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Ecosystem Status Report

For the Northeast U.S. Continental Shelf Large Marine Ecosystem

by the Ecosystem Assessment Program

Northeast Fisheries Science Center
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Ecosystem Status Report

For the Northeast U.S. Continental Shelf Large Marine Ecosystem

Ecosystem Assessment Program, Northeast Fisheries Science Center July 2009

Main Findings

The Northeast U.S. Continental Shelf Large Marine Ecosystem (NES LME) has undergone sustained perturbations due to environmental and anthropogenic impacts over the last four decades, resulting in fundamental changes in system structure.

Thermal conditions in the NES LME are changing due to warming of coastal and shelf waters and cooling in the northern end of the range. As a consequence, there has been a constriction of thermal habitats in the ecosystem, a northward shift in the distributions of some fish species and a shift to a warmer-water fish community.

Zooplankton community structure has also changed in concert with climate and physical processes acting over the North Atlantic Basin indicating the importance of remote forcing to the function and structure of this ecosystem

Important changes in some components of benthic communities, notably increased abundance of sea scallops and lobster are evident, reflecting changes in fishery management and/or ecological conditions.

The direct and indirect effects of species-selective harvesting patterns have also contributed to shifts fish community composition which is now dominated by small pelagic fishes and elasmobranch species (skates and small sharks) of low relative economic value.

The trajectory of regional human population size suggests that anthropogenic pressure in the ecosystem will continue to increase.

The Northeast U.S. Continental Shelf is classified as experiencing ecosystem overfishing according to published criteria for this designation, although improvement in the condition of several resource species has occurred and exploitation effects have been reduced for some system components over the last decade.

Contents

1 Introduction

The Northeast U.S. Continental Shelf Large Marine Ecosystem (NES LME) is a dynamic, highly productive, and intensively studied system providing a broad spectrum of ecosystem goods and services [1, 2]. This region, encompassing the continental shelf area between Cape Hatteras and the Gulf of Maine (Figure 1.1), spans approximately 250,000 km^2 and supports some of the highest revenue fisheries in the nation. The system has historically undergone profound changes due to very heavy exploitation by distant-water and domestic fishing fleets [3]. Further, the region has experienced changes in climate and physical forcing that have contributed to large-scale alteration in ecosystem structure and function. Projections of future climate change highlight the need to understand the effects of natural and anthropogenically driven perturbations to this system and to devise effective management and mitigation strategies in response to these changes.

In this report, we track changes in key indicators of climate, physical forcing, ecosystem dynamics, and the role of humans in this system. These indicators can be broadly classified into natural and anthropogenic ***drivers***, resulting ***pressures***, and ecosystem ***states*** (see ***Glossary***). Drivers are identified as forcing factors such as climate and

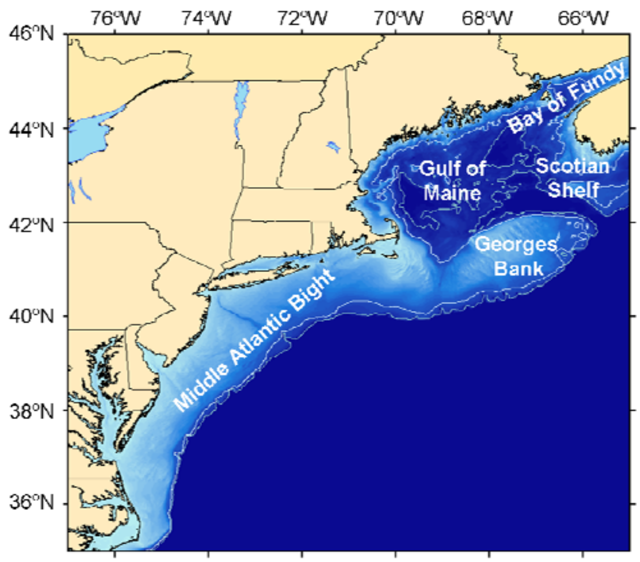

Figure 1.1 Map of study region on the Northeast continental shelf of the United States.

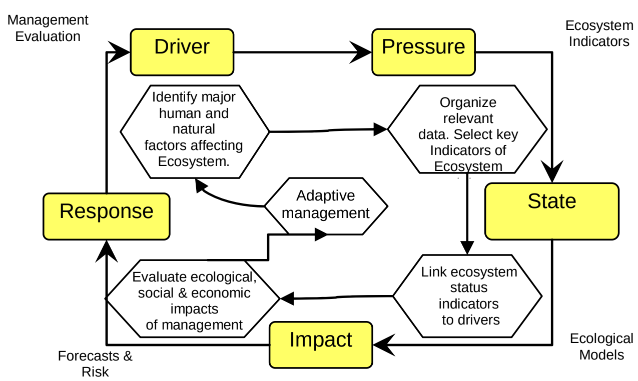

Figure 1.2 Driver-Pressure-State-Impact-Response sequence.

human population size underlying a constellation of pressures exerted on the system. These pressures include human-related impacts such as removal or degradation of living marine resources through harvesting, shipping, pollution, and impacts on the coastal zone such as habitat loss. Climate-related pressures include changes in atmospheric and oceanographic processes directly or indirectly affecting marine life. We distinguish external physical pressures representing large-scale ocean-atmospheric processes affecting this system from internal physical pressures as representing local or regional physical manifestations of these broader pressures. We then identify indicators of ecosystem state potentially affected by these drivers and associated pressures with a focus on holistic or integrative metrics of ecosystem condition. State variables include metrics such as the abundance of different species groups and measures of productivity.

Changes in ecological state variables can result in impacts on ecosystem services which in turn may require a management response (Figure 1.2). For example a driver such as changes in seafood demand, might result in increased fishing pressure to meet this demand, leading to a change in the abundance (state) of exploited species with an *impact* on the economic value of the catch. This would then be followed by a specified management response.

Our objective is to characterize changes in the system state variables in relation to these forcing mechanisms and to identify change points in system dynamics. An understanding of the inter-relationships between drivers, pressures and states is an essential prerequisite to moving toward an ecosystem approach to management.

2 Climate Forcing

Climate patterns over the North Atlantic are important drivers of oceanographic conditions and ecosystem states. Steadily increasing atmospheric carbon dioxide levels can not only affect climate on global and regional scales but alter critical aspects of ocean chemistry. Here, we describe the atmospheric forcing mechanisms related to climate in this region including large-scale atmospheric pressure systems, natural ocean temperature cycles in the North Atlantic, components of the large-scale circulation of the Atlantic Ocean, and issues related to ocean acidification.

North Atlantic Oscillation Index

Climate and weather over the North Atlantic are strongly influenced by the relative strengths of two large-scale atmospheric pressure cells -- the Icelandic Low and the Azores High [4]. As the relative strengths of these two pressure systems vary, characteristic patterns of temperature, precipitation, and wind fields are observed. An index of this dipole pattern has been developed based on the standardized difference in sea level pressure between Lisbon, Portugal and Reykjavík, Iceland in the winter (December-February; see ***Glossary*** for a description of methods used to create standardized indicators). This North Atlantic Oscillation (NAO) index has

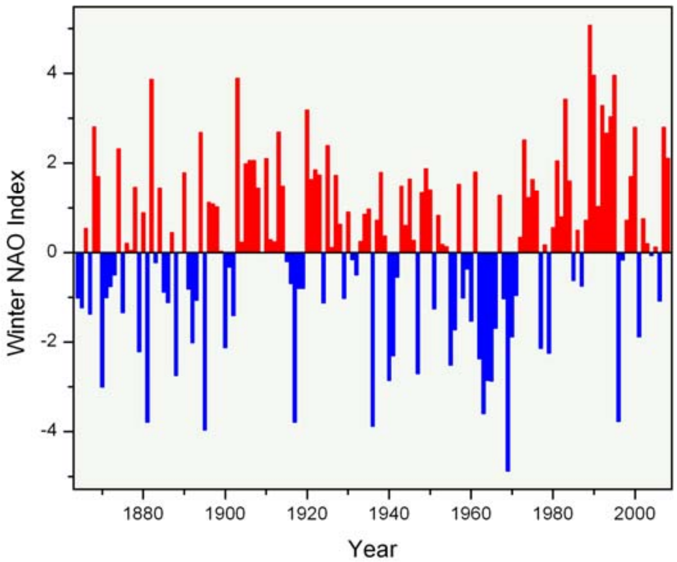

Figure 2.1 Trends in the winter North Atlantic Oscillation Index over the last century expressed as standardized anomalies.

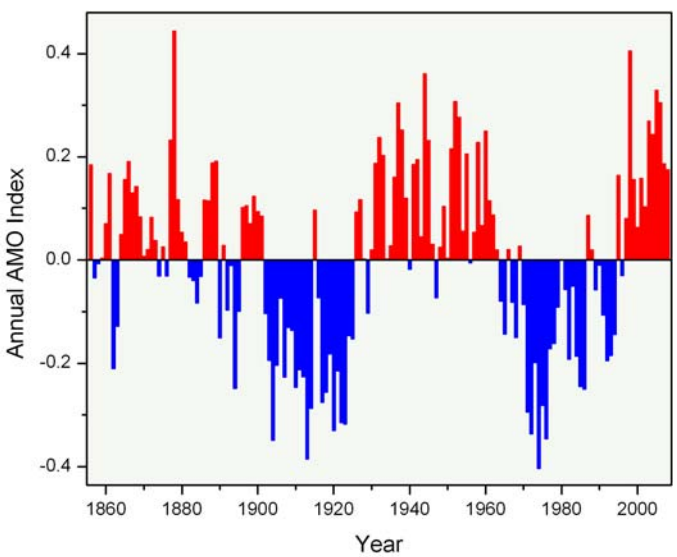

Figure 2.2 Trends in the Atlantic Multidecadal Oscillation Index expressed as standardized anomalies.

been related to key oceanographic and ecological processes in the North Atlantic basin [5].

When the NAO index is high (positive NAO state), the westerly winds shift northward and increase in strength. Additionally, there is an increase in precipitation over southeastern Canada, the eastern seaboard of the United States, and northwestern Europe. Water temperatures are cool off Labrador and northern Newfoundland, influencing the formation of Deep Labrador Slope water, but warm off the United States. Conversely, when the NAO index is low (negative NAO state), there is a southward shift and decrease in westerly winds, decreased storminess, and drier conditions over southeastern Canada, the eastern United States, and northwestern Europe. Water temperatures are warmer off Labrador and Newfoundland, but cooler off the eastern United States. Since 1972, the NAO has primarily been in a positive state (Figure 2.1), although notable short-term reversals to a negative state have been observed during this period. Changes in the NAO have been linked to changes in plankton community composition in the North Atlantic, reflecting changes in both the distribution and abundance of warm and cold-temperate species.

Atlantic Multidecadal Oscillation

Multidecadal patterns in sea surface temperature (SST) in the North Atlantic are represented by the Atlantic Multidecadal Oscillation (AMO) index. The AMO signal is based on spatial patterns in SST variability after removing the effects of anthropogenic forcing on temperature, revealing natural long term cycles in SST. The AMO is characterized by warm and cool phases [6] with periods of approximately 20-40 years. The AMO index is related to air temperatures and rainfall over North America and Europe and is associated with changes in the frequency of droughts in North America and the frequency of severe hurricane events. The AMO is thought to be related to the North Atlantic branch of the deep thermohaline circulation (for more see ***The Gulf Stream*** below) which is in turn directly related to dynamics of the Gulf Stream.

The AMO index shows a relatively cool period starting in the early 1960s, extending through the mid 1990s. Since 1997, the AMO has been in a warm phase (Figure 2.2). If past patterns continue to hold, the warm phase will potentially continue for the next several decades.

Carbon Dioxide Levels

Carbon dioxide (CO_2) emissions have increased rapidly from the inception of the industrial age as a result of burning of fossil fuels and other human activities (Fig. 2.3). The rate of addition of this greenhouse gas is an order of magnitude greater than any observed over the last million years [7]. This increase in emissions has led to increases in atmospheric CO_2, which holds important implications for oceans chemistry and the ecology of marine systems. Approximately 40% of emitted CO_2 has been absorbed by the ocean, buffering the effect on atmospheric levels but resulting in increases in

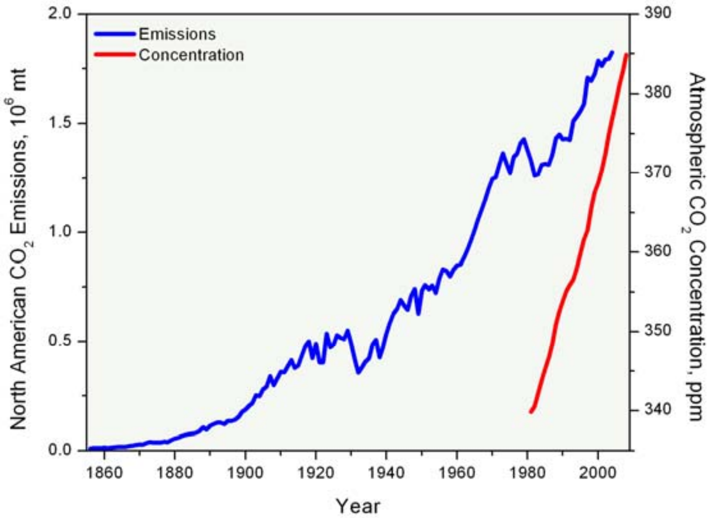

Figure 2.3 Trends in estimated North American CO_2 emission and globally averaged marine surface atmospheric CO_2 concentrations (annual mean; parts per million).

dissolved CO_2 and a concomitant decrease in pH of ocean waters. Dissolved CO_2 is critical in photosynthesis and primary production, fueling the base of marine food webs. Further, dissolved CO_2 is used to form tests, shells and otoliths of some marine phytoplankton and animals ranging from mollusks to fish.

Uptake of CO_2 has resulted in ocean acidification, potentially disrupting the ability of organisms to form calcium carbonate structures as noted above and affecting the biogeochemical cycles of many compounds. Chemical speciation of phosphorus, nitrogen, and other elements that are essential to ocean productivity is also affected by increasing acidification (see Glossary for further information on biogeochemical cycles and chemical speciation). Ocean acidification may also affect oxygen saturation levels, resulting in hypoxia in coastal systems. The full consequences of ocean acidification for living marine resources are not fully understood, but the ecological and economic impacts of decreasing pH levels are potentially very high.

Broad-scale time series of ocean pH measurements are not currently available to assess the effects of ocean acidification in this region. However, agreement between atmospheric CO_2 and dissolved CO_2 in ocean waters is good in regions where estimates of both are available. Globally averaged marine surface atmospheric CO_2 has increased 13.2% since 1981 (Figure 2.3).

3 Physical Pressures

The physical environment of the NES LME is impacted by climatic drivers in two ways. First, as noted above, climate oscillations (e.g., NAO, AMO) and long-term trends (e.g., warming, acidification) affect the larger North Atlantic environment. These large-scale environmental pressures affect the internal physical environment of the NES LME, but also external pressures at its boundaries. The external pressures include the Gulf Stream at the southern and offshore boundary, the Labrador Coastal current at the northern boundary, riverine discharges at the land boundary and winds at the atmospheric boundary. In addition to these external pressures, climate processes also affect the internal physical environment directly, including temperature, salinity, and stratification. These physical pressures in turn cause various ecosystem changes, which are discussed in sections 4-6.

The Gulf Stream

The Gulf Stream system is an important component of global climate and an important physical pressure on ecosystems in the North Atlantic. The Gulf Stream carries much of the heat from the tropics to higher latitudes and results in milder climates in Europe compared to similar latitudes in North America (for example Ireland vs. Labrador). This warm water then cools at high latitudes and sinks, forming a deep southward cold current that balances the northward warm surface current. This process of deep thermohaline circulation known as the Meridional Overturning Circulation and plays an important role in regulating the earth's climate.

Measuring the Meridional Overturning Circulation is difficult owing to the large-scale nature of the circulation system and the variability in the system at short-time scales. One long-term index is the volume transport of the Florida Current which has been measured from the early 1980s to the present [8]. The Florida Current is part of the southern portion of the Gulf Stream system and previous analyses of this data series found a negative relationship between the NAO and Florida Current transport. The suggested mechanism is that a positive

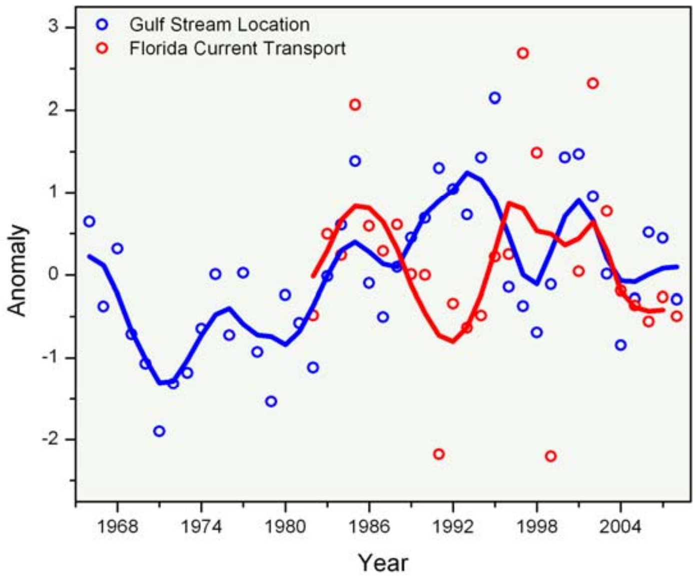

Figure 3.1 Trends in the Florida Current transport and Latitude of the Gulf Stream Index expressed as standardized anomalies.

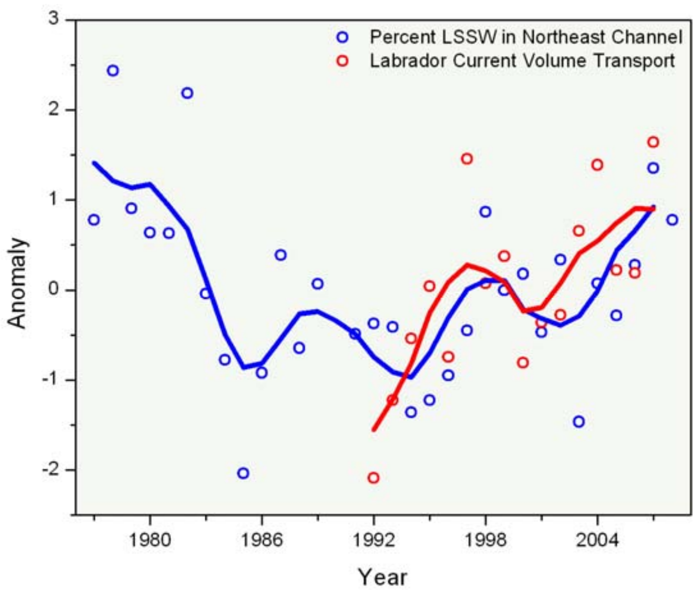

Figure 3.2 Trends in volume transport of the Labrador Current along southwest Newfoundland and the percent of Labrador Subarctic Slope Water in the Northeast Channel of the Gulf of Maine (as anomalies).

