enhanced research on fish movement, and factors influencing foraging responses will be productive. Technological advances in acoustic tags, archival tags, and tag deployment are likely to continue and we expect that future biologists will be able to record fish movements in many regions of the northern hemisphere (Sheridan et al. 2007).

Another aspect of biocomplexity and spatial ecology is stock structure (Hilborn et al. 2003). Genetic stock structure implies little movement between geographically separated populations, whereas ecological metapopulation structure, where there is potential of movement to the degree of affecting demographic rates, is an adaptation that contributes to overall population stability (Hanski 1991). Climate effects on the interaction of landscape, fish movement, and population structure are important topics of future research. Population structure adds great complexity to the management of fisheries and sometimes managers often do not want to hear that there is fine-scale structure in their populations, but when multiple stocks are managed as one, vulnerable populations are in danger of overexploitation (Fu and Faning 2004). Local adaptation of different populations to environmental conditions and movement between populations are key issues in the interaction of stock structure and population dynamics.

30.2.3 Fisheries Interactions and Local Ecology

As fisheries scientists strive to develop sufficient understanding of the ecosystem to model the environmental and economic trade-offs associated with fishing, there will be an increased demand for improved understanding of the factors governing species co-existence in a variable environment. There will be a need for new types of field experiments designed to assess the foraging response of fish to changing habitat conditions and to predict how these changes will influence competition and predation. One approach is to establish a network of focused field locations for detailed behavioral studies. Scientists can scale up findings from these local regions to inform whole ecosystem models. These focused sites should build on the Before After Control Impact (BACI) framework to utilize the comparative approach for understanding fish behavioral responses to different types of environmental disturbance (Smith et al. 1993). Wilson et al. (2003) provide an example of this type of study where scientists attempted to utilize the comparative approach to assess the response of fish to fishing.

Our current understanding of food–web interactions, life-history strategies, and trophic effects of fisheries is based primarily on large-scale analyses and models with relatively little consideration of the explicit effects of spatial variability (e.g., Aydin 2004; Hollowed et al. 2000; Christensen and Walters 2004). While the development of multispecies and whole ecosystem models represents advancements in fisheries modeling, these models rely on extremely simple interaction terms between predator and prey. While these parameterizations may be adequate for evaluating energy pathways in food webs, they fail to address the complex issues of behavioral responses of predator and prey (schooling), competition and resource limitation, and environmental disturbance (Walters and Kitchell 2001; Bakun 2001). Patterns of interaction between species (e.g., predator–prey), and the strength of these interactions are mediated by behavior, abundance of alternative predators and prey, and environmental disturbance (Chesson 2000; Rice 2001). New research programs are needed to address these deficiencies.

Advances in our understanding of foraging behavior will also require careful review of the spatial and temporal scales of the interaction. Species interactions involve complex processes between climate, predators, and prey that occur on short time scales and small space scales. Fisheries scientists are beginning to recognize these complex processes. For example, Fauchald et al. (2006) found evidence that schooling fish migrations were influenced by the age structure, and the density of the school relative to available prey. Next-generation studies will focus on the role of climate in determining these interrelated factors. There may be critical foraging interactions that happen at local scales, particularly for central place foragers, or at foraging hotspots (Croll et al. 1998). Behavioral responses to predator and prey densities may reveal new functional interactions between species. Walters and Kitchell (2001) hypothesize that juvenile trophic interactions and behavior at local scales can cause depensatory recruitment dynamics in target species. They further suggest that we study juvenile survival rates and recruitment performance, abundance trends of potential competitors in juvenile rearing areas, and diet compositions of juveniles and competitors. In addition, it is important to assess the spatial and temporal dynamics of juvenile foraging behavior (i.e., determine the dimensions of the "foraging arena"). These types of localized process-oriented studies of fish behavior are examples of the research envisioned by the initiative described here.

30.2.4 Modeling Tools to Integrate

In the future, there will be increased demand for models that accurately assess the economic and ecological trade-offs of natural resource use. How we manage our fisheries and how we view the impact of environmental changes like climate effects on fisheries is bound by our concept of how ecosystems are organized. Is it hopelessly complex and chaotic, or ordered and hierarchical? One approach to understand how ecosystems work is a "top-down" modeling approach, which in the vernacular of systems biology is hypothesis-driven, thereby making a model of how we think the system works and comparing it to the data. Another approach, again in the terminology of systems biology is a "bottom-up" approach, which combines as much information that we know about the system as possible and then try to reconstruct it in a grand ecosystems model. Probably in the long run, both approaches are needed in a push–pull dynamical interaction to craft the most predictive description.

Four-model modifications could be incorporated into existing models in the near future. First, current individual-based models often lack the validation that is applied in stock assessments. Analysts need to revise coupled biophysical models to enable them to tune parameters governing fish responses to their environment to field observations in a manner similar to stock assessment procedures. To achieve this, long-term commitments to egg, larval, and juvenile surveys will be required. We expect that technological developments will enable scientists to collect many observations through remote sensing making this added requirement for data collection affordable. Adapting existing models to track observed and predicted outcomes will enable scientists to track uncertainty in biophysical interactions and to adapt interagency research efforts to target the most important processes governing recruitment.

Second, quantitative fisheries biologists could accelerate research on functional responses by empirical studies. This would be accomplished through a coordinated effort involving field and modeling exercises. Humston et al. (2004) provide a framework for conducting this type of analysis where different patterns of dispersion are generated by applying different foraging behaviors. Simulated larval distributions are statistically compared to observed data to select the foraging behavior that provides the best fit to the observations.

