Northeast Fisheries Science Center Reference Document 12-07

Ecosystem Status Report for the Northeast Shelf Large Marine Ecosystem - 2011

by the Ecosystem Assessment Program

April 2012

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by the Ecosystem Assessment Program
NOAA National Marine Fisheries Service
Northeast Fisheries Science Center, 166 Water St., Woods Hole, MA 02543

US DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Northeast Fisheries Science Center
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Northeast Fisheries Science Center Reference Documents

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Ecosystem Status Report

For the Northeast Shelf Large Marine Ecosystem

Northeast Fisheries Science Center **2011**

Main Findings

- ***The Northeast Shelf Large Marine Ecosystem (NES LME) can be divided into four Ecological Production Units, which can in turn provide spatial domains for Ecosystem Based Fisheries Management.***
- ***Atlantic basin scale climate indices, the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation, are at extreme levels, which is reflected in local scale changes in temperature and precipitation, among other parameters.***
- ***The physical nature of the NES LME continues to change, notably there has been a decline in Labrador origin water, which influences salinity and food web processes in the ecosystem, and, there has been an increase in water column stratification, which affects the vertical transport of nutrients.***
- ***Recent increases in primary phytoplankton production are not matched by increases in secondary zooplankton production raising the concern that the phytoplankton community structure is shifting to species that fail to effectively enter the food web.***
- ***Many benthic resources have increased in recent years, which can be attributed to both fishery management strategies and environmental effects. The total biomass of fish species remains high reflecting the response of interacting species groups to fully utilize the available energy in the ecosystem.***
- ***Though revenues have remained at high levels in the commercial fishing industry, employment in marine-related employment sectors has declined in recent years.***

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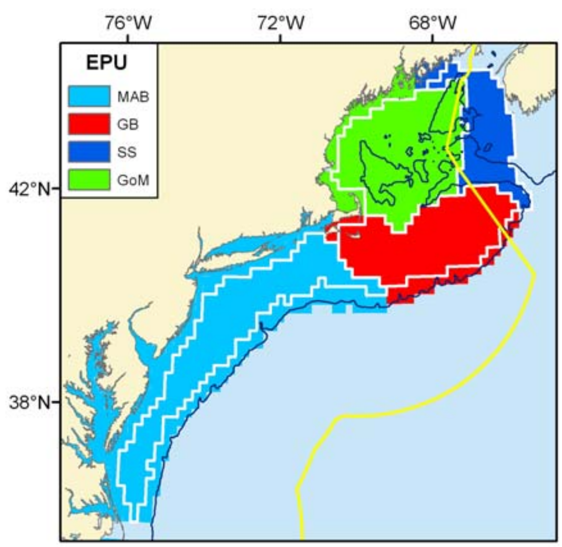
1 Introduction

The Northeast U.S. Continental Shelf Large Marine Ecosystem (NES LME) has supported important commercial fisheries for several centuries. This highly productive region has experienced important structural changes over the last several decades under intensive exploitation. Emerging evidence for important changes in physical forcing and ecological response in relation to climate variability in the North Atlantic further highlights the need to address the broad suite of anthropogenic and natural drivers in the system. Here, we update our earlier evaluation of the status of the Northeast U.S Continental Shelf Large Marine Ecosystem (*1*) and expand its focus to include further information on ecological subregions of the shelf.

A global consensus on the need to adopt a more holistic and integrated approach to management of ocean resources is now evident (*2-4*). In order to assess the status and trends of ecosystems and to evaluate the impact of different stressors, appropriate metrics must be identified and their overall utility for management validated. These metrics should be broadly representative of forcing factors and associated ecosystem states or processes. We designate the most informative and integrative metrics as indicators. Indicators can be broadly classified into natural and anthropogenic drivers, resulting pressures, and ecosystem states. For our purposes, we identify drivers as forcing factors such as climate and human population size underlying a constellation of pressures exerted on the system. These pressures include human-related impacts such as removal of living marine resources through harvesting, as well as shipping, pollution, and impacts to 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 representing local or regional physical manifestations of these broader pressures. We then identify indicators of

Figure 1.1 Map of study region on the Northeast continental shelf of the United States, showing the ecological production units. The core of each EPU is bounded by white, and the nearshore and shelf break special considerations areas are to the west or east of the core areas respectively. MAB – Mid-Atlantic Bight; GB – Georges Bank; SS – Scotian Shelf; GoM – Gulf of Maine.



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. Our objective is to characterize changes in the system state variables in response to forcing mechanisms associated with a spatially defined ecosystem. An understanding of the inter-relationships among drivers, pressures, and states is an essential prerequisite to moving toward a place-based, ecosystem approach to management.

Part of this place-based approach involves the recognition that the Northeast U.S. Continental Shelf Large Marine Ecosystem is composed of different regions with distinct patterns in oceanographic characteristics, primary production and fish distribution, among other factors. The NES LME has been divided into a set of Ecological Production Units (EPUs) based on analysis of physiographic and lower trophic level datasets (*5*) (Figure 1.1). Four primary subunits or EPUs were identified: Gulf of Maine, Scotian Shelf, Georges Bank, and Mid-Atlantic Bight. Additionally, primary subunits can be further divided, if appropriate, into nearshore and shelf break special consideration areas (denoted as white boundaries in Figure 1.1). The boundaries of the EPUs are open, and in our model formulations we permit movement of water, organisms and human vessels across them. These EPUs therefore provide a starting point for spatial considerations of ecosystem based management in the NES LME and are useful in framing the analyses presented in this report.

2 Climate Forcing

Climate patterns over the North Atlantic are important drivers of oceanographic conditions and ecosystem states. Steadily increasing atmospheric carbon dioxide levels not only affects climate on global and regional scales but also alters critical aspects of ocean chemistry. Here, we describe the atmospheric forcing mechanisms related to climate in this region including natural ocean temperature cycles in the North Atlantic, components of the large-scale circulation of the Atlantic Ocean (the so-called ocean conveyor belt system), large-scale atmospheric pressure systems, and issues related to changes in ocean salinity due to freshwater inputs.

Atlantic Multidecadal Oscillation

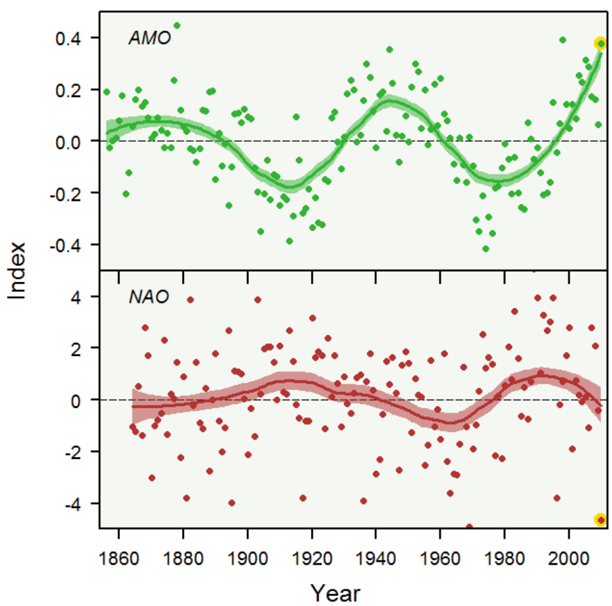
Multidecadal patterns in sea surface temperature (SST) in the North Atlantic are represented by the Atlantic Multidecadal Oscillation (AMO) index. The AMO signal is based on SST variability after detrending to remove the effects of anthropogenic forcing on temperature, revealing natural, long term cycles 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 hypothesized to be related to an enhancement of the North Atlantic branch of the deep thermohaline circulation, which is in turn directly related to dynamics of the Gulf Stream (*7*). The deep thermohaline circulation is the controlling mechanism of heat redistribution in the world ocean.

The AMO index shows a relatively cool period starting in the early 1960s and extending through the mid 1990s. Since 1997, the AMO has been in a warm phase that continued through 2010 (Figure 2.1). If past patterns continue to hold, the warm phase will potentially continue for the next several decades. The cool and warm phases of the AMO result in below and above average water temperature over most of the North Atlantic, respectively (Figure 2.2). However, it is notable that though the NES LME is warmer during the warm phase and cooler during the cool phase, the pattern of temperature is out of phase with the rest of the North Atlantic. Average conditions on the Shelf are cooler than conditions in either set of years associated with cool or warm phases of the AMO.