NAO results in wind patterns that reduce the volume transport of the Gulf Stream system one year later [9]. During the mid 1990s when the NAO was strongly positive, Florida Current transport was low (Figure 3.1). The link between Florida Current transport and the NAO has reduced in recent years indicating that the relationship is not simple and involves, other, yet to be defined factors.

Changes in NAO are also related to shifts in the position of the north wall of the Gulf Stream which in turn affects plankton community composition (see ***Climate Drivers, Physical Pressures, and Zooplankton Community Structure*** below). The latitude of the Gulf Stream north wall is positively related to the NAO index with a lag of approximately two years. Further examination of this relationship reveals that the correlation is dominated by the influence of the Icelandic low pressure system with the Azores High playing a relatively minor role [10]. Taylor et al. [11] subsequently showed that consideration of El Niňo-Southern Oscillation (ENSO) events further increases the predictability of the Gulf Stream position. An index of the position of the North Wall of the Gulf Stream available since 1966 reveals a shift in the early 1980s from low to high index values (Figure 3.1), reaching a peak in the mid-1990s, but characterized by subsequent multiyear reversals related to changes in the NAO index.

Labrador Slope Water

The Labrador Current flows southward from the Labrador Sea around Newfoundland and down the Nova Scotian shelf into the NES LME. This inflow is an important physical pressure and contributes to the volume of shelf water, the addition of nutrients, and the transport of plankton in the ecosystem. When the NAO is in a positive state, the volume transport of Labrador-Subarctic Slope Water (LSSW) is relatively low and does not penetrate much beyond the Gulf of St. Lawrence basin. When the NAO is in a negative state, volume transport of the Labrador Current is high and the LSSW penetrates to the Mid-Atlantic Bight, displacing Atlantic Temperate Slope Water (ATSW) further offshore [12]. During these low NAO conditions, the amount of LSSW entering the Gulf of Maine through the Northeast Channel is high.

The NAO index was low during the mid-1950s to early 1970s and was high during the late-1980s and 1990s. Over the last decade, there have been two major drops in the NAO index (late-1990s, mid-2000s). These drops in the NAO are associated with increases in the volume transport of the Labrador Current [13] and in the influx of LSSW into the Gulf of Maine at lags of approximately 12-18 months - the time it takes for the LSSW to reach the northeast shelf from northern Canadian waters (Figure 3.2). These changes hold important implications for the ecology of the region because the LSSW is colder and lower in critical nutrients than the ATSW.

River Flow

The amount of freshwater entering the ocean is another important pressure that responds to climatic drivers. Freshwater transports pollutants and nutrients to the continental shelf, which can affect coastal ecosystems. Nutrient over-enrichment – termed eutrophication – is a major problem in many coastal systems and has been linked to increased algal biomass, including harmful algae species, hypoxia/anoxia, and increased water turbidity. Increased freshwater run off can also affect coastal circulation through the influx of less dense water on the continental shelves. Most freshwater enters marine systems through rivers, rather than direct precipitation or runoff. River flow is tightly correlated across the northeastern region, resulting in coherent freshwater forcing along the entire coastal boundary (Figure 3.3). Complex long-term patterns have been identified. Tootle et al. [14] found interactions among different climate drivers affecting river flow; for example, the AMO and ENSO (El Niňo Southern Oscillation) signals combine to affect river flow in the southern part of the region. Earlier work by Visbeck et al. [15] found links between river flow in the northeast and NAO. A time series of river flow suggests the effect of multiple factors (Figure 3.3). Earlier in the time series (1950-1970) there appears to be one long cycle of 18-20 years. However, after the late-1970s, the period and magnitude of oscillations appeared to decrease. Recent years, 2005 and 2006 have had high stream flows.

Winds

Winds are an important pressure on shelf ecosystems. They act to mix the water column and drive horizontal currents. In the NES LME, winds are responsible for breaking down seasonal stratification in the fall and for causing reversals in the general southwestward surface currents during summer. The NOAA Pacific Fisheries Environmental Group maintains records of wind stress over the global ocean: wind stress is the force of the wind on the surface of the ocean. The greater the wind stress, the more horizontal mixing and the more force for driving currents. These long-term records indicate substantial inter-annual variability in wind stress (Figure 3.4). Over the past 10 years wind stress has been higher, but has recently decreased. Similarly,

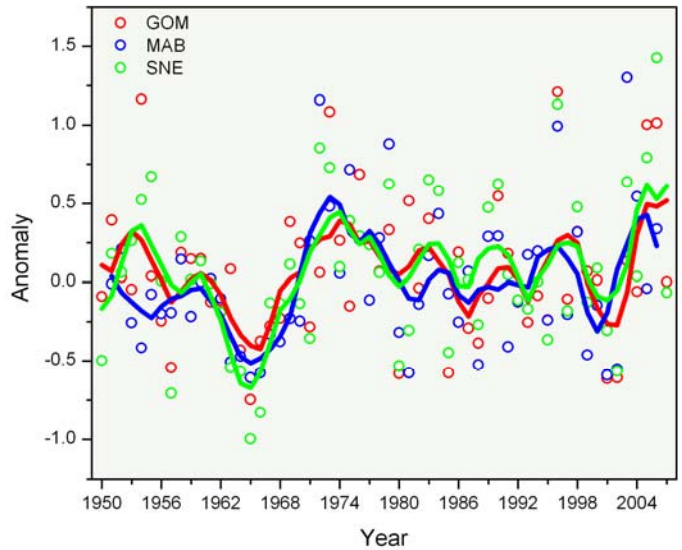

Figure 3.3 Trends in river flow from 25 rivers in the Mid-Atlantic, Southern New England and Gulf of Maine regions. Data presented as annual anomalies.

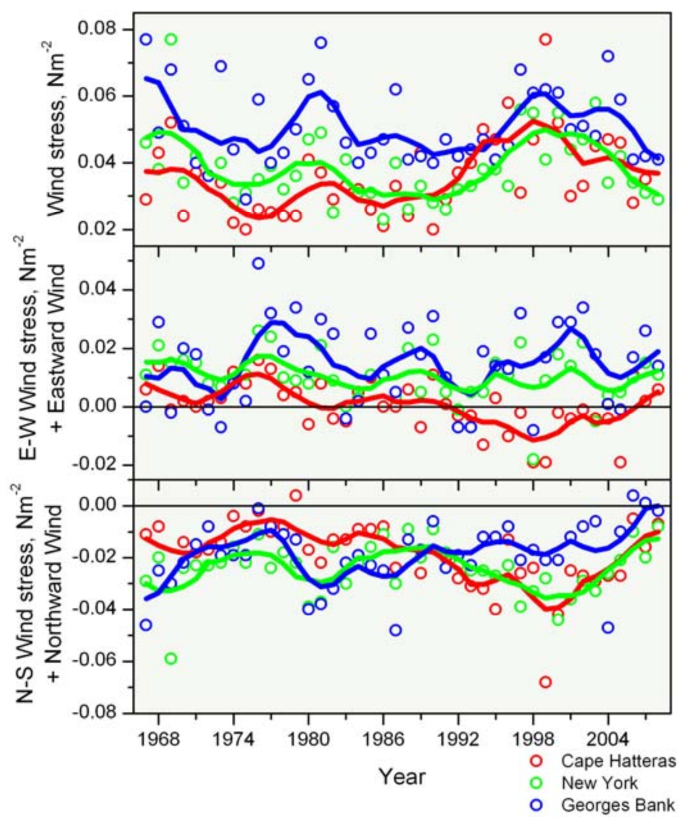

Figure 3.4 Annual averages of monthly mean wind stress. Top panel shows the magnitude of wind stress; middle panel shows the east-west component of wind stress, and bottom panel shows north-south component of wind stress.

the amount of eastward wind stress (wind force from west to east) is also variable. In the northern part of the system, wind stress has been primarily from the west, but has switched from the west to the east in the southern part of the system. Southward wind stress is

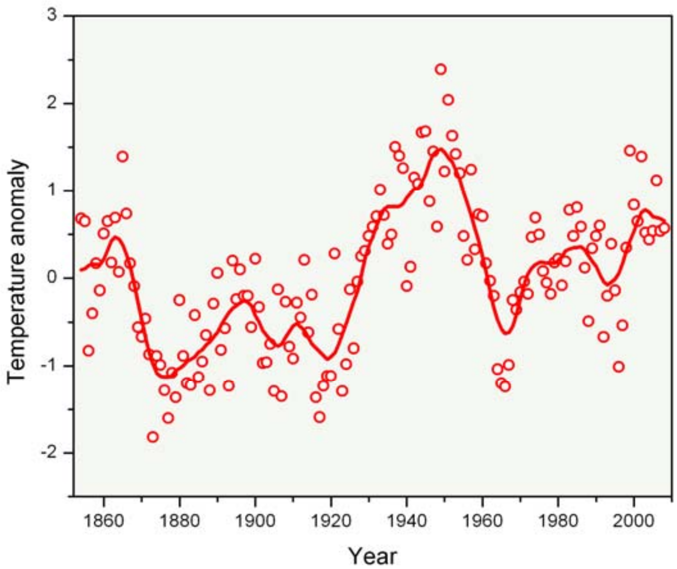

Figure 3.5 Annual mean sea surface temperature anomaly for the northeast U.S. continental shelf and adjacent waters from the ERSST v3 dataset.

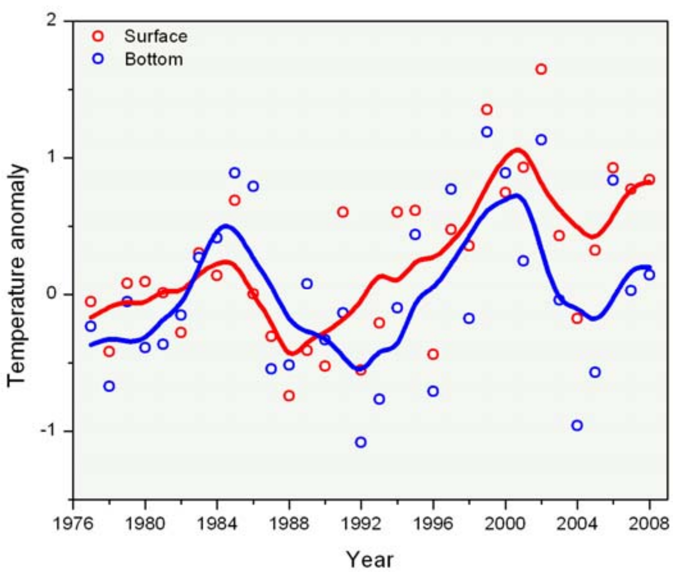

Figure 3.6 Mean surface (red) and bottom (blue) temperatures from the NEFSC survey programs. Anomalies show the mean value for 1977-1987 as 0, above the mean as positive and below the mean as negative (see Mountain [3])

also variable, but has increased in the south and decreased in the north. These changes in wind stress may be linked to the NAO, as well as a northward shift in the location of the jet stream [16]. Despite the uncertainty as to the cause of the inter-annual variability, these changes in wind will have impacts on local physical conditions and local marine resources.

Temperature

Temperature is one of the most important governing environmental factors for marine organisms. Marine organisms have minimum and maximum temperatures beyond which they cannot survive. Additionally, they have preferred temperature ranges. Within the bounds of these thermal limits, temperature influences many processes including metabolism, growth, consumption, and maturity. Thus, changes in temperature will have far-reaching impacts on species in the ecosystem and on the ecosystem itself. Temperature in the NES LME has varied substantially over the past 150 years (Figure 3.5). The late 1800s and early 1900s were the coolest in the 150 year record. This relatively cool period was followed by the warmest period in the record: 1945-1955. There was a rapid drop in temperatures through the 1960s followed by a steady increase to the present. Current temperatures are not as warm as experienced during the early 1950s, but they are within half-a-degree. Temperatures from specific coastal sites along the U.S. northeast coast follow this same pattern [17].

Temperatures measured on the continental shelf by the Northeast Fisheries Science Center (NEFSC) tell a slightly different story (Figure 3.6). These measurements have been made since the late 1970s, so the time series are shorter. Measurements from within 5 m of the surface exhibit an increase from the early 1980s to the present and mirror the temperature patterns described above. Temperatures from within 10 m of the bottom appear similar to surface temperatures, but there is no long-term trend. Rather, there is multi-decadal variation on the order of 2°C.

Satellite-derived maps of annual mean SST available since 1985 reveal interesting spatial patterns of annual differences in temperature. We've selected three years to illustrate different conditions on the shelf (expressed as deviations from the average for 1998-2008). Sea surface temperature was uniformly warm on the shelf in 1999 (Figure 3.7 upper). In contrast, cool shelfwide temperatures prevailed in 2004 relative to the average conditions during 1998-2008 (Figure 3.7 middle). In 2007, most of the shelf system was close to the average temperature except for southern Georges Bank and the Scotian Shelf which were colder than average (Figure 3.7 bottom). Other years also reveal regional differences in temperature conditions that reflect more localized variation.

Temperature trends on the shelf and in coastal waters are resulting in changes in the availability of thermal habitat for marine life. There has been an overall increase in the area occupied by warm waters (≥16°C) by about 10% over the period 1982-2008 (Figure 3.8). Similarly, the area occupied by colder water (≤4°C) has increased by approximately 20%; this increase was most pronounced from the early 1980s to mid-1990s. The increase in the areas of the warmest and coldest thermal habitat has squeezed the area of intermediate thermal habitat (5-15°C). The decrease in intermediate thermal habitat has been consistent throughout the time series and has totaled a 15-20% reduction. Thus, cold temperate species are experiencing a general reduction in available habitat and warm-temperate species are experiencing and general increase. In addition, strictly cold water species may be experiencing an increase in habitat.

Average Temperature Preference of Finfish

As water temperatures increase, we expect fish species that prefer cool waters (cold-temperate species) in the ecosystem to respond by shifting their distribution northward to avoid warm waters. We would also expect that their abundances will decrease. However, species that prefer warm water (warm-temperate species) will also shift their distribution northward, but will likely increase in abundance. An indicator of this multifaceted biotic response to warming temperature is the mean preferred temperature of the fish community (Figure 3.9). The preferred temperature of the community was calculated by weighting the mean preferred temperature of each species by its biomass for both the spring and fall surveys. The mean preferred temperature of the community can be seen as an indicator of three processes; a change in water temperature, a change in community assemblage, and a change in the spatial distribution of fish stocks.

Similar to direct measurements of temperature, mean preferred temperature of the fish community has increased over both the fall and spring bottom trawl time series. While the preferred temperature of the spring fish community has shifted by approximately 0.5°C over the 40-year spring time

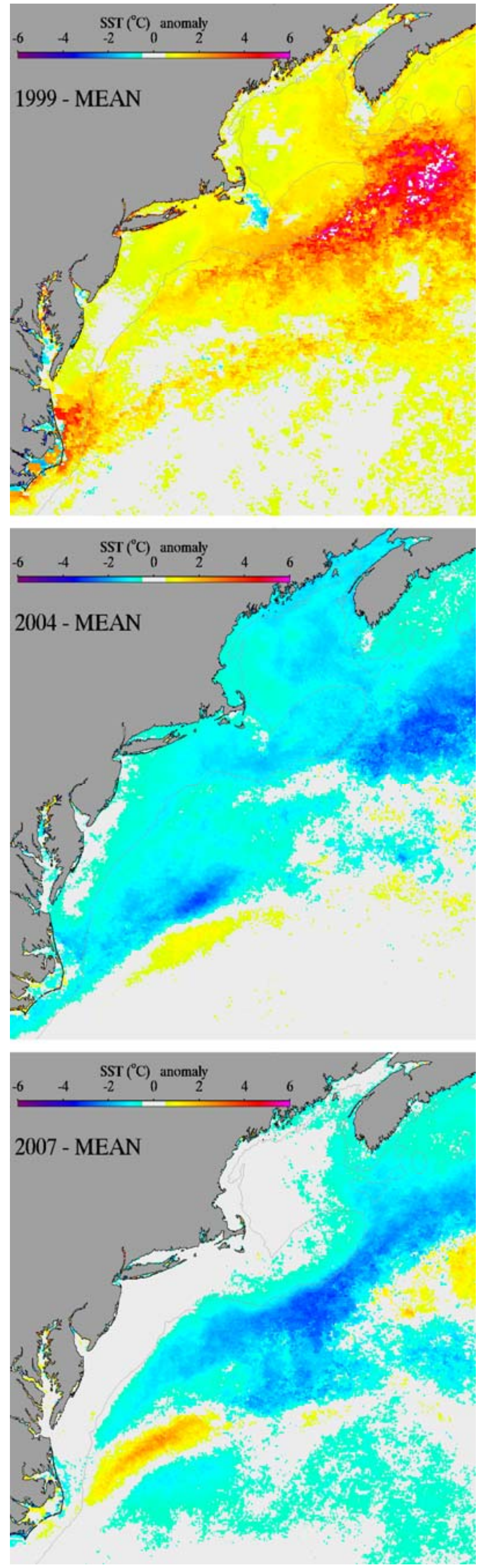

Figure 3.7 Sea surface temperature patterns for the northeast continental shelf for selected years (1999 upper; 2004 middle; and 2007 lower). Temperatures expressed as deviations from average conditions during 1998-2008).

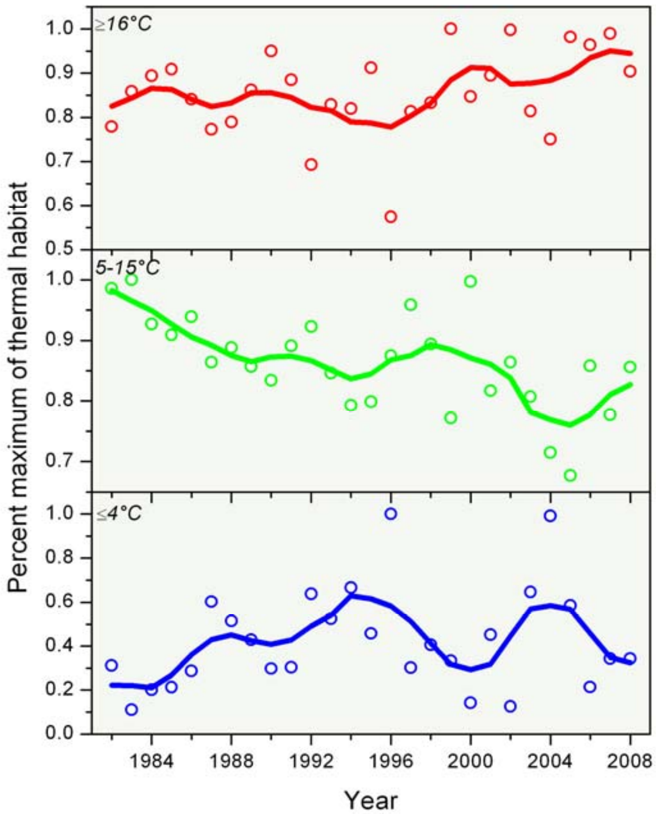

Figure 3.8 Amount of thermal habitat expressed as a proportion of the maximum amount of thermal habitat observed over the time series. Original data were in 1°C bins and were grouped here based on a preliminary analysis of common time trends.