Third, if ocean habitat volumes could be measured, then an index of volume of habitat could be incorporated in spawner recruit relationships to account for interannually varying probability of intraspecific competition for resources (Iles and Beverton 2000).

In the long term, we see a future marked by innovations in spatial models that track the ontogeny of fish and shellfish in response to seasonal shifts in environmental conditions in three dimensions. Given the creativity of modelers and the technological advances occurring in computational power, new types of models will be developed and tested. Next-generation models should be able to forecast the impact of climate variability and fishing on fish and shellfish. Coupled biophysical models are currently used to track larval dispersal pathways, lower trophic-level production, and habitat characteristics (Ito et al. 2004, Baretta et al. 1995). We expect that the next generation of individual-based models will likely incorporate Bayesian treatment of parameter selection to identify what model formulation best fits the data.

Finally, we expect that lower trophic level and larval dispersal and survival models will be coupled to spatially explicit population dynamics models to track the full life cycle of marine fish and shellfish. In the short term, we expect that modelers will debate issues of scale and complexity in an attempt to resolve the trade-offs between simplifying the system to capture the main controlling processes influencing population dynamics (e.g., spawner–recruit relationships modified with ecosystem indices) and an attempt to capture biological realism by tracking individual behavior through the full life cycle. First-generation versions of these full life cycle, coupled biophysical, predator–prey models include ERSEM (Baretta et al. 1995) and NEMEROFISH (Megrey et al. 2007). Likewise, stock assessment biologists have been simulating future population dynamics for decades and several examples of techniques for incorporating environmental forcing in spawner–recruit relationships exist. We expect that the most useful model configuration will draw from both simulation approaches. Simulations of older life states can track complex behavioral responses of fish and shellfish to regional ocean conditions, fish density, predator abundance, and prey availability. Next-generation models should allow the user to assess the performance of different management strategies under different climate scenarios. This will require interactions between ecosystem modelers, climatologists, oceanographers, and stock assessment scientists. This interface will extend existing management strategy evaluation (MSE) techniques to include multispecies interactions to evaluate implications of harvest strategies under a variable climate.

Friedman (2005) predicts that as the world becomes more connected through the Internet the generation of new ideas will accelerate. We expect that the Internet will serve as a catalyst for rapid development of next-generation models in fisheries science as well. Some modelers are already providing software for common use by the fisheries community (Schunte et al. 2007). We expect that virtual laboratories will emerge where fisheries modelers from around the world will collaborate to develop techniques for incorporating biological complexity into ecosystem simulations. In the short term, international marine science organizations such as International GLOBEC, ICES, and PICES will continue to serve as catalysts for the exchange of information between scientists.

30.3 Conclusions

Our review of the evolution of scientific thought regarding climate and fisheries revealed that breakthroughs in thinking were often achieved through interdisciplinary research. Through the leadership of a few key individuals the barriers that once partitioned fisheries biologists and oceanographers have disappeared and fisheries oceanography is now an accepted field of study. While some barriers have fallen, there continues to be a need to merge the disciplines of fisheries management and fisheries science, and fisheries science and ecology. Mangel and Levin (2005) encourage the inclusion of ecology in the teaching of fisheries science. Quinn and Collie (2005) extend this recommendation to include some training in fisheries management to allow future scientists to recognize the difficulties facing managers as they attempt to balance the competing goals of resource conservation and use. In the context of climate and fisheries questions, training in oceanography, ecology, and management will be needed to develop scenarios that forecast changes in ocean conditions, the demand for fish, the constraints to the resource, and the responses of fish to these factors.

As we look to the future, we expect that major breakthroughs in recruitment studies will come from a better understanding of the concept of scale, and the properties that exist at the frontiers between scales (breaks). Such enhanced understanding includes the potential hierarchical ordering of scale. The interaction between individual processes and the organisms of interest and how those interactions lead to regulation and control of populations are key questions in population biology. Studies of cybernetics are needed to examine the processes of control and regulatory feedback, and whether the interactions of parts of the system result in self-organization. For that matter, are marine ecosystems self-organizing at all?

We envision a future where mathematical ecologists and modelers will develop forecasting tools to assess hypotheses regarding climate impacts on fishing. In the latter half of the twentieth century, fisheries biologists had sufficient data to recognize decadal patterns in fish production. These findings, and their potential impact on commercially exploited fish populations, resulted in the formation of interdisciplinary research teams to understand the processes underlying fish responses to climate shifts. These two events represent only part of the scientific method where a general hypothesis has been proposed based on retrospective studies and the hypothesis has been refined through field and laboratory research. The scientific method requires that we begin to test the hypothesis, and future fisheries scientists are likely to utilize a combination of field observations and modeling to make these tests. We see the shift to hypothesis testing as an evolution where models are used to predict fish responses to climate and these predictions are evaluated against observations. We anticipate that the collection of biological and physical observations will be enhanced through technological developments that allow underway sampling from ships of opportunity and remote sensing.

Our review also reveals the need for renewed interest in fish behavior. Throughout the twentieth century, fisheries scientists were primarily focused on estimating the abundance of fish stocks. This was a natural first step needed to ensure conservation of the resource. However, knowledge of fish behavior will be needed to address questions of ecosystem impacts of climate and fishing. We expect that this area of research will grow considerably in the next few decades. Major progress will likely come through the development of a few well-monitored sites where real-time or seasonal patterns of fish behavior will be monitored. These sites will serve as at-sea laboratories where conditions can be manipulated to assess the responses of fish to different environmental conditions.

We hope that this chapter, and volume in general, will be viewed as our prediction of future trends in the field of fisheries science. As the disciplines coalesce, we look forward to watching the outcome of our collective experiment in climate and fisheries.

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