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 (*8*). As the relative strengths of these two pressure systems vary, characteristic patterns of

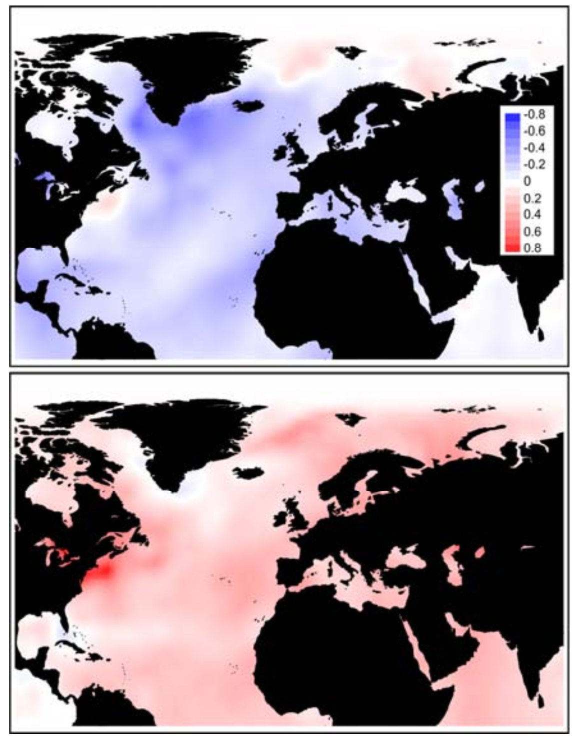
Figure 2.1 Smoothed trends in the winter AMO and NAO over the last ~150 years expressed as standardized anomalies. Data for 2010 highlighted in yellow.



temperature, precipitation, and wind fields are observed. An index of this dipole pattern has been developed based on the difference in sea level pressure over the Azores and over Iceland in winter (December- February). This North Atlantic Oscillation (NAO) index has been related to key oceanographic and ecological processes in the North Atlantic basin (*9*).

When the NAO index is high (positive NAO state) there is a northward shift and increase in westerly winds, and an increase in precipitation over southeastern Canada, the eastern seaboard of the United States, and northwestern Europe. High NAO years are associated with cooler water temperatures off Labrador and northern Newfoundland, influencing the formation of Deep Labrador Slope water, but warmer temperatures off the United States. Conversely, when the NAO index is low (negative NAO state), there is a southward shift and decrease in westerly winds and storminess, along with drier conditions over southeastern Canada, the eastern

Figure 2.2 Temperature anomalies in °C during cool (top panel) and warm (bottom panel) phases of the AMO. Anomalies formed by comparing upper and lower AMO quartile years to the long-term mean.



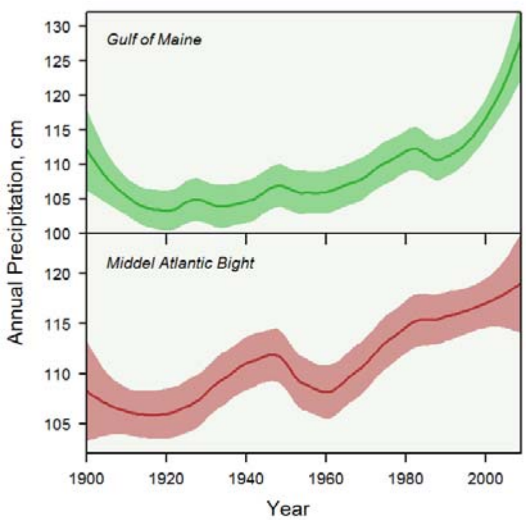
United States, and northwestern Europe. Low NAO years are associated with warmer water temperatures off Labrador and Newfoundland but cooler temperatures off the eastern United States.

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 in recent decades, and the 2010 index value was the second lowest in the time series. 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.

Freshwater Input via Precipitation

Precipitation affects a wide range of ocean processes such as salinity, water column stratification, coastal circulation, and nutrient supply. Precipitation can have a dominant effect on salinity in the Middle Atlantic Bight (*10*), whereas freshening associated with the Labrador current is thought to be dominant in the Gulf of Maine (*11*). Increased precipitation in the catchment areas associated with the Northeast Shelf would be expected to increase nutrient supply to the ecosystem, especially in the near coastal and river plume areas, resulting in

Figure 2.3 Smoothed trends of annual precipitation in the Gulf of Maine and Middle Atlantic Bight catchment areas over the last century.



increased production during seasons with higher rainfall (*12*). Precipitation of all types has increased in the catchment regions associated with the Northeast Shelf to levels not seen in a century-long national database. Average annual precipitation in the Gulf of Maine area has been trending to record high levels over the past two decades of the time series (Figure 2.3). This has likely compounded the freshening associated with the Labrador Current. Precipitation was episodically high in the Middle Atlantic Bight during the 1950s, but not as high as the levels over the last three decades.

3 Physical Pressures

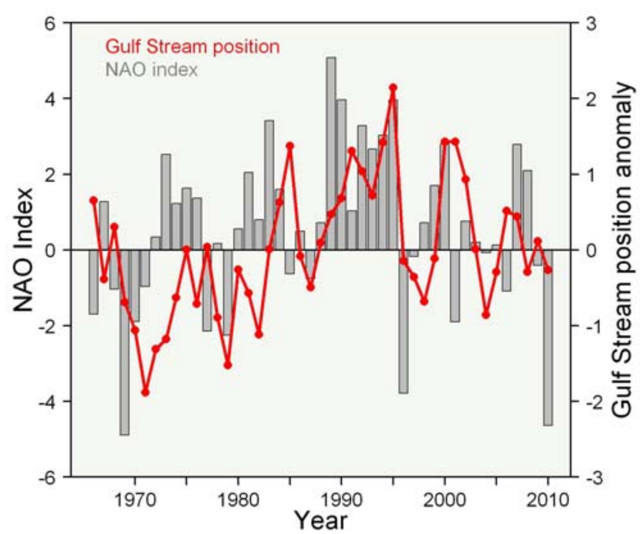
Oceanographically, the NES LME is located on the western boundary of two large oceanic gyres which span the North Atlantic Basin. The source waters feeding the NES LME include contrasting water masses carried by the converging currents from these two gyres: the Gulf Stream carrying warm and salty water from the south and the Labrador Current carrying cold and fresh water from the north. Climate oscillations (e.g., NAO, AMO) and long-term trends (e.g., warming, acidification) can lead to changes in the intensity of these currents, their position relative to the NES LME, and the water masses that they carry *(13-16)*, ultimately influencing the physical environment of the NES region.

Climate drivers impact the physical environment of the NES LME through a combination of external pressures at its boundaries and direct effects on internal conditions. External influences on the NES include the Gulf Stream at the southern and offshore boundary, the Labrador Current at the northern boundary, river discharges at the coastal boundary and winds and atmospheric fluxes at the sea surface. In addition to these external pressures, climate processes also directly influence the internal physical environment of the NES, altering the horizontal and vertical distribution of temperature and salinity. The combination of these physical pressures can cause significant 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 and its extension transport a significant amount of heat from the tropics to higher latitudes. Vigorous cooling along the Gulf Stream's path returns a considerable amount of this heat to the atmosphere, influencing storm tracks in the

Figure 3.1 Index expressing the position of the north wall of the Gulf Stream and the wintertime North Atlantic Oscillation index, both expressed as standardized anomalies. A positive Gulf Stream anomaly indicates a northward shift in the position.

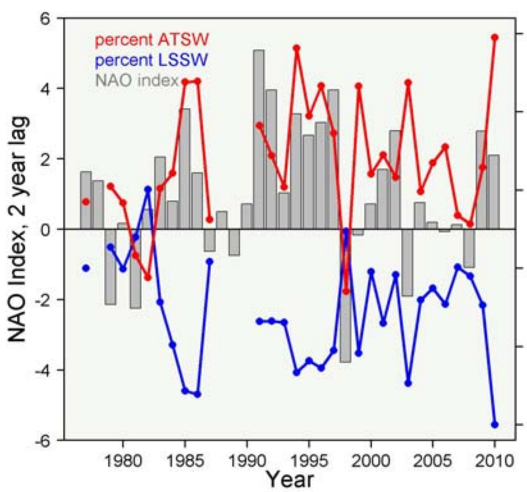


North Atlantic and resulting in milder climates in Europe compared to similar latitudes in North America (e.g., Ireland vs. Labrador). At high latitudes, the cooled water sinks and ultimately returns southward in deep-reaching currents beneath the warmer tropical and subtropical waters. This so-called Atlantic Meridional Overturning

Circulation (AMOC) plays an important role in regulating earth's climate and the Gulf Stream is a dominant component of its vertical circulation.