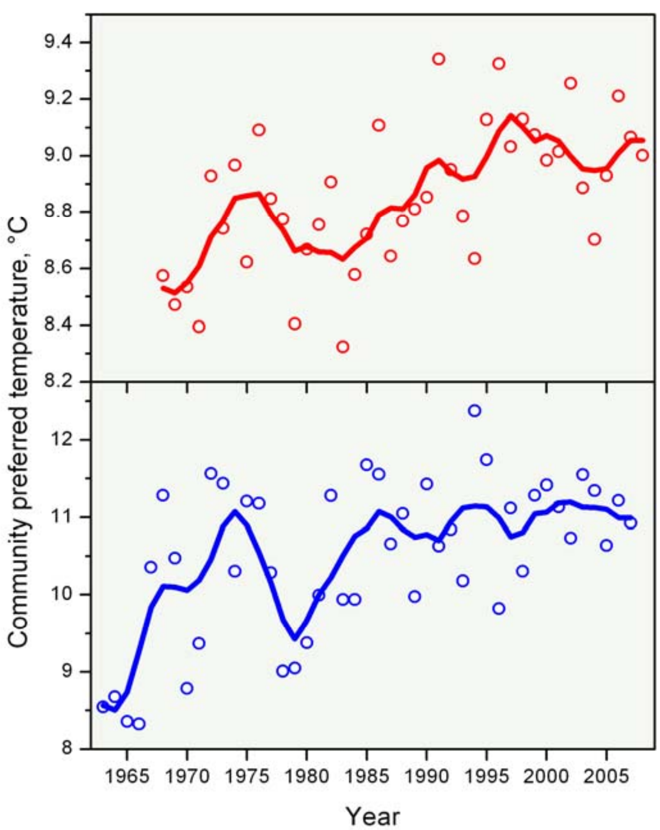

Figure 3.9 Mean preferred temperature of the finfish community (°C) for the Fall (red) and Spring (blue) NEFSC multispecies bottom trawl surveys.

series, the preferred temperature of the fall community has increased by almost 2°C over the 45-year fall time series. This indicates that the fish community of the NES LME has shifted such that warm-water species are more abundant than cold-temperate species. Because the southern boundary of many cold-temperate species and the northern boundary of many warm-water species occurs within the ecosystem, this indicator suggests that the boundary between these two assemblages has shifted northward such that the area occupied by warm-water species is greater than the area occupied by cold-temperate species.

Distribution Shifts

To illustrate shifts in northward distribution patterns of some fish species, we show the spatial distribution of red hake in the NES LME for three time periods; 1968-1980 (Figure 3.10 upper) 1981-1994 (Figure 3.10 middle) and 1995-2008 (Figure 3.10 lower). Red hake is a cold-temperature species whose center of biomass has shifted poleward over time as temperatures have increased. Abundance of red hake steadily diminished on the outer shelf region of the Middle-Atlantic Bight and now is principally concentrated in the western Gulf of Maine.

Salinity

Most aquatic organisms also are affected by salinity – the amount of salt in the water. Organisms in nearshore environments are adapted to wide ranging salinities owing to the interaction between freshwater (salinities of 0) and ocean-water (salinities in the 30s). However, many organisms found on the continental shelf, slope and deep-sea are sensitive to small changes in salinity because they are adapted to more constant conditions. The NEFSC has also been measuring salinities on the continental shelf since the mid-1970s (Figure 3.11). Surface and bottom salinities track similarly with general decreases in salinity from the mid-1970s to the late-1990s. From the late 1990s into the early 2000s there were slight increases in salinity, followed again by decreasing salinity in recent years.

Stratification

During much of the year, portions of the NES LME are stratified. Stratification is a term for layers

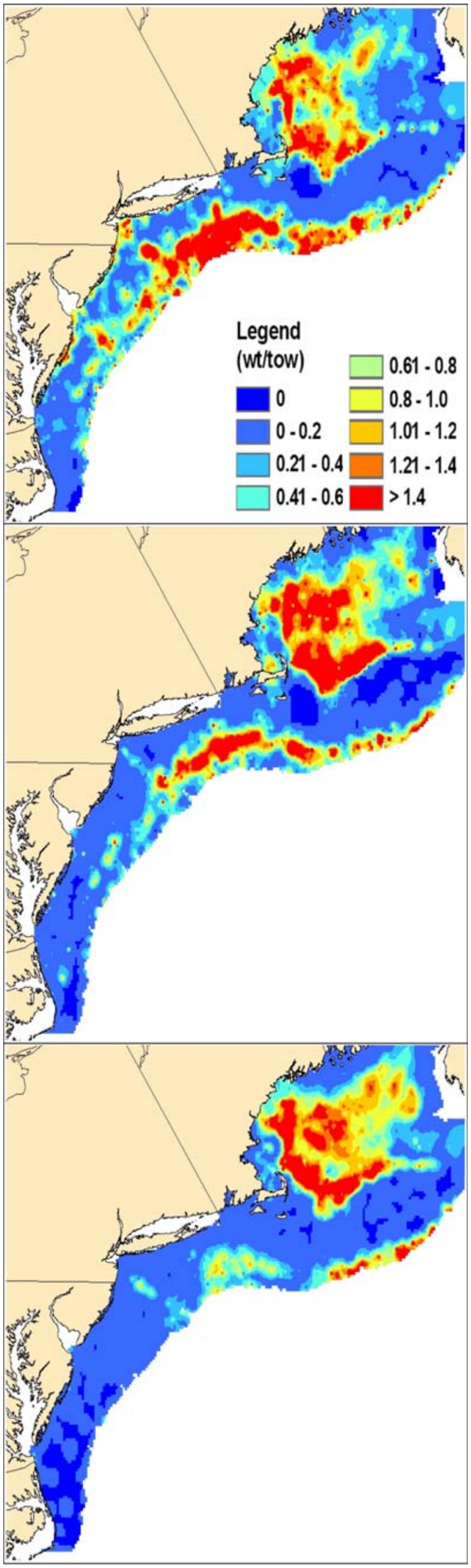

Figure 3.10 Distribution of red hake on the northeast continental shelf for three time periods; 1968-1980 (upper), 1981-1994 (middle), and 1995-2008 (lower) based on NEFSC spring bottom trawl surveys.

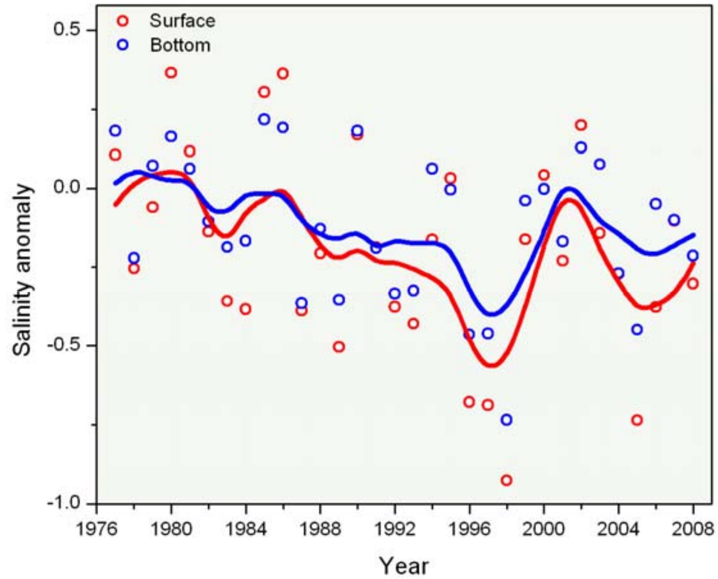

Figure 3.11 Mean anomaly of surface (red) and bottom (blue) salinities from the NEFSC survey programs. Anomalies show the mean value for 1977-1987 as 0, above the mean as positive and below the mean as negative (see Mountain [3]).

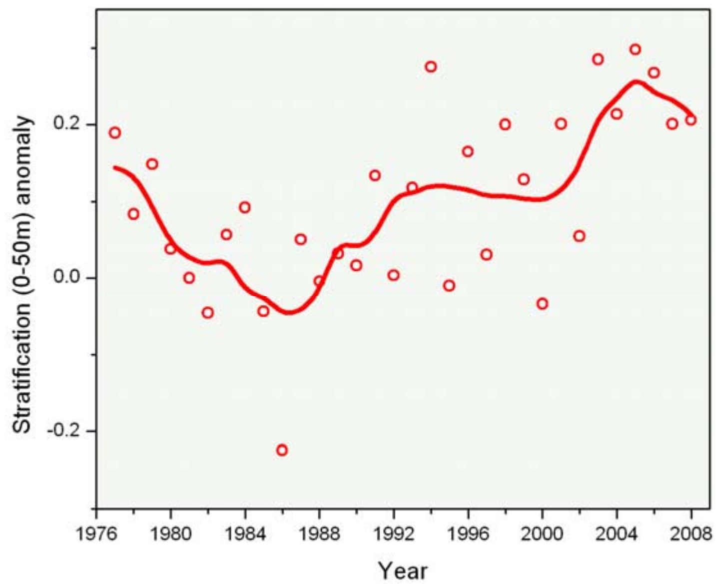

Figure 3.12 Mean annual stratification over the northeast U.S. continental shelf measured as the density different between the surface and 50 m (NEFSC). Anomalies show the mean value for 1977-1987 as 0, above the mean as positive and below the mean as negative.

of water of different densities stacked on top of one another. If there is no stratification, density is uniform throughout the water column and mixing is uninhibited. If denser water overlays less dense waters, the denser waters sink thereby mixing the water column (this occurs as the surface ocean cools in the fall). If less dense waters overlays more dense water, the water column is stable and it takes some kind of force to mix the water column. The greater the stratification, the greater the difference in density from the surface to depth, and the more force required to mix the water column. The issue of stratification is important, because deeper waters are often nutrient rich, thus increased stratification makes it harder for these nutrient rich waters to make it to the surface where they can be used by primary producers. The major components of water density are salinity and temperature. Thus, the NEFSC measurements of temperature and salinity (Figures 3.6 and 3.11) can be used to measure stratification. Stratification decreased from the mid-1970s to mid-1980s and then increased again (Figure 3.12). The temporal pattern in stratification is similar to that of surface temperatures and thus, the ecosystem-wide patterns in stratification seem to be linked to the warming of surface layers (e.g., less dense) and the relatively constant temperatures at depth (e.g., constant density). However, low salinity pulses move through the system from north to south over 1-2 year periods, and thus the effect of salinity is blurred in this ecosystem-wide stratification measure. In regional representations (e.g., in the Gulf of Maine), the effects of both temperature and salinity on stratification would be clearer.

4 Primary and Secondary Production

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Trends in Primary Production

Primary production of the NES LME is governed by the photosynthetic activity of a wide range of phytoplankton species. Phytoplankton is the base of the aquatic food web and globally accounts for nearly half of the total photosynthesis on the planet with the balance of global production coming from terrestrial sources [18, 19]. Though some of the photosynthetically-derived organic matter within the NES LME originates from outside the ecosystem, these inputs are minor. For example, some organic materials derived from estuarine phytoplankton, terrestrial plants, and submerged aquatic vegetation enters the ecosystem with river discharges.

One proxy measure of phytoplankton biomass is the concentration of chlorophyll in the water column. Shipboard sampling for phytoplankton in the NES LME is not sufficient to provide a comprehensive depiction of phytoplankton biomass in the entire ecosystem, nor is it representative of the complete annual production cycle. However, we can characterize these parameters using ocean color

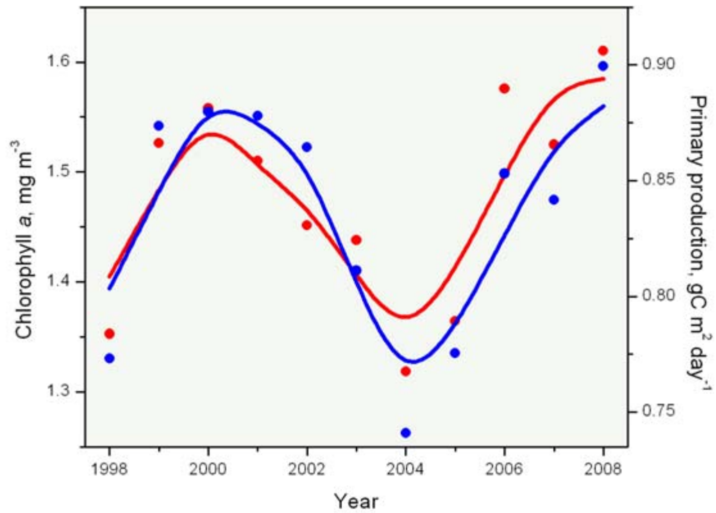

Figure 4.1 Annual mean chlorophyll concentration (red symbols) and primary production (blue symbols) for the Northeast Shelf Large Marine Ecosystem.

remote sensing data, which provides much greater spatial and temporal coverage compared with ship-based sampling. In 2008, the mean chlorophyll concentration in the NES LME was approximately 1.6 mg m-3 which is the highest annual concentration of the satellite data time series (Figure 4.1). Chlorophyll concentration has varied over the last decade; chlorophyll increased in the late 1990s, declined between 2000 and 2004, and subsequently increased to the maximum observed in 2008.

A key limitation with the use of satellite data is that it only represents the concentration of chlorophyll in the upper part of the water column. In some seasons, parts of the ecosystem can develop subsurface chlorophyll maxima due to the limited availability of nutrients in the upper part of the water column. As a result, surface chlorophyll measurements may underestimate the total water column biomass. There are, however, specific phytoplankton models that use surface chlorophyll measurements to estimate chlorophyll concentrations throughout the water column.

Measures of chlorophyll concentration have a number of ecological applications. The biomass represents the standing crop available for grazing by zooplankton and other primary consumers. The amount of phytoplankton biomass in the water column, particularly during seasonal bloom events, is a useful predictor of the rate of energy flow from the pelagic zone to the benthos. Many of the resource species of the NES LME are benthic organisms and are dependent on mechanisms to transfer energy from the pelagic zone to the benthos [20]. Additionally, satellite derived chlorophyll can be incorporated into models that relate the standing stock of phytoplankton biomass to the rate of carbon fixation.

Marine primary production is the rate at which dissolved inorganic carbon (CO_2) is photosynthetically fixed by phytoplankton into organic carbon such as carbohydrates and sugars. Primary production is a fundamental biological parameter that affects global carbon cycling, trophic food-web dynamics, and ecosystem health [18, 19]. In addition to chlorophyll concentration, production models use other satellite derived parameters such as the amount of photosynthetically available solar radiation and sea surface temperature. The average primary production of the NES LME is approximately 0.85 grams carbon m^{-1} day^{-1} (Figure 4.1). Trends in annual primary production mirror those of the chlorophyll concentration, including the peak production rate in 2008.

Spatial Distribution of Chlorophyll

Strong spatial and interannual differences in annual chlorophyll concentration are evident in satellite-derived maps of the NES LME. For example, Figure 4.2 shows chlorophyll concentration patterns for the three years corresponding to those selected for temperature change on the shelf (Figure 3.7). In 1999, chlorophyll levels were higher than the 1998-2008 average in the Gulf of Maine and on Georges Bank, but below average in the southern Middle Atlantic Bight (Figure 4.2 upper). By comparison, chlorophyll concentrations were uniformly below average on the shelf in 2004 with the exception of the Nantucket Shoals-Northwestern Georges Bank region (Figure 4.2 middle). In 2007, chlorophyll concentrations were lower in the western Gulf of Maine and Bay of Fundy but above average in the central-Middle-Atlantic Bight and southwestern Georges Bank (Figure 4.2 lower).

Annual Phytoplankton Cycle

The abundance of phytoplankton changes seasonally, alternating between bloom and inter-bloom periods (Figure 4.3). The seasonal biomass cycle for the NES LME shows the highest abundances associated with the spring bloom period. The winter period has a minor peak in January followed by relatively low levels of chlorophyll through early March. The spring bloom on the shelf

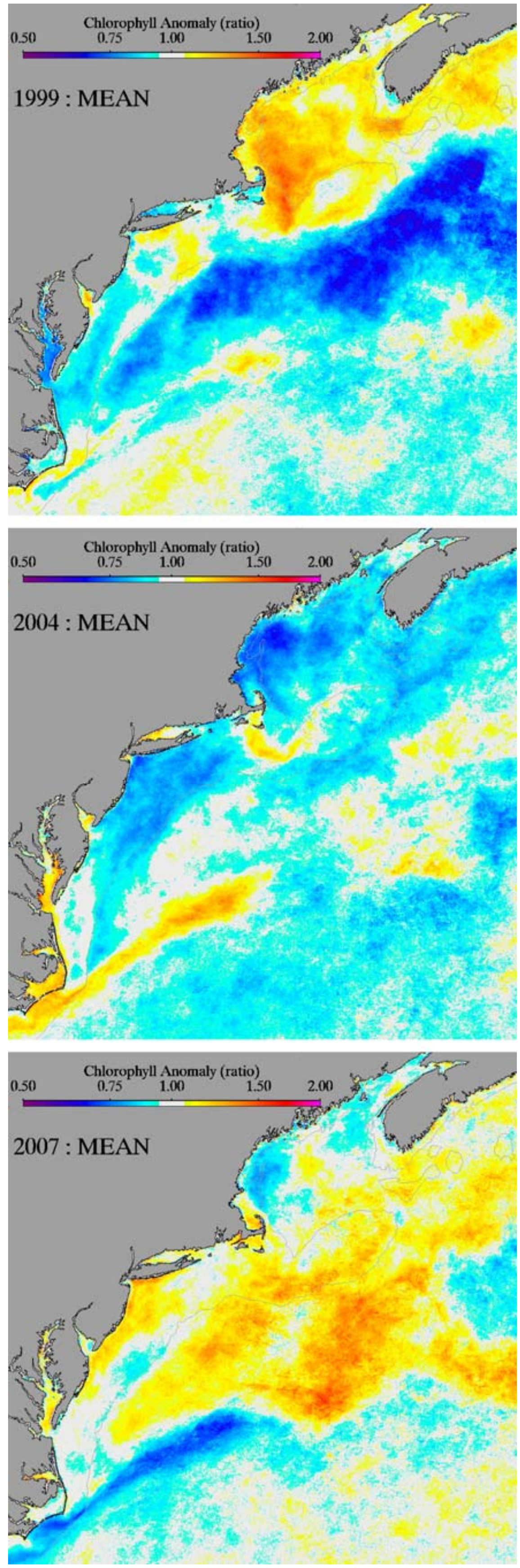

Figure 4.2 Chlorophyll concentration patterns for the northeast continental shelf for selected years (1999 upper; 2004 middle; and 2007 lower). Chlorophyll expressed as deviations from average conditions during 1998-2008).

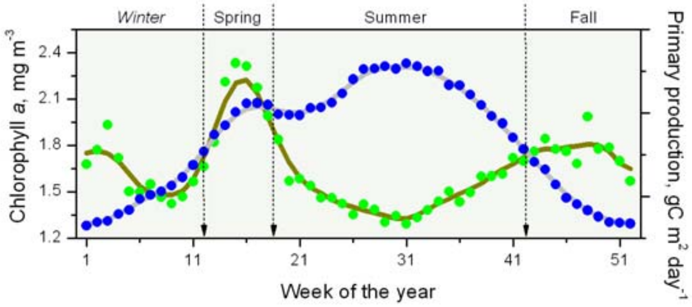

Figure 4.3 Annual chlorophyll biomass (green symbols) and primary production (blue symbols) seasonal cycles for the Northeast Shelf Large Marine Ecosystem.

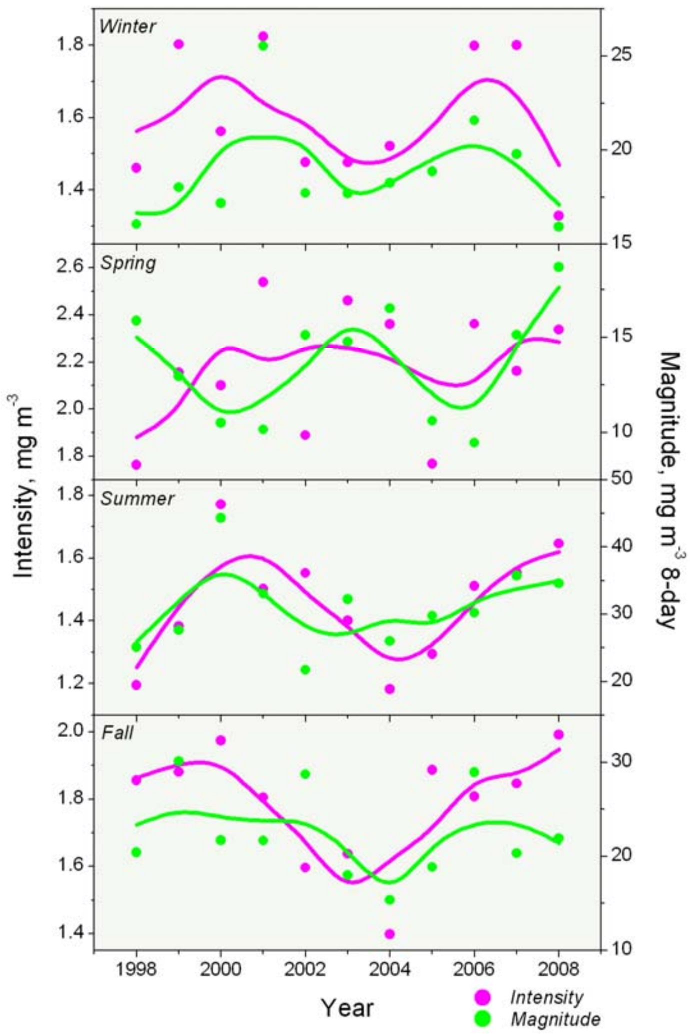

Figure 4.4 Seasonal bloom intensity and magnitude for the Northeast Shelf Large Marine Ecosystem.

usually begins in April and lasts for 4-6 weeks. The summer inter-bloom period is typically a period of low chlorophyll concentrations primarily due to nutrient limitation. The fall period can be highly variable year to year and can be represented by a period of gradually increasing chlorophyll concentrations or marked by distinct bloom events in some parts of the ecosystem.

The annual cycle of primary production differs from that of chlorophyll in that it reflects changes in phytoplankton photosynthesis rather than changes in phytoplankton biomass. The spring bloom appears as a secondary peak to the summer maximum that dominates the production cycle (Figure 4.3). The summer maximum in primary production is the result of greater available solar radiation that limits production in other times of the year. Thus higher rates of primary production can be maintained with relatively low levels of phytoplankton biomass. An active area of research is attempting to quantify the fraction of the summer production that is available to higher trophic levels.

Plankton blooms can be quite variable which affects the way pelagic and benthic resources use the primary production associated with the bloom. To quantify these characteristics, two measures of bloom size are used; chlorophyll intensity and chlorophyll magnitude, which respectively reflect the concentration and duration of the bloom. Bloom intensity is the mean chlorophyll concentration for the seasonal time period in a region. Bloom magnitude is the mean chlorophyll concentration for a seasonal time period multiplied by the duration of the time period. In some years, the time period start or stop dates were not obvious from the annual data, in these cases the climatological time period was used instead.

The intensity and magnitude of the phytoplankton component of the food web for the winter period were relatively low for 2008 despite the high annual levels of chlorophyll shown for the entire year (Figure 4.4). The winter period bloom intensity was approximately 1.6 mg m^{-3}, with lowest values in the time series at approximately 1.3 mg m-3 in 2008. Bloom magnitude follows that same trend as bloom intensity for the winter bloom period. Winter bloom activity may hold importance to a number of species that have young that feed early during the spring.

The spring bloom period is a dominant feature of the phytoplankton cycle over most of the Northeast Shelf. Though the duration is short, the timing of the bloom is considered critical to many species. The spring period is a time of high phytoplankton concentration, which provides the food resource for zooplankton grazers. However, the bloom often produces phytoplankton concentrations in excess of what can be used in the water column, thus providing material for the benthos. Compared to other bloom periods, the spring bloom has a greater intensity but lower magnitude due to the short duration of the bloom (Figure 4.4). Bloom intensity and magnitude are not well correlated during the spring bloom period, reflecting the highly variable nature of the spring bloom. In 2008, the spring bloom was about average, with respect to the 11-year time series.

The summer interbloom period is the longest period, but is characterized by relative low chlorophyll concentrations. The summer has the greatest amount available sunlight, so despite lower chlorophyll intensity levels, it is the period of highest primary production. The data for the summer bloom (Figure 4.4) largely mirror the time series trends seen in the annual mean chlorophyll concentration and primary production for the entire ecosystem (Figure 4.1). The summer 2008 interbloom intensity level was the second highest in the time series, while the bloom magnitude was close to the mean.

The fall bloom period is an important and sometimes overlooked part of the production cycle that is affected by many factors, including weather events, that mix nutrients into the euphotic zone. In some parts of the ecosystem, such as the Gulf of Maine and Georges Bank, the fall bloom is a distinct event of equal or greater size than the spring bloom. In some years, however, the fall bloom does not fully develop and thus there is no temporal or spatial phytoplankton event that can be considered a fall bloom. In some parts of the ecosystem, such as the Middle Atlantic Bight, the fall production period is a continuous part of the winter production cycle; though a period of higher production it is not really a distinct bloom event. As with the spring bloom, the enhanced chlorophyll concentration results in periods of enhanced benthic flux, delivering energy to the benthic portion of the ecosystem. The 2008 fall bloom intensity was the highest in the time series (Figure 4.4), while the fall bloom magnitude was about average. The fall magnitudes tend to be second only to the summer magnitude values.

Mean daily primary production rates were computed for the same bloom periods as determined from the chlorophyll biomass seasonal cycle (Figure 4.5). The annual primary production seasonal cycle is dominated by the peak in production associated with the summer and the high amount of solar radiation that occurs during that time of the year. There is often a second peak in production associated with the spring bloom, but the seasonal cycle of primary production is not as structured as the chlorophyll cycle. The seasonal trends in mean primary production reflect the mean annual trend, especially the spring and summer production periods. The primary production rates are lowest during winter. The 2008 winter primary production rate was close to the seasonal mean for the time series, thus winter production was not a major contributor to the overall system production.

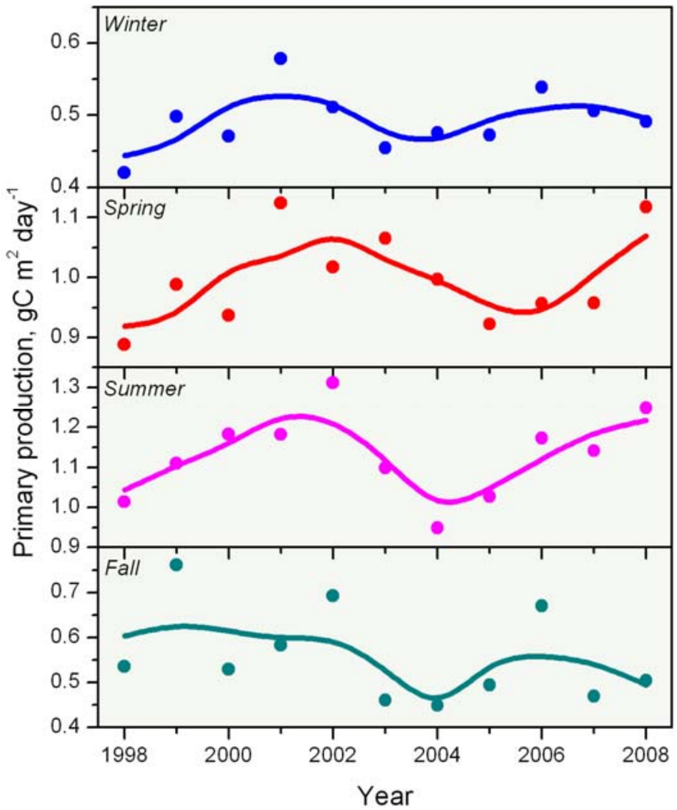

Figure 4.5 Primary production rates associated with the partitioned production cycle for the Northeast Shelf Large Marine Ecosystem.

In summary, phytoplankton productivity has been increasing in recent years and by a number of production indices it appears 2008 is among the most productive years the ecosystem has experienced over the past decade. This increase represents on the order of a 20% increase in energy input into the ecosystem since the localized minimum in production that occurred in 2004.

Color Index

Another measure of phytoplankton abundance is the Continuous Plankton Recorder (CPR) Color Index. The CPR is a mechanical instrument that is towed behind merchant vessels. Water enters the

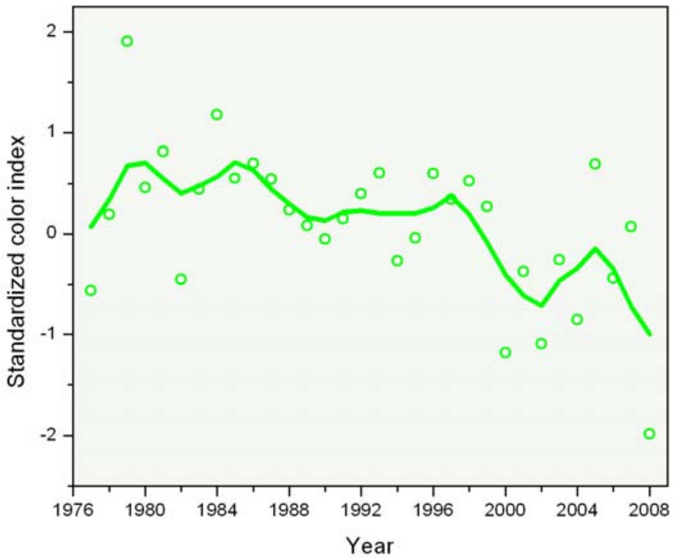

Figure 4.6 Standardized color index from three Continuous Plankton Recorder routes on the northeast U.S. shelf ecosystem: across the Gulf of Maine (1961-present), from New York to Bermuda (1977-present), and across Georges Bank (1992-present).

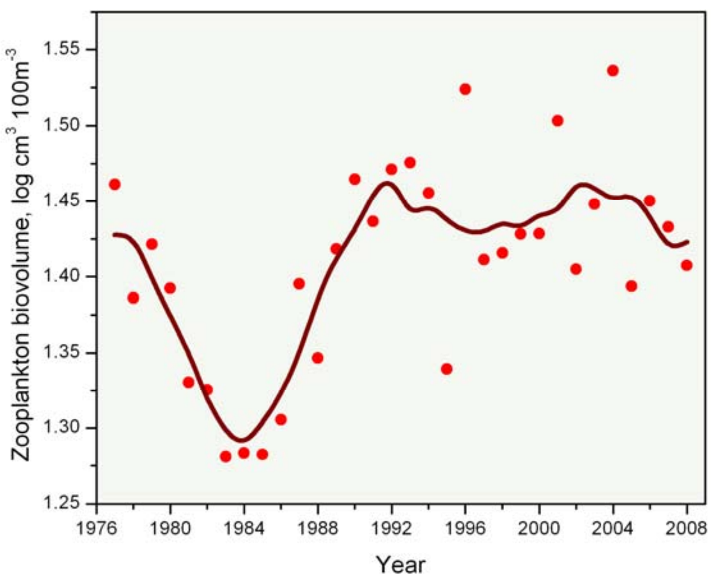

Figure 4.7 Time series of annual zooplankton biovolume from the northeast U.S. continental shelf ecosystem. Approximately 600-800 samples are included annually. Biovolume is log-transformed and then averaged across all samples.

CPR and is filtered through a piece of silk. The silk slowly advances as the CPR moves through the water and thus a continuous record of plankton 10 m below the surface is recorded. The color of the silk is assessed relative to standard color charts to estimate the quantity and density of phytoplankton, thereby providing an indicator of overall abundance of phytoplankton. This method is very selective because the mesh of the silk is large relative to the size of most phytoplankton, thus the index is best viewed as a measure of the abundance of larger phytoplankton (e.g., diatoms and large dinoflagellates).

Although this index is crude compared with satellite measures of chlorophyll concentration, the CPR color index has been used since the early 1960s providing a longer time series. Three CPR routes are operated in the NES LME. Combining the color index data from these three routes shows an overall decline in color (and by proxy larger phytoplankton) over the series (Figure 4.6). This decline in larger phytoplankton has important implications for food webs in the ecosystem and may indicate a shift to smaller phytoplankton in recent decades (e.g., smaller dinoflagellates).

Zooplankton Abundance

The energy produced by phytoplankton is transferred via three main pathways. Some energy is transported directly from the water column to the bottom fueling benthic production. A recent study hypothesizes that this route is responsible for high recruitment of the 2003 year-class of haddock [21]. Unfortunately, there is little long-term data to evaluate the direct contribution of primary production to benthic habitats nor to overall benthic productivity. Future research and observations are needed owing to the potential importance of this route to fisheries production in the ecosystem.

A second pathway of energy from primary production is remineralization by bacteria and microzooplankton – the so called microbial loop. Some of this energy remains in the microbial loop, some sinks to the benthos, and some is consumed by zooplankton. Although very little data exists on bacteria and microzooplankton in the NES LME, the microbial foodweb is believed to be extremely important in the energy flow on Georges Bank [22].

The third route of energy produced by phytoplankton is consumption by zooplankton. Traditionally, this energy route has been the most studied and NEFSC has been monitoring zooplankton abundance and species composition since the 1970s. These monitoring efforts involve deploying a small (61 cm diameter), fine meshed (333 μm) net at numerous locations throughout the ecosystem. The net is deployed from the surface to near the bottom, providing an integrated sample through the entire water column. Currently, the NEFSC's sampling includes six surveys with ~120 stations over the whole ecosystem; these surveys are designed to capture seasonal and annual trends, but not smaller-scale variability.

One measure of zooplankton abundance is the volume of material collected in the net, termed zooplankton biovolume (Figure 4.7). This relatively simple indicator is related to the amount of zooplankton biomass. Levels of zooplankton biovolume have been remarkably consistent over the past 20 years with some inter-annual variability. In the early years of the time series, there was a marked drop and recovery in zooplankton abundance, with variable but near constant values since the late 1980s. The pattern of a decrease in the early 1980s, recovery in the late-1980s and fluctuating but near constant values through to the present is also seen through much of the seasonal cycle (Figure 4.8). This pattern is not as obvious in July-August, in part because of missing data in the late-1980s and early 1990s. This pattern also is not found in the winter months (Jan-Feb). Zooplankton biovolume and thus secondary production is at its lowest in winter, and highest winter biovolumes were observed in the early 1990s.

Another measure related to secondary production is the absolute number of copepods (Figures 4.9). Copepods, microscopic animals related to lobsters and crabs, are the primary grazers on phytoplankton and microzooplankton, and are the primary food source for forage fishes (e.g. herring and mackerel) and for young groundfishes (e.g., cod, haddock). Copepods are also an important food source for many baleen whales and the endangered right whale feeds primarily on a species of copepod – *Calanus finmarchicus* – which is very rich in lipids. The total number of copepods in the spring was relatively low and decreased from the late 1970s to early 1990s. Abundance then increased and has been fairly constant since. The decrease and recovery early in the time series is more evident in copepod abundance in the fall, than the spring. Interestingly, fall abundance has also been declining since about 2000, diverging from the nearly constant levels in spring copepod number.

Recent work has found that the composition of the zooplankton community has changed over time [23]. Specifically, several species of small copepods increased in abundance in the 1990s resulting in an increase in total zooplankton abundance. The community composition changed again around 2000 consistent with the drop in zooplankton abundance in

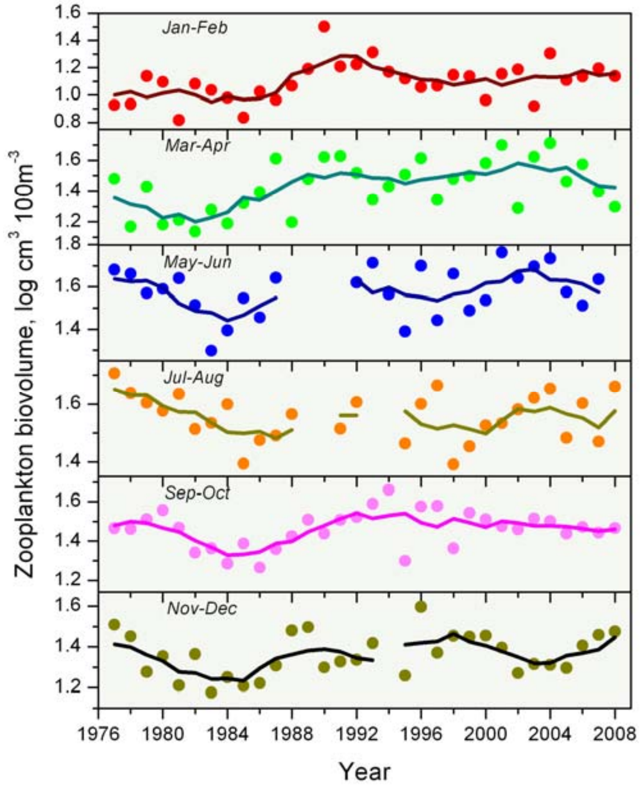

Figure 4.8 Time series of seasonal zooplankton biovolume from the northeast U.S. continental shelf ecosystem. Approximately 100-150 samples are included in each two month period in each season. Biovolume is log-transformed and then averaged across all samples.