Measurements of the Atlantic Meridional Overturning Circulation have only recently become available from estimates of the meridional flow integrated across the width of the North Atlantic (*17*). However, studies suggest that fluctuations in the strength of the AMOC are associated with changes in the basin-scale circulation in the North Atlantic, including shifts in the Gulf Stream path (*18*). Furthermore, shifts in the north-south position of the Gulf Stream are strongly correlated with temperature changes in the slope region offshore of the NES (*19*) and are a reliable indicator of bottom water temperature on the shelf (*20*): a northward shift in the Gulf Stream is associated with warmer shelf temperatures. Shifts in the position of the north wall of the Gulf Stream are a leading indicator of conditions on the shelf and indirectly related to the distribution of some commercially important fish species (*20*) as well as changes in plankton community composition (*21*).

Figure 3.2 Percent of Labrador Subarctic Slope Water (LSSW, blue) and Atlantic Temperate Slope Water (ATSW, red) in the deep Northeast Channel of the Gulf of Maine. The wintertime North Atlantic Oscillation index is also shown, shifted forward in time by two years (gray bars).



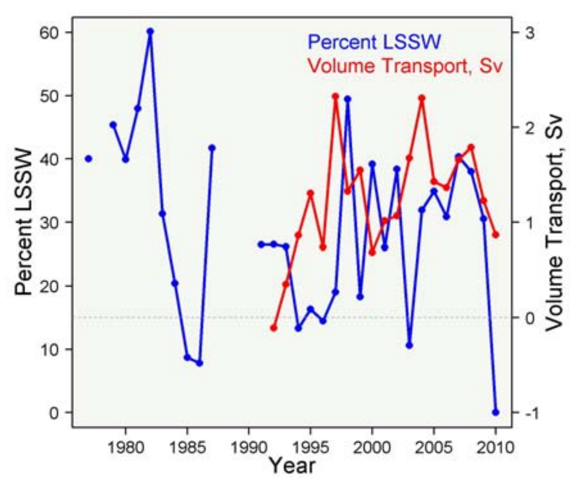
Interannual shifts in the position of the Gulf Stream are correlated with atmospheric fluctuations over the North Atlantic, including the changes in wind stress and buoyancy forcing that are associated with the NAO. The latitude of the Gulf Stream north wall is positively correlated with the NAO with a lag of 1-2 years (*22*). 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 early-1990s, and characterized by subsequent multiyear reversals related to changes in the NAO index. Interestingly, the relationship between NAO and Gulf Stream position is not as clear after year 2000. Around this time, the character of the NAO changes, shifting away from prolonged periods of high or low toward a weaker higher-frequency oscillation.

Labrador Current

The northeast U.S. shelf ecosystem is located at the downstream end of an extensive interconnected coastal boundary current system that carries a combination of cold/fresh arctic-origin water, accumulated coastal discharge, and ice melt thousands of kilometers around the boundary of the subpolar North Atlantic. The Labrador Current is one regional component of this boundary current system that flows southward along the western boundary of the Labrador Sea and whose shallow and deep branches are parts of the larger basin-wide gyre circulation in the northern North Atlantic. Together with the southward-flowing Deep Western Boundary Current, the deeper Labrador Current is also considered part of the returning cold/fresh half of the northern AMOC. Ultimately, a portion of these cold/fresh waters carried by the Labrador Current feeds into the northeast U.S. shelf ecosystem via the Gulf of Maine.

The Labrador Current provides two of the three main sources of water entering the NES ecosystem: Labrador Shelf Water is the coldest and freshest water and is confined to the shelf, while Labrador-Subarctic Slope Water (LSSW) is a deeper cold/fresh water mass that arrives along the continental slope. These northern-

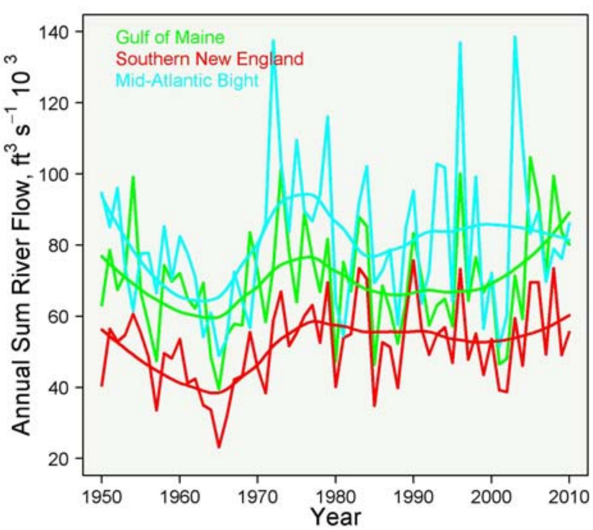
Figure 3.3 Percent of Labrador Subarctic Slope Water (LSSW, blue) in the deep Northeast Channel of the Gulf of Maine together with the Labrador Current transport computed from satellite altimetry along the edge of the Grand Banks of Newfoundland (red; courtesy of G. Han, DFO Canada). Positive transport is associated with equatorward flow.



source waters combine with the deep warm/salty southern-origin Atlantic Temperate Slope Water (ATSW) to define the temperature, salinity, stratification, and nutrient content of the shelf water within the NES ecosystem. Variations in the properties and/or relative proportion of the source waters can lead to significant changes in stratification, nutrient loads, and community composition within the ecosystem.

There is compelling evidence that variations in the composition of the slope water in the Gulf of Maine are correlated with basin-scale atmospheric forcing in the North Atlantic (specifically the NAO). 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 (*23*). 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 (*24*). During these low NAO conditions, the amount of LSSW entering the Gulf of Maine through the Northeast Channel is high and bottom temperatures are colder and fresher (*25*).

Figure 3.4 Trends in river flow from 25 rivers in the Mid-Atlantic, Southern New England, and Gulf of Maine regions. Data are presented as sum of monthly streamflows. 2010 data is incomplete.



Over the last decade, the NAO index has been characterized by short-lived reversals, with the most recent negative anomaly reaching magnitudes not seen since the 1970s (Figure 3.2). Negative NAO reversals precede increased influx of LSSW into the Gulf of Maine by roughly 2 years through the late 1990s. The increased influx of LSSW follows an increase in Labrador Current transport, occurring approximately 1 year earlier (Figure 3.3). Similarly, periods of positive NAO predict a rise in the influx of ATSW through this same period. However, similar to the relationship between the NAO and the Gulf Stream, the relationship between NAO and the hydrography of the Gulf of Maine appears to break down during the most recent decade (Figure 3.2). Nutrient observations suggest that since the early 2000s the inflow to the Gulf of Maine has included a greater proportion of Labrador Shelf Water over slope components, potentially muting the response to the NAO (*26*). It remains to be seen whether the record-low NAO, beginning in 2010, will force a lagged shift in the slope water composition. However, it is clear that the link between climate pressures and responses in the NES are complicated by the competing influence of multiple advective sources (e.g., shelf versus slope). Nonetheless, these changes hold important implications for the ecology of the region.