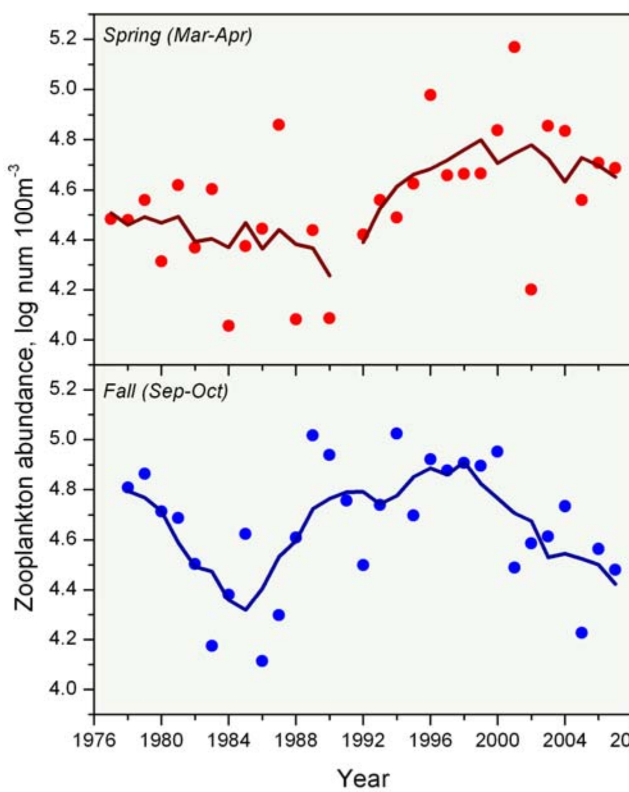

Figure 4.9 The abundance of copepods per 100 m^3 on the northeast U.S. continental shelf ecosystem in spring and fall based on approximately 100-150 samples each season. Time series for the spring and fall are shown because sampling coverage through time was best during these seasons.

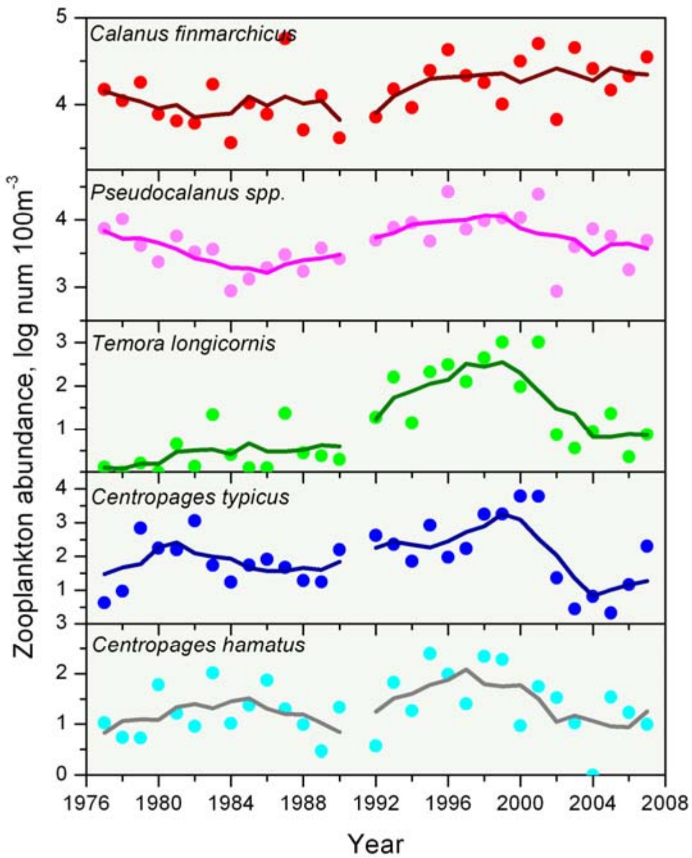

Figure 4.10 The abundance of five species of copepods per 100 m^3 on the northeast U.S. continental shelf ecosystem in spring based on approximately 100-150 samples each season.

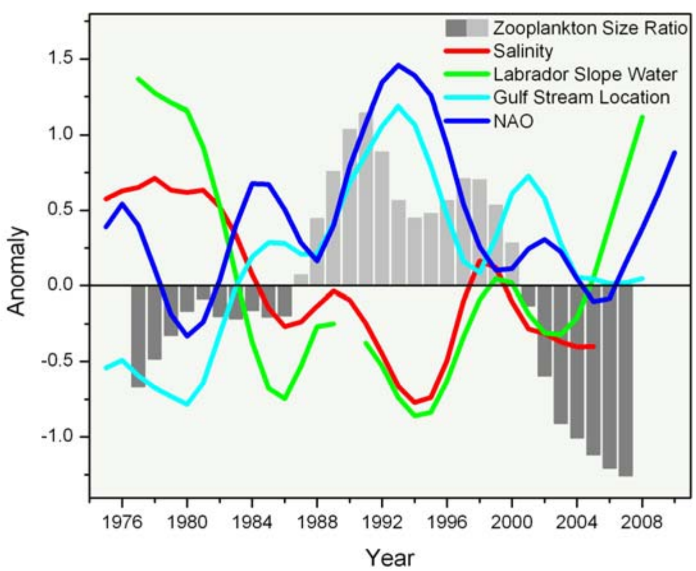

Figure 4.11 Trends in zooplankton size index, salinity, percent Labrador Slope Water, Gulf Stream location, and NAO. All data are presented as anomalies to standardize the y-axis scale and a 10 year smoother was applied to emphasize decadal trends. NAO was adjusted 2 years forward and shelf salinity was adjusted 3 years back based on a cross-correlation analysis. Zooplankton size index is an indicator of the abundance of small copepods (*C. typicus*, *C. hamatus*, *T. longicornis*, and Psuedocalanus spp.) compared to large copepods (*C. finmarchicus*).

the fall. Individual copepod species can serve as indicators of these broader changes in overall species composition (Figure 4.10). During the spring, *Pseudocalanus* spp., *Temora longicornis*, *Centropages typicus*, and *Centropages hamatus* were all more abundant in the 1990s compared to the 1980s and the 2000s. *Calanus finmarchicus* was more abundant during the 1990s and 2000s compared to the 1980s.

Climate Drivers, Physical Pressures, and Zooplankton Community Structure

Zooplankton community structure is linked to both climate drivers and physical pressures. At the decadal scale, increase in the NAO, northward movement of the Gulf Stream, decreases in Labrador Slope Water and decreases in salinity are linked to changes in zooplankton community structure (Figure 4.11). This chain of drivers, pressures, and state responses indicates that the northeast U.S. shelf ecosystem is affected significantly by remote climate forcing [12]. That said, the specific processes that result in changes in zooplankton community structure remain unresolved and the implications for the remainder of the ecosystem are unclear.

5.1 Benthos

The organisms that live on the bottom or directly in the sediments are referred to as benthos. As noted earlier, benthic animals play an important role in energy transfer in marine systems. Benthic species such as mollusks filter phytoplankton and suspended detritus from the water column while other groups depend on the organic content of sediments or detritus that has reached the seafloor for their energetic needs (e.g. certain species of marine worms). Other benthic organisms, such as sea stars, are predators on mollusks and other benthic species. The benthos also comprises important prey items of fish and larger crustaceans. Over two thousand species of benthic invertebrates have been identified on the Northeast Continental shelf although most are relatively rare. Benthic species of the NES LME (including lobsters, crabs, scallops, clams, and sea urchins) support major commercial and recreational fisheries, including some of the highest revenue fisheries in the region.

Temporal Trends of Selected Species

Information on longer term trends in abundance is available only for selected commercially and recreationally important benthic species based on directed research vessel surveys and related stock assessments. The sea scallop, *Placopectin magellanicus*, the highest value fishery in the NES LME, has increased dramatically in abundance over the last decade (Figure 5.1). This dramatic overall increase is related to the implementation of effective management measures including reductions in fishing effort, constraints on crew size, gear restrictions, and the establishment of long-term closed areas in late 1994. Population estimates of the ocean quahog, *Arctica islandica*, indicate a sharply declining population trend over the last decade and a half (Figure 5.1) following a more modest decline since 1980. In contrast, estimates of population size of the surf clam *Spisula solidissima* show a general increase until the mid to late 1990s followed by a sharp decline. The relative abundance of the American lobster *Homarus americanus* on the NES LME has increased markedly over the last two decades (Figure 5.1) until 2004 after which there has been an overall decline in NEFSC bottom trawl survey indices for this species. An aggregate assemblage of crab species, including the commercially harvested red crab (*Geryon quinquidens*), the jonah crab (*Cancer borealis*) and the rock crab (*Cancer irroratus*) exhibit high variability and no clear trend in NEFSC trawl surveys.

Fish Diets as Indicators of Change in the Benthos

Some species are known or suspected to be important in the dynamics of the food web [24] but are not routinely surveyed to assess changes in their abundance. One way to compensate for this is to use fish as 'samplers' [25, 26] for groups that are understudied, under-sampled or otherwise under-determined. We can calculate an index of relative abundance from the percent frequency of occurrence of these organisms in the stomachs of major predators in the food web. Many fish species consume food items in proportion to the abundance of the prey although other factors such as the availability of alternative prey can sometimes also be important. Examples of the representation of some

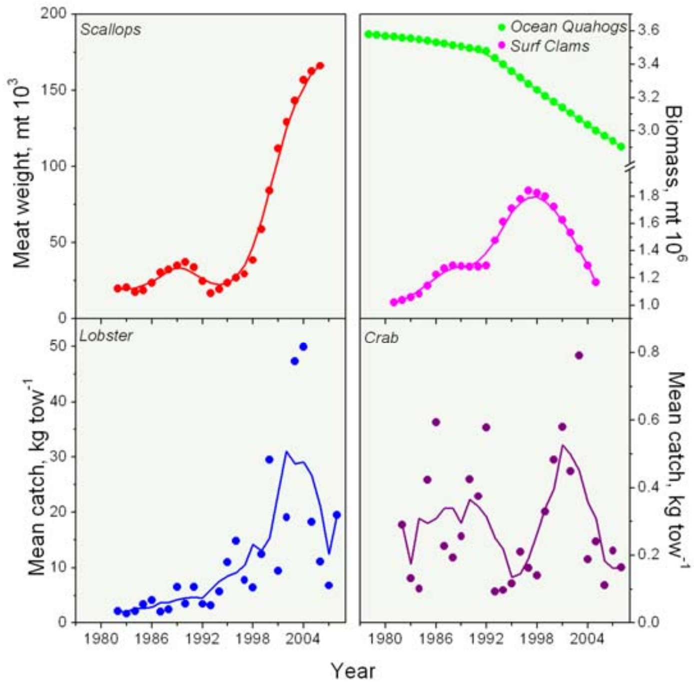

Figure 5.1 Trends in abundance of sea scallops based on NEFSC scallop surveys, American lobster and crab species based on NEFSC bottom trawl surveys, and surf clam and ocean quahog stock assessment models.

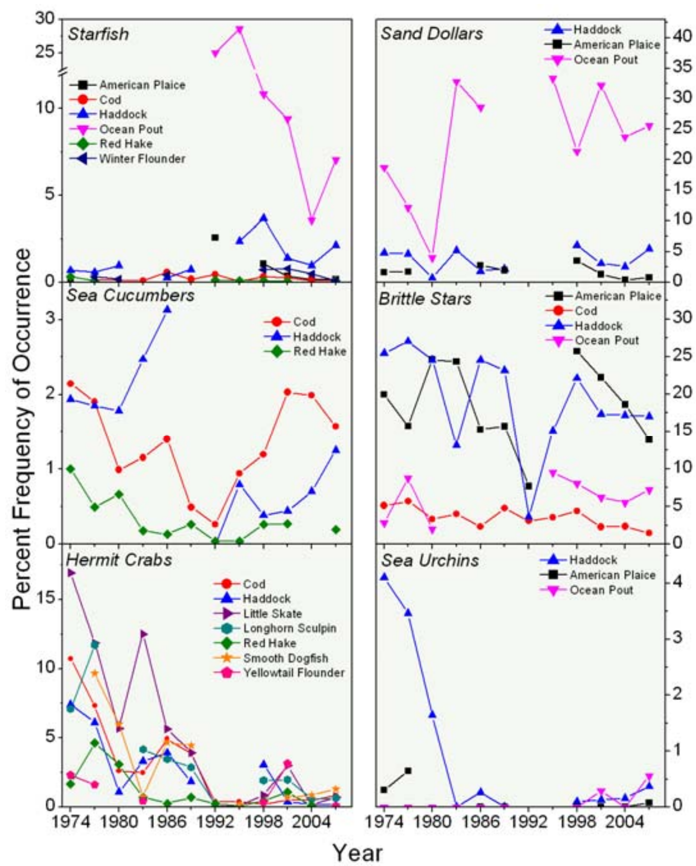

Figure 5.2 Index of relative abundance for macrobenthos species groups (3 yr blocks). Indices are based on using fish predators as samplers, representing how often one of these organism groups occurs in stomachs of fish sampled in this ecosystem.

important macrobenthic groups in the diets of selected fish 'samplers' are provided in Figure 5.2. The estimates derived in this way exhibit substantial variability but also demonstrate a broad coherence among the fish species used as samplers. Among the echinoderms, sea cucumbers show a decline followed by a recent increase in the diets of several predators. Starfish generally varied without trend at low levels, except for showing a decline in ocean pout, Brittle stars, sea urchins and sand dollars similarly varied without trend at relatively low levels, except for urchins showing a decline in haddock and sand dollars showing an increase in ocean pout. Finally, we note a general decline in hermit crabs in the diet of a number of predators over time (Figure 5.2). The importance of monitoring change in benthic communities is well recognized [27] and the direct and indirect sampling methods described here for benthos of the NES LME meet a critical need.

6 Upper Trophic Levels

This section provides a community-level perspective on changes in fish populations over time to complement more traditional species-based approaches *(c.f.* http://www.nefsc.noaa.gov/sos/). We focus on species groups for which consistent time series information (i.e., extending a decade or more) are available. We note that continuous time series data are not generally available for major species groups such as marine mammals, sea birds, and sea turtles in this region and these groups are not further analyzed here. Because of their ecological importance, however, we do provide information on projected consumption of fish and other prey items by marine mammals as one indicator of their role in ecosystem structure and function.

Integrative measures can provide further insights into how an ecosystem responds to a wide range of pressures and drivers. This "big picture" view of the biotic components of the food web provides a better sense of relationships among its component species and processes of energy flow within this ecosystem.

The species comprising a community and those targeted by a fishery can be characterized by how they are partitioned into different habitats. For example, demersal fish (species such cod, haddock, and flounders) are found in near-bottom waters or associated with the seabed. In contrast, pelagic fish

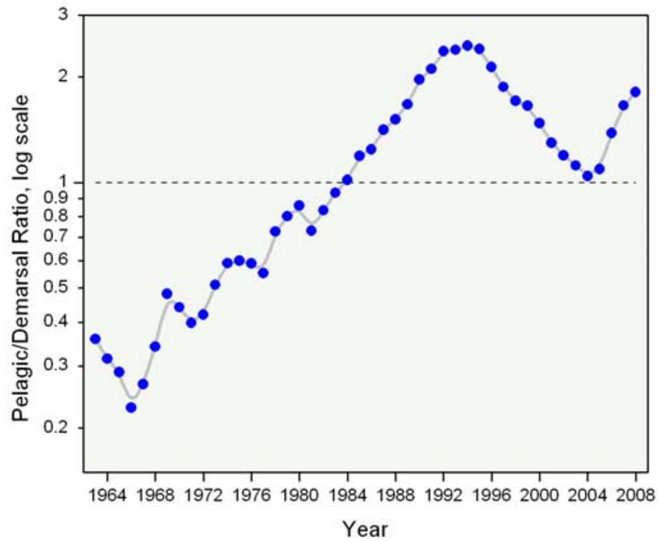

Figure 6.1 Ratio of pelagic to demersal fish species caught in NEFSC autumn bottom trawl surveys.

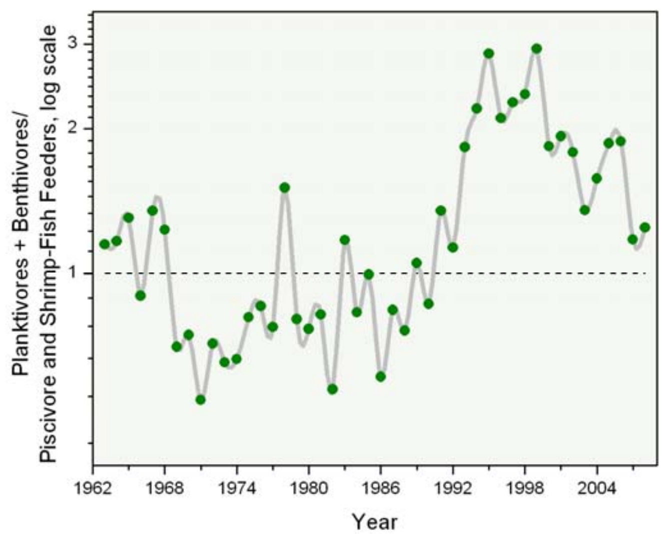

Figure 6.2 Ratio of lower tropic level feeding guilds, Planktivores and Benthivores, to upper trophic level feeding guilds, Piscivores and Shrimp-Fish feeders, biomass caught in NEFSC bottom trawl surveys.

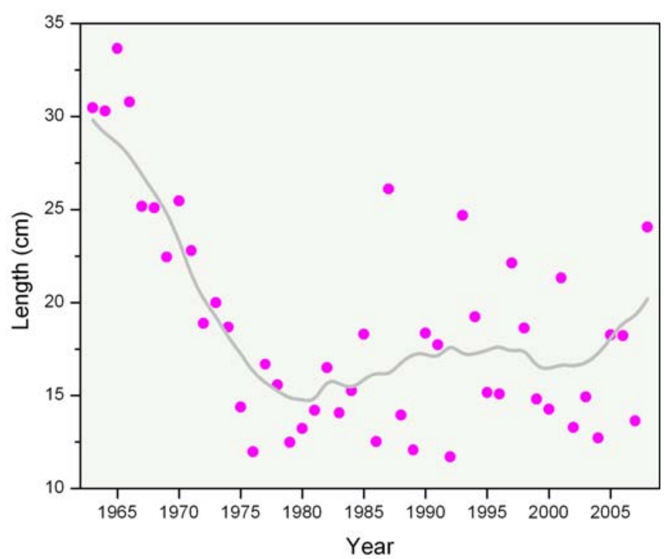

Figure 6.3 Mean length (cm) of all finfish species caught in NEFSC bottom trawl surveys.

(species such as herring and mackerel) are typically found higher in the water column. An index of the ratio of pelagic to demersal fish provides important insights into relative changes in these two major groups of fish and pathways of energy flow (Figure 6.1;[28, 29]). At a coarse level, this ratio indicates where energy is processed in the ecosystem. In the 1960s, the demersals were dominant in the ecosystem. This was followed by a more even ratio in the 1970s to early 1980s (reflective of declines in demersals and increases in pelagics; *c.f.* Fig. 6.7). Then, in the 1990s, the pelagics dominated fish biomass before declining in the early 2000s. Pelagics are now beginning to increase to a ratio double that of demersals.

An alternative way to explore pathways of energy flow is by partitioning the fish community into various feeding guilds. The ratio of planktivores and benthivores to piscivores and shrimp-fish feeders (Figure 6.2) shows changes in the relative importance of lower and upper trophic level fish groups (planktivores and benthivores are generally lower trophic level feeders, implying that there is less energy needed to make their food; *c.f.* Figure 6.3). The groups are also distinguished by relative size (usually piscivores—fish that eat other fish—tend to be larger species). During the earlier part of the time series, the ratio was below 1.0 with less feeding at lower trophic levels, implying an imbalanced food web [28]. Since the mid 1990s, the ratio has been higher than 1.0 indicating that there are relatively fewer fish feeding on other fish, and by implication, a shift towards lower trophic levels, more prominence of invertebrate prey, and likely smaller fish in the ecosystem.

We can also characterize the fish community and species of commercial and ecological significance with respect to their size distribution [28, 29]. An indicator of overall mean length, taken from the lengths of all finfish species caught in fisheries independent surveys, shows the size composition of the entire fish community (Figure 6.3). There was a decline of almost one half from the 1960s to mid 1970s from an average fish size of approximately 30 cm (~12 inches) to 17 cm (~6 ½ inches). There has been some change thereafter, but effectively the mean size of fish has been between 15 and 20 cm for the past 30 years, with only recent signs of an increasing trend. This would indicate that the average size of fish in this entire ecosystem has declined. It appears that fishing pressure on larger organisms has resulted in declines in their average size while there has also been an increase in smaller bodied fish (particularly small pelagic fish such as herring and mackerel; see Figure 6.1).

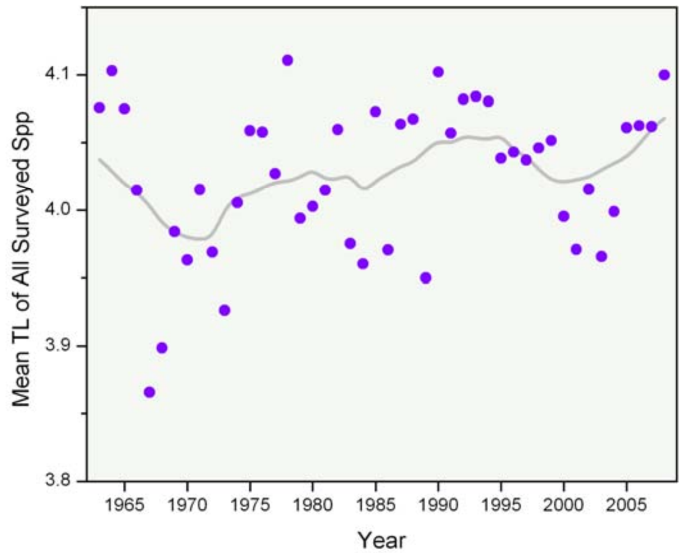

Figure 6.4 Average trophic level of all finfish species caught in NEFSC bottom trawl surveys.

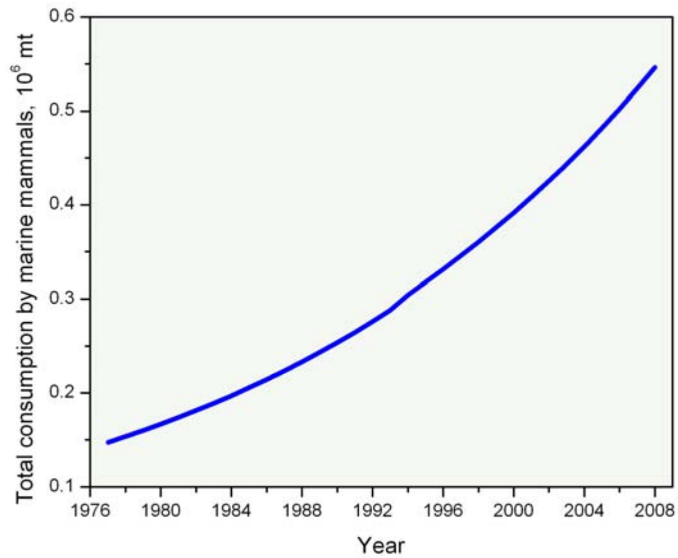

Figure 6.5 Estimated total consumption of selected marine mammal species (million mt).

The 'trophic level' of a species (its place in the food web) is an important aspect of understanding not only the (implied) size of species in an ecosystem, but also the transfer of energy in the system [27]. We can determine the trophic level of a species by examining its diet. It is then possible to determine the mean trophic level in the sampled community by weighting the trophic levels of individual species by their abundance (biomass) and averaging over all species.

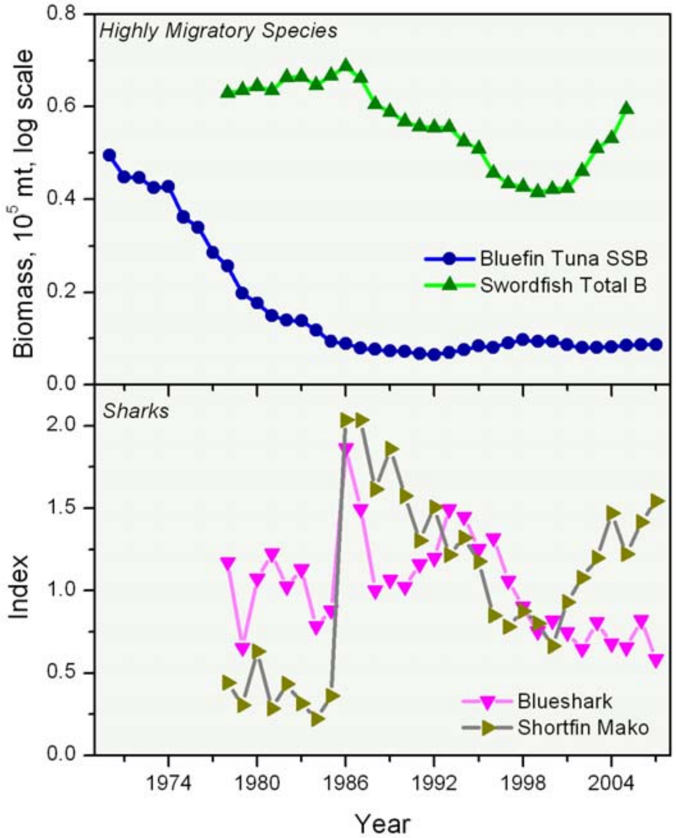

Figure 6.6 Estimates of biomass for highly migratory species (top) and indices of abundance for two major sharks (bottom, CPUE) for the northwest Atlantic.

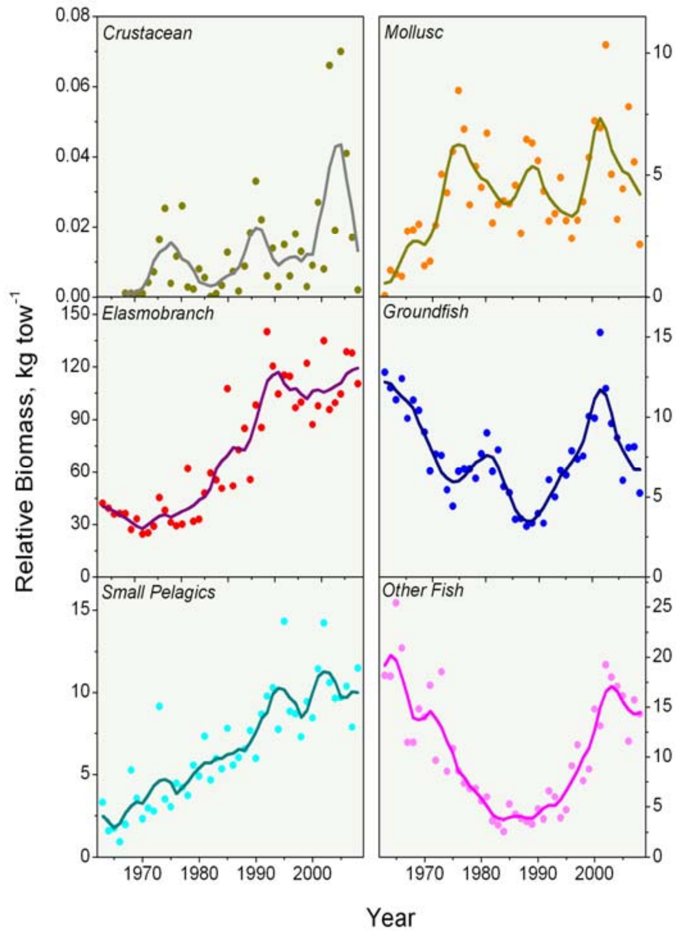

Figure 6.7 Mean catch (kg) per tow caught in NEFSC bottom trawl surveys by species group.

The mean trophic level is an indicator of how much energy is transferred to species feeding higher in the food web. The mean trophic level of species captured in the NEFSC bottom trawl surveys has remained relatively stable over time (average TL= 4.05) but has varied from lower values in the late 1960s to mid 1980s and a slightly increasing trend in recent years (Figure 6.4).

Consideration of feeding by selected marine mammal species provides important insights into upper trophic level processes. Consumption was calculated based on survey estimates of marine mammal biomass, food habits, and modeled estimates of metabolism [30]. Marine mammal consumption indicates how much energy is flowing through the system to upper trophic levels that have a special status (Figure 6.5). Many mammal species are protected or managed and monitored distinctly from targeted fish species. The index also shows how much food was removed by these organisms and indicates an increase in marine mammal consumption over time, largely reflective of increasing populations of some toothed whales and seals. It is interesting to contrast this to the amount of food eaten to total fisheries landings in the region (c.f., Figure 6.1), particularly of forage species such as herring and mackerel, to get a sense of the relative magnitude of the different sources of removal experienced by these fish and invertebrates.

Biomass trends of selected highly migratory species found in the North Atlantic are shown in Figure 6.6. These indices are for the entire north Atlantic, but are indicative of trends for these species in the NES LME. Species such as tunas, swordfish, and sharks all feed at or near the top of a food web. Declines in these species have served as proxies for ecosystem and stock overfishing. The biomasses of these highly migratory species have declined since the 1970s and 1980s to currently lower values. Certainly yellowfin tuna and the two species of sharks exhibited a notable peak in the mid to late 1980s, but their biomasses have mostly declined since then. Only swordfish and shortfin mako have shown a slightly increasing trend in recent years.

Changes in biomass of taxonomically-related fish species are provided in Figure 6.7. These indicators show the relative biomass of major fish groups that are often commercially targeted in the

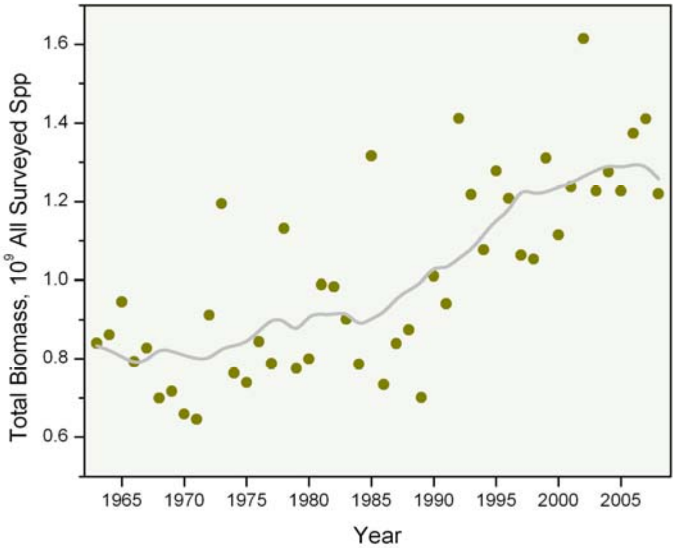

Figure 6.8 Total biomass of all species caught in NEFSC bottom trawl surveys (million mt) based on areal expansion of catch per tow data without adjustment for survey catchability.

NES LME. Note the obvious and sustained increases in small pelagics and elasmobranchs over time. The groundfish and other finfish show a general decline through the end of the 1980s, followed by recovery in recent years due to various management measures. The index values for these groups however have declined again in recent years.

Trends in total biomass based on all species captured in the trawl surveys indicate a steady increase over time (Figure 6.8), reflecting the increases in major species groups such as the elasmobranchs and small pelagics with other groups contributing during different time periods. Implications of this increase, as well as potential underlying causes (related to various abiotic and human drivers) are discussed in the next section.

7 Anthropogenic Factors

Landing by Major Species Group 1960-2007

Total landings for major groups of fishes and invertebrates from the NES LME have generally declined during the last four decades (Figure 7.1). Landings of groundfish (Atlantic cod, haddock, silver hake, yellowtail flounder etc.) and small pelagic fishes (primarily Atlantic mackerel, herring, and menhaden) peaked in the mid 1960s to the mid 1970s during a period of heavy fishing by foreign distant water fleets.

Groundfish landings peaked at 703,000 t in 1965 with the appearance of a very strong year class of haddock (Figure 7.1). However, serial depletion of groundfish occurred very rapidly and landings declined to about 30% of the peak by 1978. Groundfish landings have continued to decline since the mid 1970s due to severe overfishing and, more recently, to regulatory intervention to rebuild depleted stocks; currently they are a minor component of total system removals.

Landings of small pelagic fishes reached 988,000 t in 1973 but declined to about 31% of this peak value by 1984 due to the collapse of the Georges Bank herring stock and a severe decline in Atlantic mackerel. Recovery of the Atlantic herring and mackerel stocks during the late 1980s and sustainable landings of Atlantic menhaden are responsible for relatively robust landings, averaging about 360,000 t from 1977-2007.

Landings of other finfish (redfish, Atlantic croaker, black sea bass etc.) and crustaceans (primarily American lobster) have been relatively stable during 1960-2007.

Landings of molluscs increased during the early 1980s due to a rapid expansion of the surf clam and ocean quahog fishery by the U.S. industry (Figure 7.1). With the recovery of the scallop resource in the mid to late 1990s, this category of landings (molluscs) now comprises the largest proportion of current landings (Figure 7.1).

Trophic Level of the Landings

It has been recognized for some time that a substantial level of depletion of large picivorous fish has occurred on a global basis during the last 40-50 years of fishery exploitation [27, 31, 32]. In some cases this has resulted in the loss of important predators, the shortening of food chains, and simplification of marine ecosystems, depending on the region. Measuring this effect is not easy, but several metrics have been proposed for assessing these impacts, including trophic level of catch [27] and catch-per-unit-effort of community biomass [31]. These metrics are designed to measure the overall impact of fishing on large regions of the global oceans.

The mean trophic level of landings (TLL) was calculated for the NES LME during 1960-2007 to monitor possible changes in the trophic structure in the region. This method accounts for the trophic level of each species in the landings weighted by the total landings of each species in a given year. The

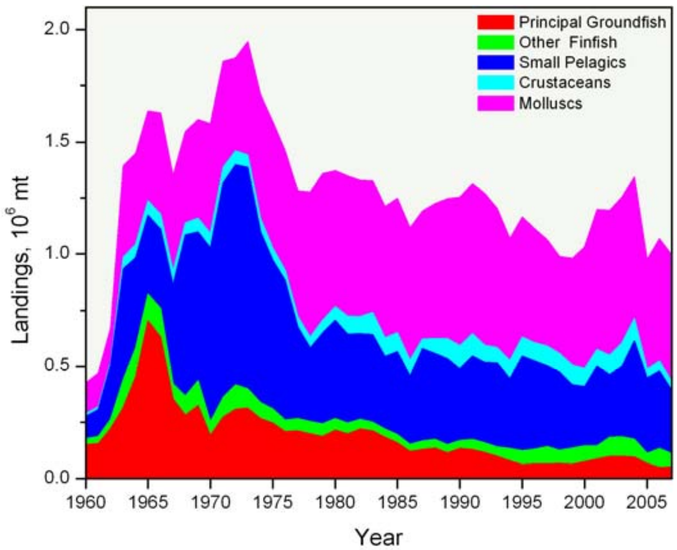

Figure 7.1 Landings by species group (million mt) landings for the Northeast continentals shelf LME.

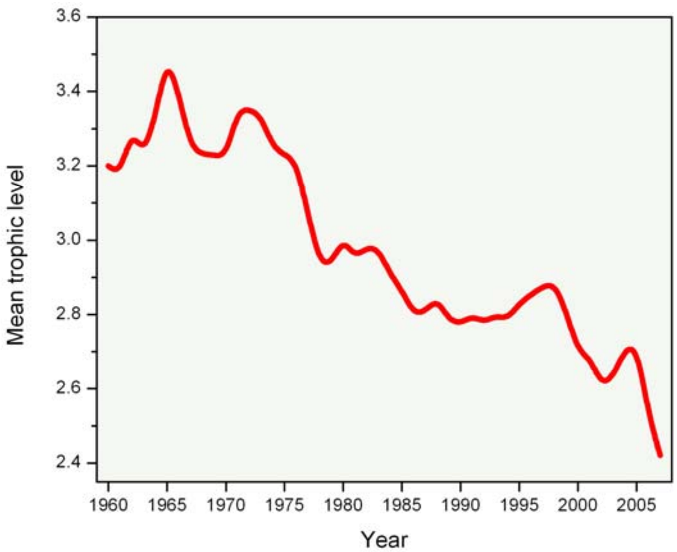

Figure 7.2 Mean trophic level of landings for the Northeast continental shelf LME.

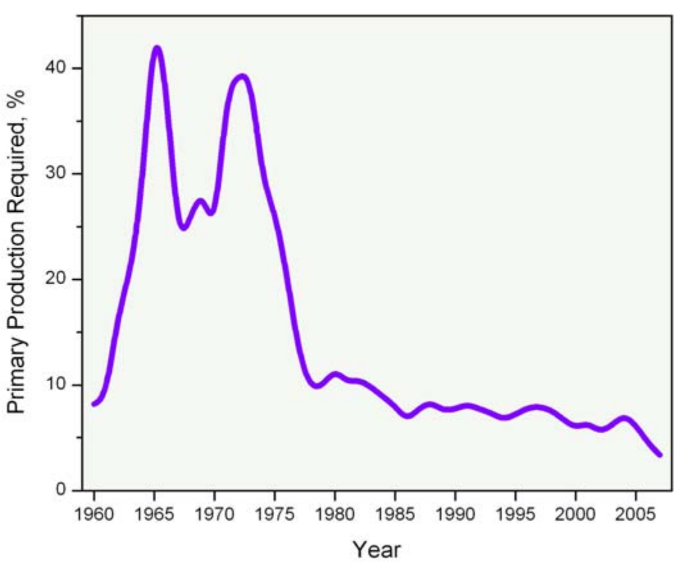

Figure 7.3 Total primary production required to support landings.

TLL for the system has declined steadily since 1960. This reflects the changes that have been observed in large piscivorous fish in the region during the 1960s and as recently as in the 1990s, as well as a major change in the composition of the landings. More recently, landings have been dominated by molluscs and small pelagic fishes. The higher TLL in the 1960s reflects the representation of cod, haddock, and silver hake in the ICNAF fishery, while the decline in the 1970s reflects a high proportion of small pelagic fishes in catches by the distant water fleets of that era (Figure 7.2). Further declines in the 1980s reflect the dominance of surf clams, ocean quahogs, Atlantic menhaden, and continued declines in groundfish in the landings by the U.S. industry, after the imposition of extended jurisdiction (the 200 mile limit) in 1977. The continued decline in TLL in the 1990s and through 2007 resulted from directed fishing on large spiny dogfish, white hake, and cod, coupled with increased landings of Atlantic mackerel, Atlantic herring, sea scallops, and steady landings of Atlantic menhaden (Figure 7.2). Note that these results differ from those based on research vessel surveys (Figure 6.4) in that the survey estimates do not include shellfish and that the small pelagic fishes at lower trophic levels are less catchable in the bottom trawl surveys than demersal fish. Over the almost 50 year period, the TLL in the region declined by more than a full trophic level, perhaps suggesting a much more simplified ecosystem at present, and a focus on landing species that are at a much lower trophic level.