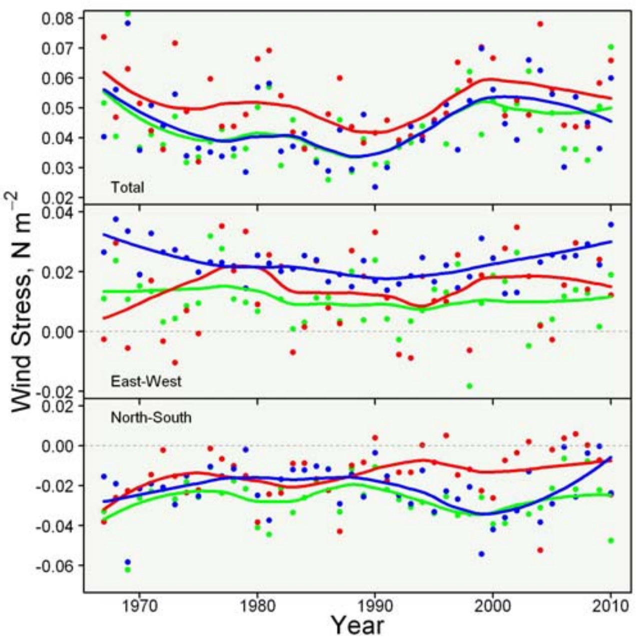
River Flow

The amount of freshwater entering the ocean is another important pressure that responds to climatic drivers. Freshwater run-off transports pollutants and nutrients to the continental shelf, which can affect coastal ecosystems. Nutrient over-enrichment (or 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 in the Gulf of Maine and Southern New England regions, resulting in coherent freshwater forcing in the northern portion of the region. River flow into the Mid-Atlantic region is somewhat different than for the Gulf of Maine and southern New England (Figure 3.4). Complex long-term patterns have been identified for river flow in the region. Tootle et al. (*27*) found interactions among different climate drivers affecting river flow; for example, the AMO and ENSO (El Ninõ Southern Oscillation) signals combine to affect river flow in the Mid-Atlantic part of the NES LME. Earlier work by Visbeck et al. (*28*) found links between river flow in the northeast and the NAO. A time series of river flow suggests the effect of multiple factors (Figure 3.4). Prior to 1970, river flow appears to fluctuate on longer time scales, while the period decreases later in the record. In general, stream flow into all three regions has increased over the past decade, with the largest increases occurring in the Middle Atlantic and Gulf of Maine regions.

Winds

Winds are an important pressure on shelf ecosystems. Wind stress (the force of the wind on the surface of the ocean) acts to vertically mix the water column and drive horizontal currents. The greater the wind stress, the more vertical mixing and the more force for driving horizontal currents. In the NES LME, winds are responsible for

Figure 3.5 Annual averages of monthly mean wind stress near Cape Hatteras (blue), New York (green), and Georges Bank (red). 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.

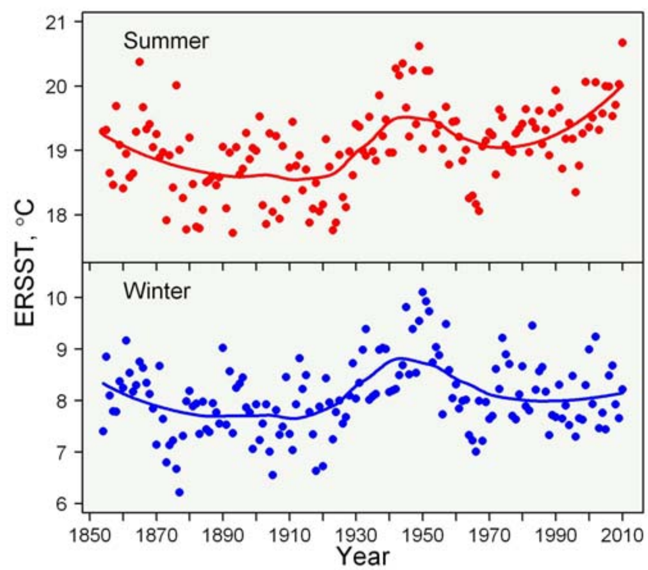


breaking down seasonal stratification in the fall and for causing reversals in the generally southwestward surface currents during summer. In addition, winds blowing along a coastal boundary will drive a vertical circulation in the water column near shore, drawing deeper waters upwards toward the surface where they are carried away from the coast (upwelling) or driving surface waters downward toward the bottom where they are carried offshore (downwelling). Because of the shape of the coastline in the NES, north-south winds have the greatest impact on the along shelf flow in the southern Mid-Atlantic Bight, while east-west winds are more important along the inner shelf of New England. Long-term records from NOAA Pacific Fisheries Environmental Group indicate substantial interannual variability in the magnitude and direction of the wind stress over the NES LME (Figure 3.5). Wind stress increased during the 1990s and has remained relatively high through the 2000s. Winds over the NES are consistently directed out of the northwest (blowing eastward and southward). While there is considerable interannual variability in the magnitude of the winds there is little long-term trend over the length of the record. However, during the past five years the mean direction of the winds has changed, becoming more eastward than southward, particularly in the vicinity of Cape Hatteras. These changes in wind stress may be linked to the NAO, as well as a northward shift in the location of the jet stream (*29*). Despite the uncertainty as to the cause of the inter-annual variability, these changes in wind will impact 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

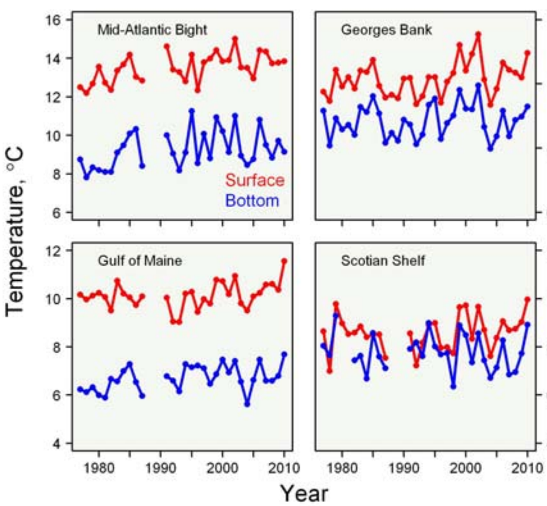
Figure 3.6 Long-term (1854-2010) summer and winter sea surface temperatures averaged over the northeast U.S. continental shelf and adjacent waters from the ERSSTv3b dataset.



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 3.6). 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 from 1945-1955. There was a rapid drop in temperatures through the 1960s followed by a steady increase to the present. Summer temperatures over the past 5 years are comparable to the warm period in the late-1940s/early 1950s and the summer 2011 surface temperature was the highest in the 157 year record. Winter temperatures in recent years, however, are near the long-term mean indicating that the seasonal range in temperature has increased (*30*).

Regional water column temperatures measured by the Northeast Fisheries Science Center (NEFSC) give spatial context to the shelf-wide trends in sea-surface temperature (Figure 3.7). Surveys began in the late 1970s, so the time series are shorter than sea-surface temperature records shown in Figure 3.6. Time series constructed within each region reveal interannual temperature fluctuations as large as 2°C near the surface and bottom. Long-term warming trends are observed

Figure 3.7 Annual mean surface (red) and bottom (blue) water temperatures from the NEFSC survey programs from the four Ecological Production Units.

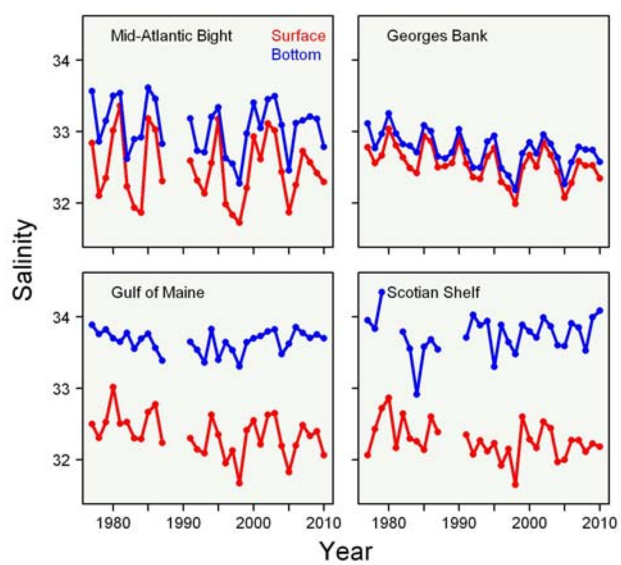


over the full water column in the Mid-Atlantic Bight and near the surface in the Georges Bank regions, equivalent to roughly 1°C warming over the length of the records. Similar warming trends are observed in near-bottom temperature records from the Gulf of Maine regions. Within the past 3 years, significant warming was observed in near-surface and near-bottom temperature records within all regions except the Mid-Atlantic Bight, where temperatures remain near normal values. Most notably, temperatures in 2010 within the upper 5 meters in the Scotian Shelf region were the warmest observed in the 30 year record. Similarly, near-bottom temperatures in this region have increased by roughly 2 degrees over the past 3 years, reaching values close to the long-term maximum.