Primary Production Required

Other approaches have been developed to measure the impact of fishing on large regions of the global oceans [33]. Thorough either direct consumption or transfer of energy, every trophic component of a marine ecosystem is connected to the primary production in that particular region. A metric known and PPR (primary production required) can be used to measure the impact of fishery removals in a particular region. This quantity measures the impact of fishing on the base of the food web and is sensitive to the amount of landings. By accounting for landings and trophic efficiencies, the percentage of primary production being utilized in a region can used to judge whether the amount removed is sustainable or excessive in relation to ecosystem overfishing.

PPR was calculated for the NES LME to monitor historic and recent fishery requirements during 1960-2007. The percentage of primary production required to support landings during the mid 1960s to 1970s was very high, averaging about 33% (Figure 7.3). This trend reflected the large scale removal of accumulated cod, haddock, and silver hake biomass that occurred over a short time horizon, an indication that this level of energy removal was unsustainable. PPR declined rapidly in the mid to late 1970s to about 10% in 1978, reflecting an overall decline in landings and a dominance of small pelagic fishes that function at a lower trophic level. PPR has slowly declined from about 10% in 1980 to less than 5% in 2007 (Figure 7.3).

PPR to Support Herring and Mackerel Landings

Atlantic mackerel and herring not only support important fisheries in the NES LME, but are also key prey items in the diets of many of the regions predators. The PPR metric was calculated separately for Atlantic herring and Atlantic mackerel to track PPR required to sustain the fisheries on these important prey species. PPR for Atlantic herring peaked at 9.4% in 1968 and at 8.6% for Atlantic mackerel in 1972 (Figure 7.4). Both of these stocks collapsed shortly thereafter, following several years of intense fishing. The percentage of these two species in the diets of predators also declined following this period of overexploitation [30]. During the early 1980s, PPR for herring dropped to below 1%, gradually increasing to about 2% in 2006-2007 (Figure 7.4). This is related to a recovery in the Gulf of Maine-Georges Bank herring complex and a gradual improvement in the herring fishery. PPR for Atlantic mackerel declined to very low levels in 1979, increased to about 1.4% in 1990, declined to very low levels for a decade, and more recently increased to about 1% (Figure 7.4). The current level of mackerel landings from the NES LME represents a small proportion of the regional primary production. The occurrence of Atlantic herring and mackerel in predator diets increased during the 1990s and 2000s following the recovery of both stocks.

The Northeast Otter Trawl Fishery

Performance in the Northeast otter trawl fishery (large mesh nets targeting groundfish, dogfish, monkfish, and skates) is a general barometer for how well the finfish industry in the Northeast has fared during the last 40-50 years. Three variables, total pounds landed, total value (in 2000 dollars) and total number of fishing vessels, were monitored during 1964-2007. Total landings have greatly declined during the period. Landings declined from a series high of 386 million lbs in 1964 to 176 million lbs in 1976, increased to 348 million lbs in 1982 and declined steadily to about 50 million lbs in 2006 (Figure 7.5). Total value averaged about 110 million dollars during 1964-1975, doubled to over 200 million dollars in 1982, and plunged to about 57 million dollars in 2006 (Figure 7.5). On a per vessel basis, average revenue actually increased during 2001-2006. The number of otter trawl vessels averaged about 300 during 1964-1976, increased to over 600 in 1984, and declined to 189 in 2006 (Figure 7.5). The general decline in these measures can be attributed to overall declines in the groundfish biomass during 1964-2007 and management restrictions implemented during the last decade. The increase in number of vessels during the late 1970s and early 1980s occurred in part because of government subsidies and short-term increases in groundfish biomass, subsequent short term increases in landings and revenue followed.

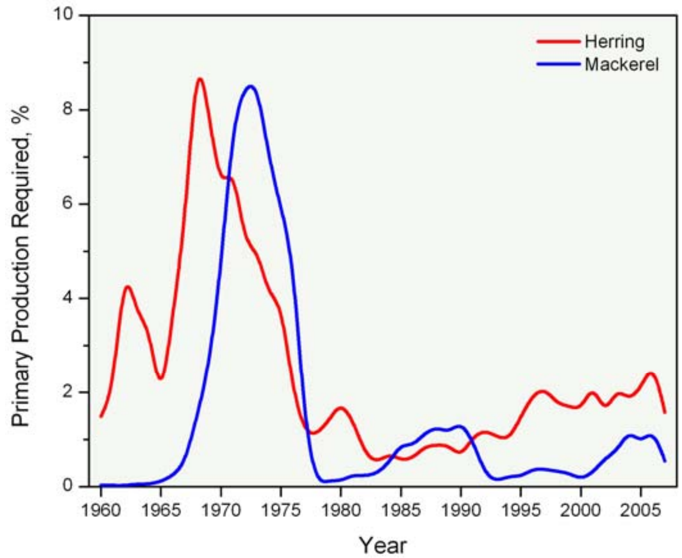

Figure 7.4 Primary production required to support mackerel and herring landings.

Population Trends and Per Capita Income

Trends in the population and per capita income for 5 coastal counties in or adjacent to large metropolitan areas in the Northeast and Mid-Atlantic

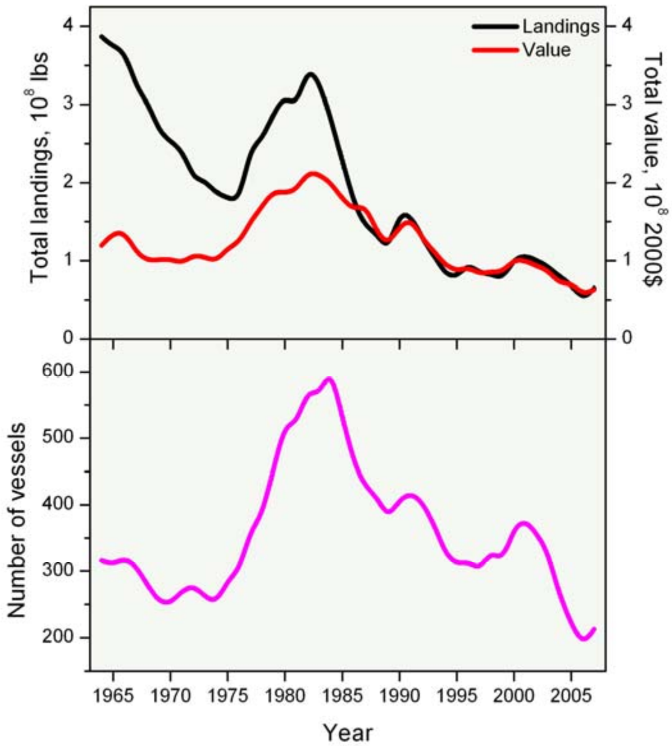

Figure 7.5 Total groundfish landings and value in the upper panel. Number of vessels in the lower.

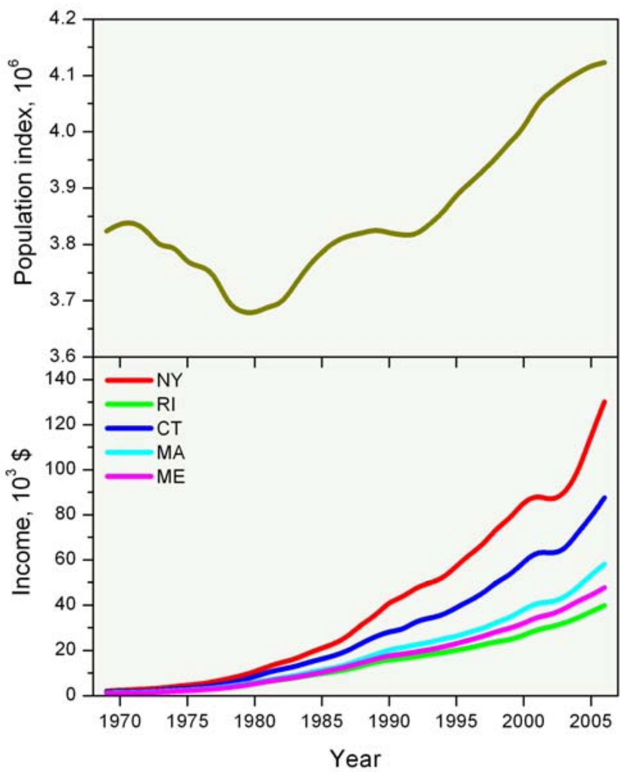

Figure 7.6 Population index and state incomes.

regions were used in this analysis of human drivers of ecosystem change. Near shore population and disposable income are proposed as indicators of seafood demand in the region. They also may be useful predictors of human impacts on near shore environments indicative of increased nitrogen loading and stress on estuarine habitats. After declining slightly in the 1970s, the northeast coastal population index increased steadily during 1981-2006 (Figure 7.6). Per capita income (measured in 2000 dollars) increased steadily from 1969-2006 particularly in the New York and Boston metropolitan areas (Figure 7.6).

8 Integrative Ecosystem Measures

The NES LME has undergone sustained perturbations directly related to human activities (particularly harvesting) and climate and environmental forcing over the last four decades. In this section, we provide an integrated evaluation of changes in anthropogenic and physical drivers, associated pressures, and ecological states for this system. We focus on information from 1977 to the present, reflecting the period for which observations were consistently available for most of the assembled indicators of drivers, pressures and states. The analysis uses 18 indicators of anthropogenic drivers and pressures, 25 metrics of climate and physical change and 26 indicators of biotic state to characterize change in ecological state on the northeast shelf (see appendix for variable names used in Figure 8.1).

We transformed each of the indicator series to standard normal deviates (where the mean is subtracted from each observation and this difference is divided by the standard deviation of the series – see Glossary) to place all variables on a common scale. We have color coded the standardized variables according to five levels (quintiles) for each series and constructed graphical arrays representing time trends for each series in each of the three major categories identified above (i.e., anthropogenic drivers and pressures; climate/physical changes; biotic state).

The time trajectory of anthropogenic drivers and related pressures indicates steady increases in human population growth in coastal counties and in disposable income. Both of these factors potentially exert pressures through increased demand for seafood, and impacts on coastal environments (through pollution, habitat loss and coastal zone alteration). In contrast, indicators related to groundfish landings, revenues and fishing effort, and mean trophic level of the catch show overall declines over time (Figure 8.1 top panel). Declines in mean trophic level of the landings reflect, in part, the transformation from a groundfish dominated fishery to one increasingly exploiting other ecosystem components, notably invertebrates and small pelagic fishes. Overall declines in the primary production required to support the observed catch for all species are related to changes in the mean trophic level of harvest and declines in the fishery removals; similar recent declines for the small pelagics are related to sharply reduced exploitation rates. The overall pattern is one of decadal-scale shifts with major declines in groundfish-related metrics in the first decade of the series as human population size and income increased. The transformation was complete by the last decade in the series.

The array of climate and physical indicators reveals a diffuse transition beginning in the mid-to-late 1990s, reflecting an increase in the climate drivers (NAO and AMO) and the suite of associated physical pressures including the temperature-related metrics, river flow, and wind stress in the more northern locations (Figure 8.1 middle panel). In contrast, the first decade showed higher salinity values and higher wind stress in the more southern locations.

Consideration of the ecosystem state variables again reveals a transformation in system state that appears to be related to both anthropogenic change and climate/physical factors. Changes in key indicators related to fishery resource status show a transition in the early 1990s (Figure 8.1 bottom panel). In particular we observed increases in total fish biomass, elasmobranchs, small pelagics, crustaceans, and the ratio of pelagic to demersal fish (which did decline at the end of the series). We attribute these increases to the direct and indirect effects of exploitation on the system. Consumption by marine mammals also increased steadily during this period.

The other major class of metrics included in the array biotic ecosystem indicators is the abundance of five major copepod species on Georges Bank in both spring and fall. These show an increase in abundance of smaller-bodied species starting in the early 1990s and extending to the early years of this decade. The period of high abundance of smaller copepod species on Georges Bank (see Figure 4.10) coincides with strong negative salinity anomalies on Georges Bank.

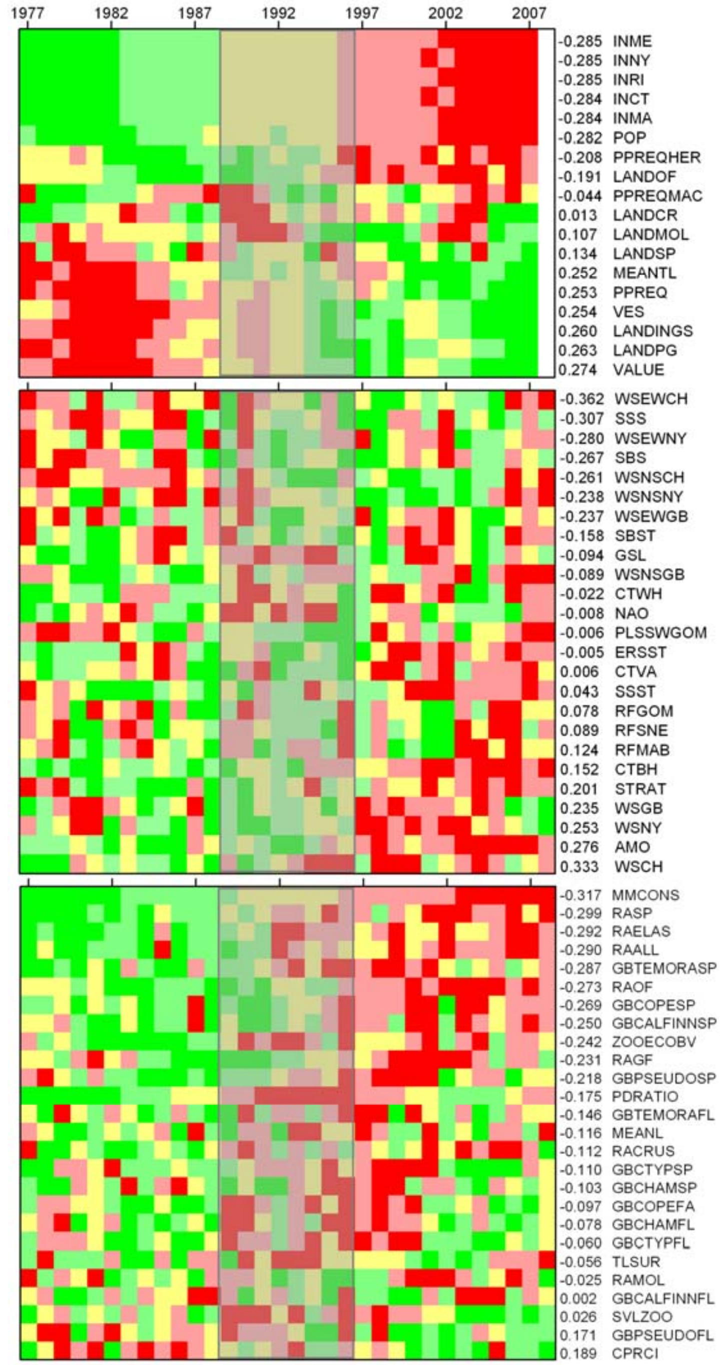

Figure 8.1 Human-related (top panel), climate and physical forcing (middle panel) and biotic ecosystem (bottom panel) indicators of change. The series have been ordered using a Principal Components Analysis to group variables showing similar patterns. Shaded box indicates transition period.

We can provide an alternative view of the changes in the driver, pressure, and state variables by first constructing a new set of indices that reduces the original large number of variables to a smaller group that combines information from the entire suite. We have used a Principal Components Analysis for this

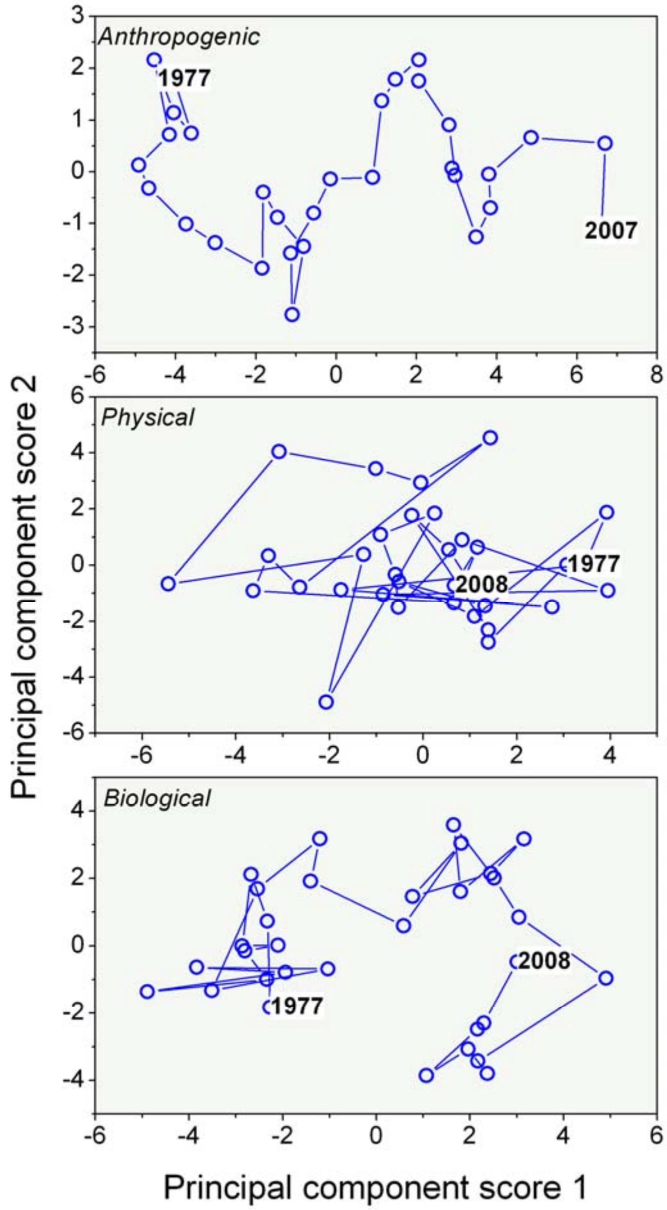

Figure 8.2 Time trajectories of change in canonical phase space for anthropogenic, physical, and biotic indicator variables.

purpose. This technique involves the construction of a set of mutually independent linear combinations of the original variables (see Glossary for a more detailed description).

Taking this approach, we find that the original set of 18 anthropogenic variables can be reduced to two 'combined' indicators that explain over 75% of the variance in the full set of indicators. The first principal component (PC) in fact accounts for 66% of the variance in the suite of indicators. The contributions of the original variables to the first PC are remarkably even, with the relative contributions of the variables reflecting strong inverse relationships between the human population and income variables and the fishery-related variables. Only the landings of crustaceans, molluscs and the primary production required for the small pelagics had low loadings (and these were strong in the second principal component as expected). A plot of the time trajectory for the first PC against the second PC provides a view of relative changes in each (Figure 8.2; top panel). The trajectory indicates a strong directional change in this set of variables as would be inferred from Figure 8.1).