Salinity

Most aquatic organisms are also 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 oceanic-water (salinities greater than 30). 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 measures salinity in combination with the temperature measurements described above (Figure 3.8). Regionally, time series show interannual salinity fluctuations as large as 1.6 salinity units near the surface and 1.3 units near the bottom, with the largest fluctuations in the Mid-Atlantic Bight. A trend of long-term freshening is observed at both the surface and at depth in the Georges Bank region, equivalent to roughly 0.4 units of freshening over the length of the record. A freshening trend is also observed at the surface in the Gulf of Maine and Scotian Shelf regions over the length of the records. Interannual fluctuations occur coherently between the surface and bottom in both the Mid-Atlantic Bight and Georges Bank regions, having a distinct 5-year cycle in the latter. By contrast, fluctuations in the Gulf of Maine and Scotian Shelf regions are not as coherent between the surface and bottom. This is likely due to the fact that deep and shallow layers in the Gulf of Maine are fed by different sources whose properties and volume may vary independently from one another: Bottom waters are fed by deep slope waters entering through the Northeast Channel, varying in response to the relative

Figure 3.8 Annual mean surface (red) and bottom (blue) salinities from the NEFSC survey programs from the four Ecological Production Units.

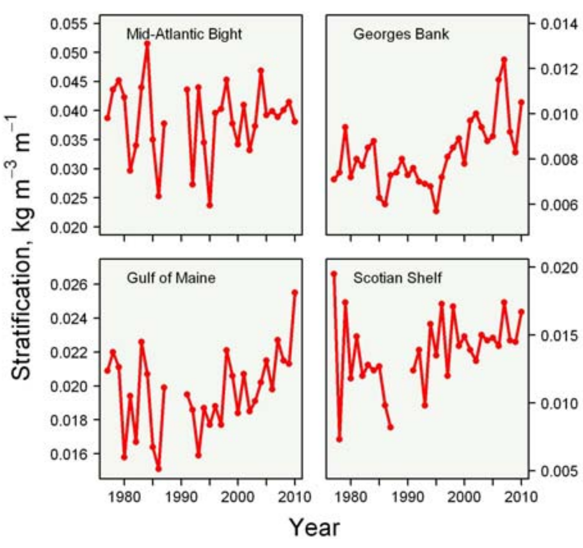


proportion of LSSW to ATSW, while surface waters are fed by northern shelf waters and the discharge of local rivers. The Scotian Shelf records indicate that salinity has increased in near-bottom waters during the past 2 years, while no corresponding change has been observed at the surface. This ecological production unit encompasses the eastern Gulf of Maine, including the deep Northeast Channel. Therefore, the increased salinity of near-bottom waters here is a direct reflection of the shift in slope water composition away from LSSW and toward pure ATSW (Figure 3.2). Surface waters in the Gulf of Maine have become fresher than the long-term average in recent years, while bottom waters show no change. This may be a consequence of remote freshening of northern shelf waters entering the Gulf of Maine, an increase in the inflow volume, and/or a change in the local freshwater discharge to the Gulf of Maine from local rivers.

Stratification

During much of the year, portions of the northeast U.S. shelf are stratified. Stratification refers to the vertical stacking of layers of water having different densities due to changes in temperature, salinity, etc. at different depths within the water column. If there is no stratification, density is uniform throughout the water column and mixing is achieved with little work. When dense water overlays less dense water, the denser water sinks, thereby mixing the water column (this occurs as the surface ocean cools in the fall). However, when less dense water overlays denser water, the water column is considered stable and it takes more energy to mix. The greater the stratification, the greater the density difference from the surface to depth and the more energy is required to mix the water column. The issue of stratification is important because deeper waters are often nutrient rich. Increased stratification makes it harder for these nutrient rich waters to be brought to the surface where they are available to primary producers.

Figure 3.9 Mean annual stratification within the four Ecological Production Units. Stratification is computed as the density difference between the surface and either 50 m depth or the water depth (for water depths less than 50 m).



Density is determined by the temperature and salinity of the water; warm/fresh water is less dense than cold/salty water. Therefore, the observations of temperature and salinity collected by the NEFSC (Figures 3.7 and 3.8) can be used to determine density, and hence stratification. Stratification is strongest in the Mid-Atlantic Bight throughout the observation period with large fluctuations about the record-long average. However, there is no significant trend in stratification in this region; it has remained near average values for the past 5 years (Figure 3.9). By contrast, stratification was near average in the Georges Bank region until the mid-1990s, but has been increasing through the current decade, particularly within the past 5 years. A similar trend is evident in the Gulf of Maine. The increasing stratification in both regions is driven by the warming and freshening of surface layers (making them less dense), coupled with less change at depth (Figures 3.8 and 3.9). In these regions, vertical temperature differences (warm water overlaying cold water) tend to be more important in determining stratification than vertical salinity difference (fresh water over salty water). By contrast, in the Scotian Shelf region (which includes the deep Northeast Channel), temperature and salinity contribute equally to the stratification.

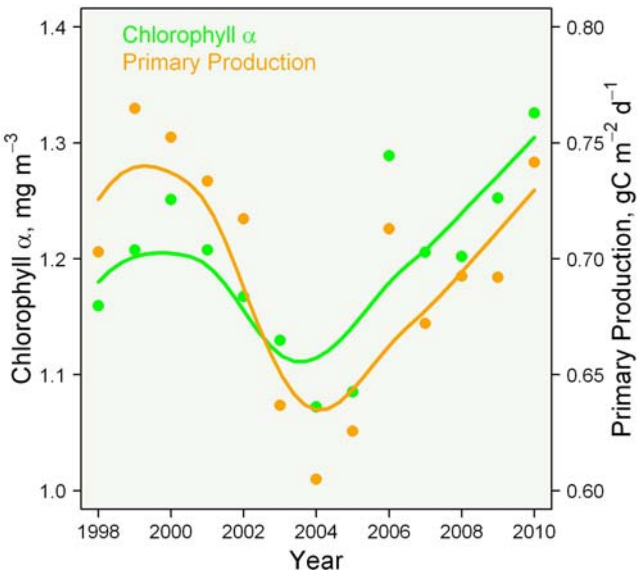
4 Primary and Secondary Production

Trends in Primary Production

A species' population size in a given ecosystem ultimately depends on the amount of production at the base of the food web. Such production is determined by the amount of photosynthesis from plants, algae, and other photosynthetic organisms. Photosynthesis involves the capture of light energy by plant pigments such as chlorophyll *a*, which is then used to convert water and carbon dioxide (CO_2) into carbohydrates and oxygen. Primary productivity (PP) is simply the rate of photosynthesis and uptake of dissolved nutrients such as nitrate, phosphate, and silicate to produce plant matter or biomass. Sea grasses and macroalgae (e.g., seaweeds) are important primary producers in shallow water environments. In the deeper parts of the continental shelf, sunlight penetration through the water column is insufficient to sustain macrophytes attached to the seabed. In these areas, single-celled microscopic organisms living in the water column, collectively known as phytoplankton, are responsible for nearly all of the primary production. Throughout the marine environment there is a wide range of marine phytoplankton species that are responsible for nearly half of the total photosynthesis on the planet (*31, 32*).

In addition to knowing the photosynthetic rates of phytoplankton, it is also important to quantify the total biomass of phytoplankton in the ecosystem. A common proxy measure of phytoplankton biomass is the concentration of the primary photosynthetic pigment, chlorophyll *a* (CHL). Pigment concentrations can be extracted and measured directly from water samples or measured remotely by observing the "color" of the water. Ocean color remote sensors on satellites measure

Figure 4.1 Annual daily mean chlorophyll *a* concentration (orange) and primary production (green) for the Northeast Shelf Large Marine Ecosystem.



the spectrum (color) of the ocean, or rather the water-leaving radiances, at a number of visible and near-infrared wavelengths. These radiance measurements are then used to estimate the near-surface concentration of CHL primarily by comparing blue and green wavelengths. Satellite estimates of CHL complement those obtained by *in situ* shipboard sampling and provide increased spatial and temporal coverage of phytoplankton dynamics that are not attainable by ship-based sampling alone. Satellite measurements of CHL and other parameters such as photosynthetic available radiation (PAR) and sea surface temperature (SST) can also be incorporated into integrated primary productivity models at the same scale and resolution as the satellite data.

In addition to being a primary food source for marine food webs, phytoplankton are also a fundamental biological component of the global carbon cycle and can significantly influence trophic food-web dynamics and ecosystem health (*31, 32*). Furthermore, the amount of phytoplankton biomass in the water column, particularly during seasonal bloom events, can be a useful indicator of the amount of energy exported from the pelagic zone to the benthos (e.g., the water column to the bottom). Many of the fishery resource species in the NES LME are benthic and are dependent on mechanisms to transfer energy from the productive pelagic zone to the benthos (*33*). In the NES LME, the annual mean surface CHL concentration is 1.20 (mg m^{-3}), and the mean daily integrated PP rate is 0.70 (gC m^{-2} d^{-1}) (Figure 4.1). The major temporal trends evident in both series are the minimum primary production observed in 2004 and an increase in primary production over the past six years. Of the four ecoregions, Georges Bank has the greatest mean annual CHL concentration, whereas the highest PP rates were observed in the Mid-Atlantic Bight (Table 4.1).

Spatial Distributions

There are large regional differences in PP and CHL in the NES LME (Figures 4.2 and 4.3). The most obvious pattern is the general onshore-offshore decrease in both PP and CHL, from the coast to the shelf break. This pattern, as well as the seasonal changes derived from the satellite data and model estimates of PP, agrees well with patterns revealed during earlier shipboard surveys, which found that the overall levels of PP in the NES LME place it among the most productive continental shelf systems in the world.

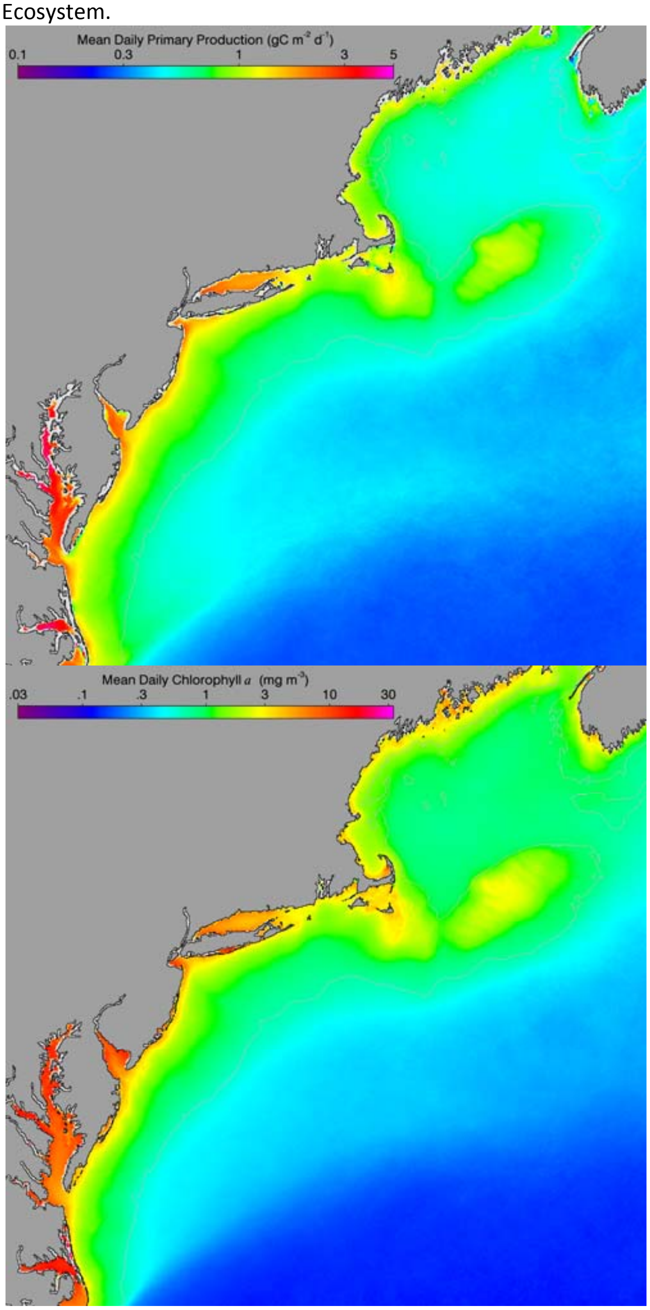
The highest levels of PP are found on Georges Bank, in the immediate near-shore areas (particularly in the Mid-Atlantic Bight), and in the major estuaries where

Table 4.1 Annual mean, minimum and maximum chlorophyll a and primary production values for the Northeast US Continental Shelf Large Marine Ecosystem and Ecological Production Units (EPU). Daily data from each subregion were used to calculate the annual averages and the years in which the minimum or maximum values occurred are listed in parentheses.

	Chlorophyll *a* (mg m^{-3})			Primary Production (mg C m^{-2} d^{-1})		
Region	Mean	Minimum (Year)	Maximum (Year)	Mean	Minimum (Year)	Maximum (Year)
NES LME	1.2	1.07 (2004)	1.32 (2010)	0.7	0.61 (2004)	0.76 (1999)
Mid-Atl. Bight	1.08	0.95 (2005)	1.14 (2006)	0.78	0.68 (2005)	0.87 (2001)
Georges Bank	1.31	1.14 (2005)	1.43 (2000)	0.71	0.63 (2003)	0.79 (2000)
Gulf of Maine	1.1	0.93 (2004)	1.29 (2010)	0.59	0.48 (2004)	0.69 (1999)
Scotian Shelf	1.08	0.95 (2004)	1.31 (2010)	0.53	0.45 (2004)	0.60 (2010)

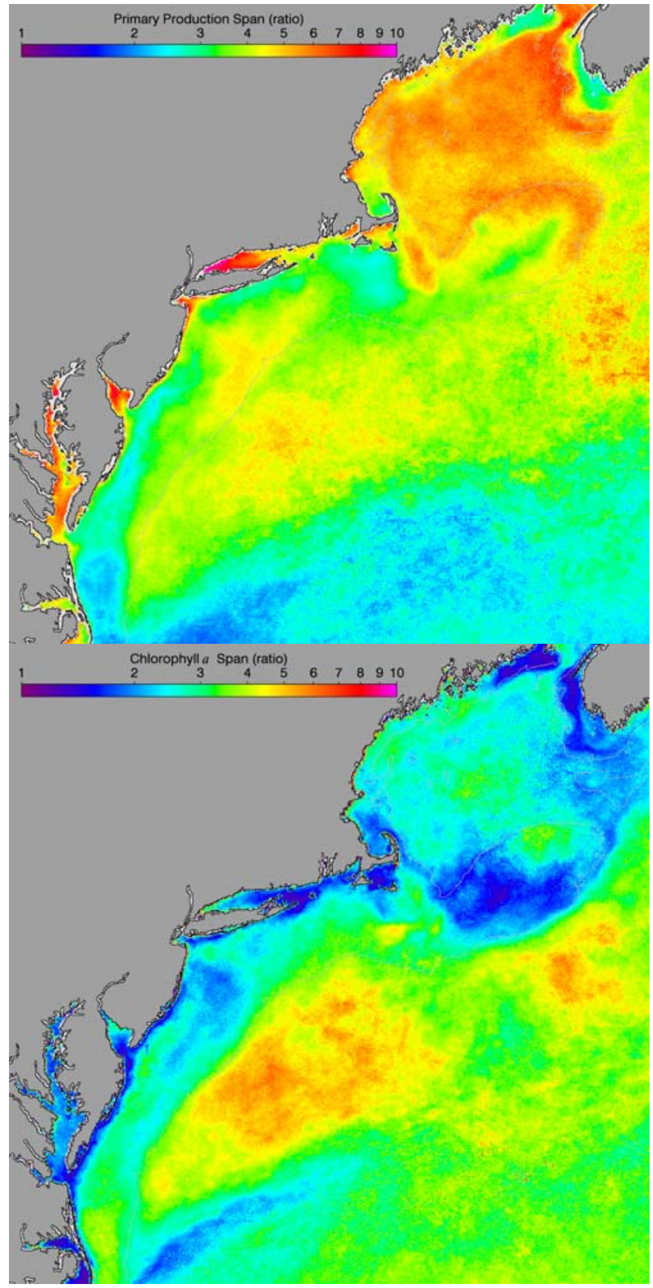
terrestrial derived nutrient concentrations are high (Figure 4.2). Elevated levels of PP (2-3 $gCm^{-2}d^{-1}$) are evident in the coastal water adjacent to and generally south of the mouths of the Hudson, Delaware, and Chesapeake Bays. Intermediate levels are found on the mid-shelf region of the Mid-Atlantic Bight and in coastal areas of the Gulf of Maine. The lowest production rates in the NES LME (about 0.5 $gCm^{-2}d^{-1}$) are over the deep basins in the Gulf of Maine. PP in the deep outer shelf Georges Bank and Mid-Atlantic Bight water is low and

Figure 4.2 Mean (1998-2010) daily primary production and chlorophyll *a* concentration for the Northeast Shelf Large Marine Ecosystem.