For the array of 25 climate and physical variables considered, we find that the first six principal components explain 75% of the variance in the full set. The first PC, which explains 20% of the variance is dominated by salinity (surface and bottom) and wind stress variables with a strong opposite contribution by the Atlantic Multidecadal Oscillation. The second PC, explaining an additional 16% of the variance, reflects strong contributions by water temperature at coastal locations, sea surface temperature on the shelf, and Gulf Stream position with opposite contributions by river flow indicators and wind stress in southern locations. Unlike the clear directional change in anthropogenic variables, a more complex and variable pattern emerges for the physical variables with no discernable trend when only the first two principal components are considered (Figure 8.2 middle panel).

Finally, a more clearly defined directional change is evident for the biotic indicator set (Figure 8.2 bottom panel). The first six principal components explain 77% of the variance of the original 26 variables. The first PC strongly reflects the relative abundance of all species groups represented in the trawl surveys, marine mammal consumption, and spring abundance indices of Georges Bank copepod species. The second component is dominated by autumn abundance of Georges Bank copepod species, the pelagic to demersal fish ration and negative loadings of marine mammal consumption, relative abundance of survey species groups.

If we plot the time course of the first principal component for each of the three major groups, we see a strongly increasing trend in the anthropogenic indicators (Figure 8.3 top panel). The trajectory of the first PC for the physical metrics is decreasing, reflecting the influence of salinity and other variables (Figure 8.3 middle panel). The PC indicator for biotic factors is again increasing as a result of the dominant influence of factors such as increasing abundance of major species groups represented in the trawl survey (Figure 8.3 bottom panel).

Ecosystem Overfishing

The need for the adoption of an ecosystem approach to management of marine ecosystems is now broadly accepted. A necessary corollary for its implementation is the specification of targets and limits to exploitation in an ecosystem context. Link [28] discusses this issue in the context of a suite of ecosystem indicators. Murawski [34] suggested that an ecosystem could be considered overfished if one or more of the following criteria were met:

- Biomasses of one or more important species assemblages or components fall below minimum biologically acceptable limits, such that:
    1) recruitment prospects are significantly impaired,
    2) rebuilding times to levels allowing catches near MSY are extended,
    3) prospects for recovery are jeopardized because of species interactions,
    4) any species is threatened with local or biological extinction;
- Diversity of communities or populations declines significantly as a result of sequential ''fishing-down'' of stocks, selective harvesting of ecosystem components, or other factors associated with harvest rates or species selection;
- The pattern of species selection and harvest rates leads to greater year-to-year variation in populations or catches than would result from lower cumulative harvest rates;
- Changes in species composition or population demographics as a result of fishing significantly decrease the resilience or resistance of the ecosystem to perturbations arising from non-biological factors;
- The pattern of harvest rates among interacting species results in lower cumulative net economic or social benefits than would result from a less intense overall fishing pattern or alternative species selection;
- Harvests of prey species or direct mortalities resulting from fishing operations impair the long-term viability of ecologically important, non-resource species (e.g., marine mammals, turtles, seabirds).

According to these criteria, Murawski [34] determined that the NES LME was subject to ecosystem overfishing.

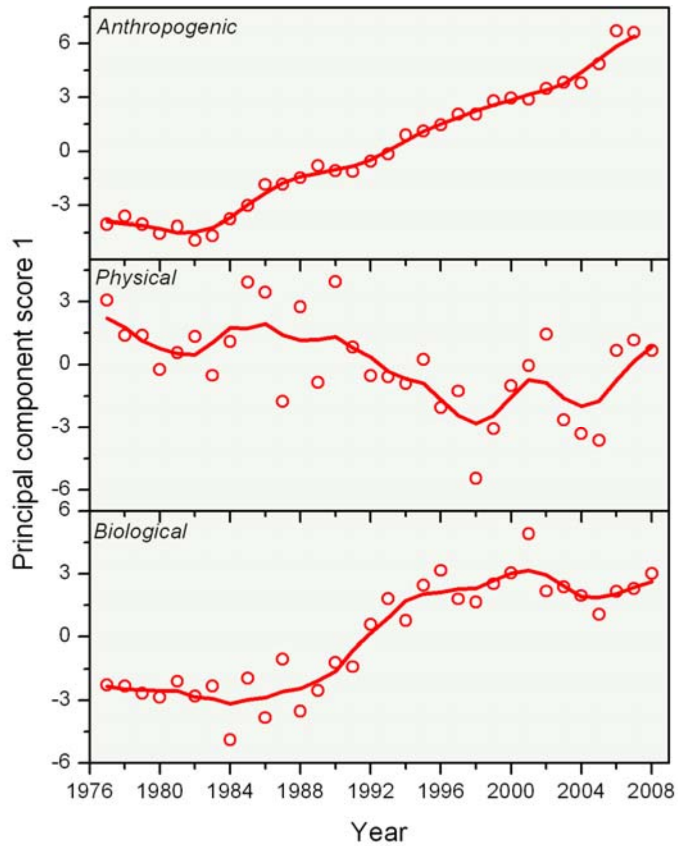

Figure 8.3 Time trends for the first principal components for anthropogenic, climate/physical, and biotic indicators.

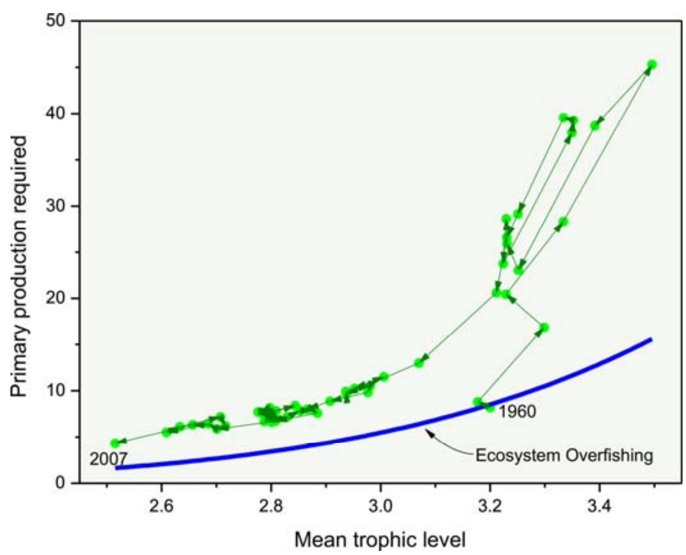

Figure 8.4 Time trajectory of primary production required and mean trophic level of the catch for the Northeast continental shelf large marine ecosystem. All points above the smooth curve are classified as overfished from an ecosystem perspective according to the criteria of Tudela et al. [1].

Tudela et al. [2] provided a meta-analysis of 49 ecosystems (including parts of the NES LME) to which these criteria could be applied and for which estimates of PPR and mean trophic level (TL) were available. The demarcation point between overfishing and sustainably fishing in the context of changes in primary production required and mean trophic level was identified using these *a priori* overfishing classifications. In this representation, losses incurred by fishing at low trophic levels affect the energy available to higher trophic levels and the interplay between the mean TL (Figure 7.2) and the primary production required to support the observed fishery yield (see Figure 7.3) determines the ecosystem classification.

Classification of ecosystem status for the NES LME for the period 1960-2007 is provided in Figure 8.4. Only at the start the series (1960-61) does the system meet the criteria of sustainable fishing at the ecosystem level according to the Tudela et al. criterion. At the height of distant water fleet activities, characterized by both high mean trophic level of the catch and high appropriation of available primary production, a steadily increasing level of ecosystem overfishing occurred. Despite the drop in PPR over the last two decades and the improvement in condition of some components of the system, the concomitant drop in mean trophic level still results in an a classification of ecosystem overfishing in 2007 (Figure 8.4).

Summary

The U.S. Northeast continental shelf has experienced large-scale perturbations over the last four decades due to human activities (notably harvesting) and environmental change (including climate-related impacts). The need for holistic assessments of ecosystem status in relation to natural and anthropogenic forcing is now widely recognized as a critical element in support of the development of an ecosystem approach to management. In particular, linking the pressures related to anthropogenic and natural drivers of ecosystem change to alteration in system status is an essential first step in developing effective management strategies. We have compiled key indicators of climate, physical dynamics, ecosystem state, and human activities and conditions to evaluate the status of this large marine ecosystem.

Decadal and multidecadal scale changes in climate and physical forcing factors affecting the ecosystem are evident at a number of different levels. Water temperatures have increased in coastal locations and on the continental shelf from a low in the late 1960s to the present. There has been corresponding increase in high temperature (>16°C) and a relative decline in intermediate (5-15°C) thermal habitat available for marine organisms. Increases in temperature and decreases in salinity have led to increases in water column stratification from a low in 1984 to the present that has had a profound effect on primary and secondary productivity.

The changes observed in some of the physical variables have been accompanied by clear changes in some of the biotic variables. The decreases in salinity have been accompanied by concomitant changes in an index of larger-bodied phytoplankton species (principally diatoms) in the ecosystem. A related index of water column stratification is closely related to the time series change in the total biomass of zooplankton and changes in the species composition copepod communities. There has been a pronounced shift from a demersal fish-dominated community to one dominated by elasmobranchs and pelagic fish. The fish community has also been affected by a persistent change in conditions that favor temperate-cold water fish community to one favoring warmer water species.

The overall biomass of the entire fish community as indexed by trawl surveys has increased over the last four decades as elasmobranchs and small pelagic fishes have increased in abundance even as other groups such as groundfish have undergone decreases. Some of these changes reflect apparent species replacements as heavily exploited species declined. The mean trophic level of fish in trawl surveys has fluctuated without trend. In contrast, the mean trophic level of the catch (invertebrates and vertebrates) has declined steadily since 1960, reflecting changes in the abundance of economically important species.

Estimates of the primary production required to support observed catch levels indicate that recent fisheries are probably more sustainable than those in the 1960s and 1980s for all species and for small pelagic species specifically.

The human component has been a critically important agent of change in this large marine ecosystem. Economic indicators for the groundfish fishery suggest that this resource has been in a long-term state of decline. Trends in human population and disposable income in the region suggest that human induced pressures on marine resources will remain high and perhaps continue to increase in the future.

Although marked improvement in the condition of some components of the NES LME is now evident under more effective management, the system remains classified as experiencing overfishing from an ecosystem perspective according to criteria of Murawski [33] and Tudela et al.[2] .

Future Directions and Research Needs

This is the first of a planned series of Ecosystem Status Reports to document change in the NES LME. We have focused on metrics of ecosystem change in response to drivers and pressures on this system. The anthropogenic drivers highlighted in this report and the associated pressures exerted have been centered on harvesting activities and their impacts on the NES LME. Although fishing is recognized as a dominant agent of ecosystem change in marine systems in general, in future editions of this status report, we will strive to incorporate additional measures of human impacts on the NES LME. Coastal development, point and non-point source pollution, and other anthropogenic factors all have important effects in nearshore waters in particular [35]. We will also seek to represent how natural and anthropogenic changes affect human communities dependent on this system for vital goods and services. The economic component of this report has focused on the iconic groundfish fishery. Future updates will include additional fishery sectors. We will also attempt to include consideration of aquaculture production, an additional important use of the marine environment.

Important local studies of the role of humans as part of this large marine ecosystem are available [36]. However, studies on the broad spatial and temporal scales represented in this report have not yet been conducted for these human-related metrics.

To date, we have applied one measure of ecosystem overfishing to characterize the state of this system. We are currently exploring other indicators of ecosystem condition in response to exploitation for consideration in future editions of this report.

We have identified strong trends in human drivers of change in this system, including population growth in coastal counties and in disposable income, both of which will result in an escalation of anthropogenic pressures. Projections of future climate change for the northeast, if realized, also will result in changes in ecosystem pressures [37]. Increases in water temperatures and changes in other hydrographic properties (salinity, stratification) are anticipated and these will affect the provision of ecosystem goods and services. Some of the changes documented in this report presage future change if current trends in temperature and other factors continue or accelerate under some climate change scenarios. The documented changes already experienced may serve as early warning indicators of future change. For example, if the current trend in water mass stratification continues, we anticipate important changes in nutrient regeneration in the system, affecting the flow of energy and overall levels of productivity. Observed changes in the amount of thermal habitat and in the relative species composition of fish communities with respect to temperature preferences indicate the potential for strong changes in fish community structure in the NES LME.

In this report, we have focused on documenting change in a suite of physical, ecological, and human variables and have made initial attempts to relate changes in ecosystem state variables to proximal pressures. These pressures are in turn related to underlying drivers of change. The observed changes in the system indicate a clear need to explore their underlying mechanistic basis and to determine causal pathways. Tracing important changes in this system has been made possible by the strong commitment to sustained monitoring by many agencies and institutions in this region. It is no less important to frame hypotheses concerning the mechanisms of change and to test these hypotheses using an appropriate combination of process-oriented research, comparative analysis, and integrative modeling.

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Glossary

Biogeochemical Cycle: The path which a chemical takes as it moves through biological organisms and abiotic areas which the organisms live in. Chemical compounds are transferred from organism to organism and to different parts of the ocean through numerous biogeochemical cycles.

Chemical Speciation: The processes by which different types (species) of chemicals are formed.

Driver: In the Driver-Pressure-State-Impact-Response sequence, a driver is generally a broad forcing factor that creates specific pressures on the ecosystem being studied.

Impact: In the Driver-Pressure-State-Impact-Response sequence, an impact is the effect on humans of a changed state in the ecosystem being studied.

Indicator: In environmental or ecological terms, an indicator is a statistic that has been shown to be representative of a particular aspect of the environment. Indicators in an ecosystem can show overall trends, can point to potential areas needing management, or can help show the effects of current management. Examples we use are temperature, salinity, biomass of species and aggregated groups, etc. One analogy is the stock quote for a company which shows the 'health' of that company in general terms. Similarly the NASDAQ is an aggregate indicator of a number of stocks, which is often used as one of the indicators to determine the economic health of the United States.

Pressure: In the Driver-Pressure-State-Impact-Response sequence, specific pressures are created by the drivers. The pressures cause changes in state of one or more elements of the ecosystem being studied.

Principal Components Analysis (PCA): A commonly used statistical technique designed to take possibly correlated sets of variables and reduces it to a smaller set of uncorrelated variables, the principal components. Each principal component (PC) is a combination of all the initial variables into one number. In each principal component, some of the original variables are typically more important than others. The first principal component can be considered the most important as it explains most of the variance. The second PC explains the next most of the variance, etc.

Response: In the Driver-Pressure-State-Impact-Response sequence, a response is a change in management strategy based on changes in state of the ecosystem and impacts on humans.

Standardized Anomalies: In statistics, an anomaly is a measure of how far from the mean a given observation is. So, if the mean temperature over 10 years in a given oceanic region is 18.2°C, and the temperature during one of the years was 16.2°C, the anomaly would be -2.0. To make comparisons more meaningful, we use standardized anomalies which effectively convert all indicators to the same scale. A standardized anomaly is each anomaly divided by the standard deviation for a set of data. So a standardized anomaly of -2 in a temperature time series is as likely (or unlikely) to occur as a standardized anomaly of -2 in a salinity time series.

States: In the Driver-Pressure-State-Impact-Response sequence, a state is the current status or value of a given facet of the ecosystem being studied.

Thermohaline circulation: Also referred to as the 'ocean conveyer belt', (or more formally, the Meriodonal Overturning Circulation), the thermohaline circulation is that part of the global ocean circulation which is driven by density gradients, which are in turn caused by temperature and salinity differences in the ocean. In general, water flowing to the north through wind driven currents, such as the Gulf Stream, sinks near the North Pole due to the creation of ice, which increases the salinity in the underlying water while also making it cold. This water flows into the ocean basins, with the bulk of it rising (upwelling) in the Southern Ocean and North Pacific. This circulation permits mixing between the ocean basins, decreasing the differences between them.

Appendix Variables for Figure 8.1

NAO	North Atlantic oscillation
AMO	Atlantic multidecadal oscillation
GSL	Gulf Stream Location
PLSSWGOM	Percent Labrador-Subarctic Slope Water in the Gulf of Maine
RFGOM	River Flow-Gulf of Maine
RFMAB	River Flow-Middle Atlantic Bight
RFSNE	River Flow-Southern New England
WSCH	Wind Stress, Cap Hatteras
WSNY	Wind Stress, New York
WSGB	Wind Stress, Georges Bank
WSEWCH	Wind Stress East-West, Cap Hatteras
WSEWNY	Wind Stress East-West, New York
WSEWGB	Wind Stress East-West, Georges Bank
WSNSCH	Wind Stress North-South, Cap Hatteras
WSNSNY	Wind Stress North-South, New York
WSNSGB	Wind Stress North-South, Georges Bank
ERSST	Extended Reconstructed SST
CTVA	Coastal Temperature, Virginia
CTWH	Coastal Temperature, Woods Hole
CTBH	Coastal Temperature, Boothbay
SSST	Survey sea surface temperature
SBST	Survey bottom sea temperature
SSS	Survey surface salinity
SBS	Survey bottom salinity
STRAT	Stratification
CPRCI	Continuous Plankton Recorder Color Index.
ZOOECOBV	Zooplankton Ecosystem Biovolume
GBCOPESP	Georges Bank Copepods, Spring
GBCOPEFA	Georges Bank Copepods, Fall
GBCALFINNSP	Georges Bank *C. finmarchicus* , Spring
GBPSEUDOSP	Georges Bank *Pseudocalanus spp.* , Spring
GBTEMORASP	Georges Bank *T. longicornis* , Spring
GBCTYPSP	Georges Bank *C. typicus* , Spring
GBCHAMSP	Georges Bank *C. hamatus* , Spring
GBCALFINNFL	Georges Bank *C. finmarchicus* , Fall
GBPSEUDOFL	Georges Bank *Pseudocalanus spp.* , Fall
GBTEMORAFL	Georges Bank *T. longicornis* , Fall
GBCTYPFL	Georges Bank *C. typicus* , Fall
GBCHAMFL	Georges Bank *C. hamatus* , Fall
SVLZOO	Small v Large Zooplankton
PDRATIO	Pelagic to Demersal Ratio
MEANL	Mean Length
TLSUR	Total Length Surveyed Species
MMCONS	Marine Mammal Consumption
RACRUS	Relative Abundance, Crustaceans
RAELAS	Relative Abundance, Elasmobranch
RAGF	Relative Abundance, Ground Fish
RAMOL	Relative Abundance, Mollusc
RAOF	Relative Abundance, Other Fish
RASP	Relative Abundance, Small Pelagics
RAALL	Relative Abundance, All Species
LANDPG	Landings, Principal Groundfish
LANDOF	Landings, Other Fish
LANDSP	Landings, Small Pelagics
LANDCR	Landings, Crustaceans
LANDMOL	Landings, Mulluscs
MEANTL	Mean Trophic Level
PPREQ	Primary Production Required, Landings
PPREQHER	Primary Production Required, Herring
PPREQMAC	Primary Production Required, Mackerel
VES	Vessels
LANDINGS	Landings
VALUE	Value
POP	Population
INNY	Income, New York
INRI	Income, Rhode Island
INCT	Income, Connecticut
INMA	Income, Massachusetts
INME	Income, Maine

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