similar to the levels in the deep basins of the Gulf of Maine. Note, however, that along the outer shelf the mean PP decreases as one proceeds along the 100m isobath from the southern flank of Georges Bank through the Mid-Atlantic Bight to Cape Hatteras. In contrast to these high primary productivity levels characteristic of

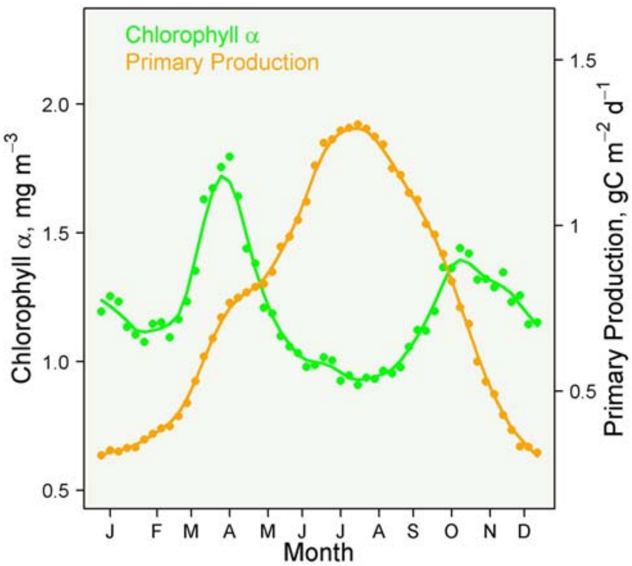
Figure 4.3 The span of primary production (PP) and chlorophyll *a* (CHL) for the Northeast Shelf Large Marine Ecosystem. The span is the ratio between the minimum and maximum monthly values and differentiates areas with large seasonal changes from those where PP and CHL is less variable.



continental shelf water, mean PP in the middle of the North Atlantic Ocean is only 0.2-0.3 $gCm^{-2}d^{-1}$.

In addition to the mean values, the span is a good indicator of how much the phytoplankton biomass and production rates vary throughout the year in a given location (Figure 4.3). For example, the CHL concentration remains somewhat steady throughout the year on Georges Bank; however, there is a large range of PP in the same region due to variations in solar radiation throughout the seasonal cycle. Similarly, the large PP span in the Gulf of Maine compared to the Mid-Atlantic Bight is due to the greater variability in photosynthetic available solar radiation in the Gulf of Maine (*34, 35*).

Figure 4.4 Seasonal mean chlorophyll *a* concentration (green) and primary production cycles for the Northeast Shelf Large Marine Ecosystem.



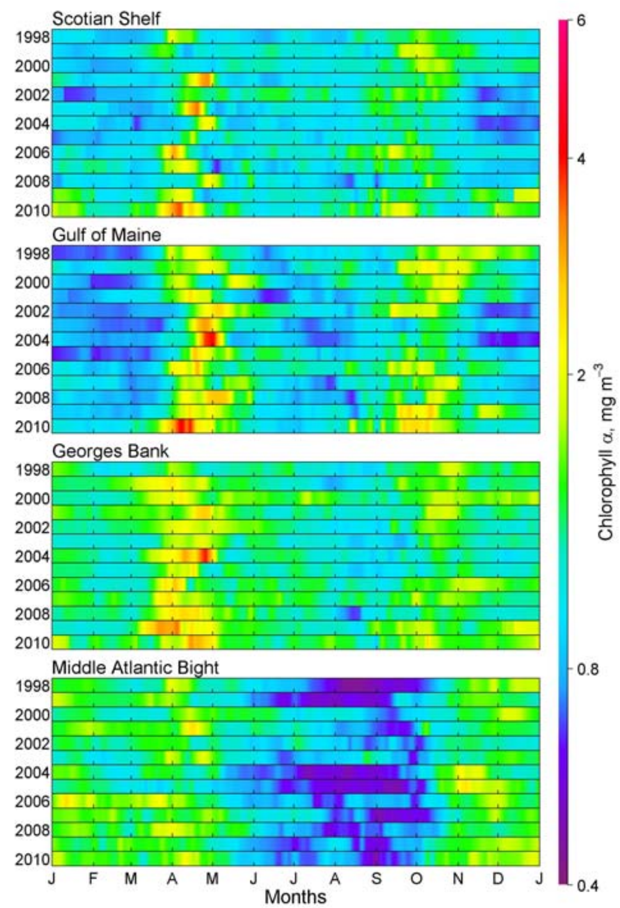
Seasonal Phytoplankton Cycle

The abundance of phytoplankton and the rates of productivity change seasonally in response to the physical environment, the availability of nutrients and sunlight, and grazing pressures (Figure 4.4). In general, CHL concentrations are greatest in the spring (March, April, and May) and the fall (September, October, and November) and lowest in winter (December, January, and February) and summer (June, July and August). In contrast, the highest rates of primary productivity are during the summer months when solar radiation is at its maximum. The annual cycle of PP differs from CHL in that PP reflects changes in phytoplankton photosynthesis rather than changes in phytoplankton biomass (Figure 4.4).

Phytoplankton blooms are characterized by a rapid increase in biomass lasting from a few days to several weeks. Spatially, the blooms can be small (due to localized features, e.g., upwelling or frontal structures), regional, or basin-wide. In the NES LME, there are regional differences in the timing and magnitude of the spring and fall blooms in additional to interannual variability (Figure 4.5). The spring and fall phytoplankton blooms can be quite variable in the initiation, peak concentration, duration, and species composition, which can affect the food availability for zooplankton grazers and the trophic transfer efficiency from phytoplankton to pelagic and benthic resources. The spring bloom period is a dominant feature of the phytoplankton cycle over most of the NES LME. Though the duration is short (~1-2 months), the timing of the bloom is considered critical to many species. The spring period is a time of high phytoplankton concentration, which provides a major food resource for marine grazers. Furthermore, the bloom often produces phytoplankton concentrations in excess of what can be used in the water column, thus providing surplus material that can be exported to the benthos.

The summer period is characterized by relatively low chlorophyll concentrations but high photosynthetic rates. The summer has the greatest amount of available sunlight, so despite lower phytoplankton biomass, it is the period of highest PP. The fall bloom period is an important and sometimes overlooked part of the phytoplankton cycle that is affected by many factors, including weather events that mix nutrients into the well

Figure 4.5 Daily interpolated chlorophyll *a* concentration by year for each ecoregion. This figure highlights the interannual variability in addition to the different bloom patterns in each ecoregion.



lit euphotic zone. There is considerable interannual variability in the timing, duration, and magnitude of the

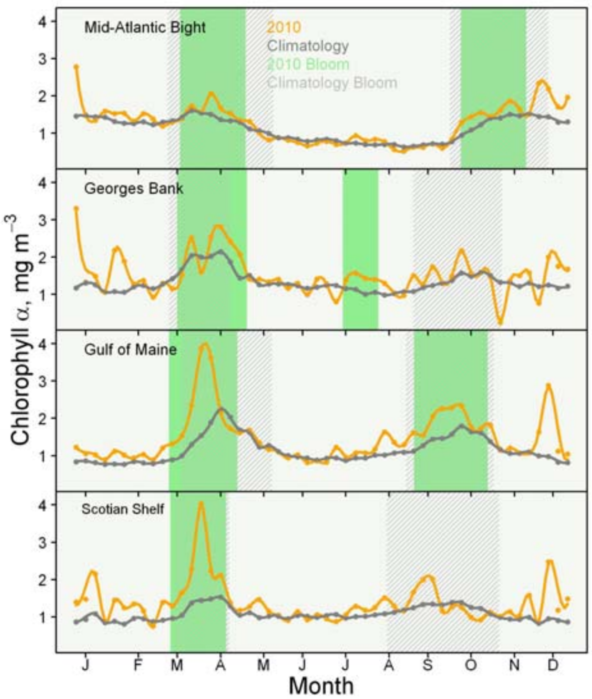


Figure 4.6 The climatological (1998-2010) and 2010 seasonal chlorophyll *a* cycle for eachecoregion, The climatological (grey) and 2010 (green) spring and fall bloom periods are represented by the shaded areas.

fall bloom and in some years, the fall bloom is a distinct event of equal or greater size than the spring bloom. In other 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.

Spatial and temporal trends in bloom variability

In the Mid-Atlantic Bight and Georges Bank EPUs, the average spring bloom starts in late-February to early-March and has average peak CHL concentrations of 1.6 to 2.3 mg m^{-3}. The spring blooms in the Gulf of Maine and Scotian Shelf often start in early to mid-March and can reach relatively high concentrations (1.5-3.0 mg m^{-3}) though the bloom period is generally shorter than the spring blooms in the Mid-Atlantic Bight and Georges Bank. In each ecoregion the maximum peak concentration of the spring bloom is often greater than the fall bloom maximum. The mean fall bloom timing is variable among the EPUs. In the Mid-Atlantic and Georges Bank the initiation of the bloom occurs in mid to late September. The magnitude of the peak is reduced, relative to the spring bloom, reaching concentrations of 1.3 to 1.6 mg m^{-3} of chlorophyll *a*. The Gulf of Maine and Scotian Shelf EPUs have initiation dates in late August and early September, and the peak concentrations of the blooms in these areas are 1.4 to 1.7 mg m^{-3}.

The trend in seasonal CHL *a* concentration for a given year within each EPU can be compared to the long-term mean values (the climatology) to detect temporal anomalies (Figure 4.6). In the Mid-Atlantic Bight, the initiation of the 2010 spring bloom coincided with the long-term mean in early March. However, the peak concentration and bloom duration were different. The spring bloom in 2010 reached higher concentrations and occurred over a much shorter period compared to the climatology. During the summer months, the mean concentration of CHL was similar relative to the long-term mean and the fall bloom was above average. There was a close correspondence between the initiation of the 2010 spring bloom and the climatology in Georges Bank. The peak values and the duration of the bloom were also similar.

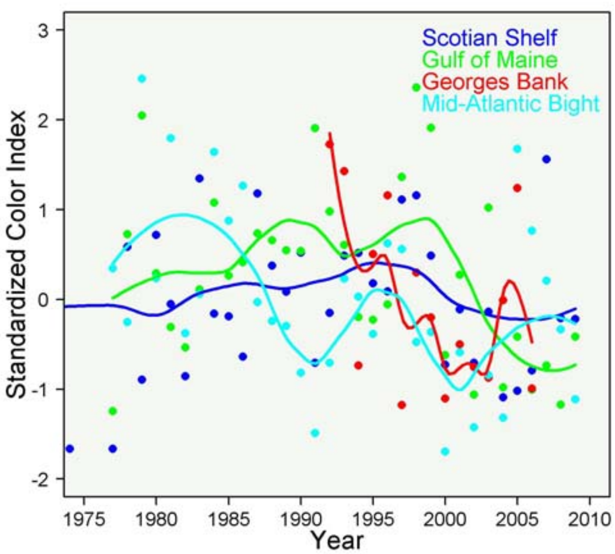
There were generally higher summer concentrations of CHL *a* in 2010 relative to the climatology, and summer bloom was detected. There was, however, no bloom detected during the fall months. The bloom detection algorithm employed here must detect a distinct discontinuity in the CHL in order to identify a bloom period. Short term pulses of CHL above the mean are often not identified as phytoplankton blooms. The spring bloom in the Gulf of Maine started during the same time period as the climatology but was characterized by a very large peak in CHL *a* concentration and a shortened bloom period compared to the climatological period. The summer and fall concentrations were higher in this ecoregion relative to the long-term mean. High spring bloom concentrations were observed in the Scotian Shelf ecoregion with similar bloom timing relative to the climatology. The summer concentration was similar in 2010 relative to the long-term mean, and no fall bloom was detected in this ecoregion.

Continuous Plankton Recorder and Phytoplankton Species Composition

An additional proxy measure of phytoplankton abundance is the Continuous Plankton Recorder (CPR) Color Index. The CPR is a mechanical instrument towed behind merchant vessels. Water enters the 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. Phytoplankton captured on the silk can then be identified and quantified. The CPR is very selective because the mesh size of the silk, which is large relative to the size of most phytoplankton, thus the resulting data are best interpreted as a measure of the abundance of larger phytoplankton, commonly diatoms and dinoflagellates.

Three CPR routes are operated in the NES LME, with sampling in all four of the ecoregions. In each ecoregion, the color index indicates strong interannual variability (Figure 4.7), but there is a long-term decrease

Figure 4.7 Time series of phytoplankton color index from the Continuous Plankton Recorder. Anomaly values are presented, which represent the annual average of monthly anomalies.



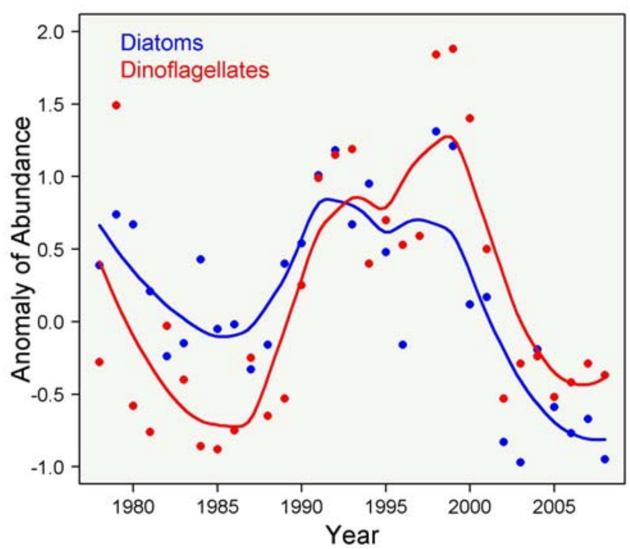
in color, indicative of a decline in the quantity of large-phytoplankton. These declines in the color index are less pronounced in the Scotian Shelf EPU and most pronounced on Georges Bank. The CPR also provides information on the species composition of the phytoplankton captured on the silk. In recent years, there have been fewer diatoms and fewer dinoflagelletes captured (Figure 4.8) indicating that larger species of both main phytoplankton groups are decreasing (*36*). Drawing from the satellite data, which shows increases in CHL, and the CPR, which shows decreases in larger phytoplankton, we infer that the number of smaller phytoplankton are increasing. This conclusion can have important implications for food webs and trophic transfer efficiency in the ecosystem. Due to the smaller size of the phytoplankton, energy, in the form of carbon that is available for consumption, will need to pass through additional trophic levels to reach higher level predators including fish and marine mammals.

In summary, phytoplankton productivity over the 13 year time series of satellite observations was at a minimum during 2003-2005 and has steadily increased during the recent years, including near-maximum rates in 2010. Despite the steady increase in phytoplankton biomass and productivity, there are indications that there has been a decline in larger phytoplankton species during the past decade. There is current ongoing research to use phytoplankton discrimination models to tease out the major phytoplankton functional groups from the satellite data, which will then be compared to the data collected by the CPR and additional *in situ* measurements collected during recent ecosystem monitoring cruises of the NES LME.

Zooplankton Abundance

The energy produced by phytoplankton is transferred to higher trophic levels via three main pathways. Some energy is transported directly from the pelagic zone to the benthos, fueling benthic production. A recent study

Figure 4.8 Time series of diatoms and dinoflagellate abundance from the Continuous Plankton Recorder. Anomaly values are presented, which represent the annual average of monthly anomalies.



hypothesizes that this route is responsible for high recruitment of the 2003 year-class of haddock (*37*). Unfortunately, there are insufficient long-term data to evaluate the direct contribution of primary production to benthic habitats or to overall benthic productivity. Future research and observations are needed, given the potential importance of this route to fisheries production in the ecosystem.

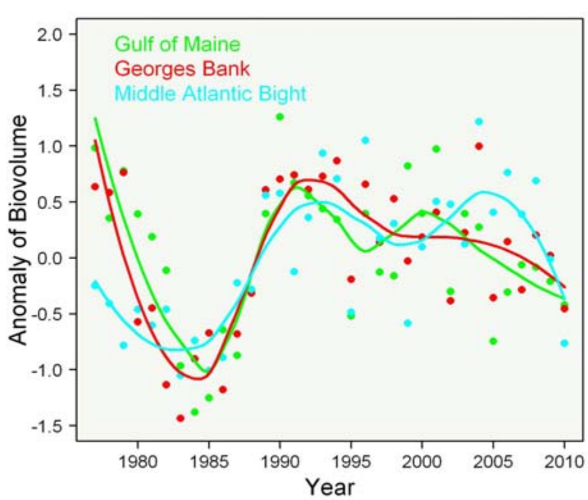
A second pathway of energy from primary production is remineralization by bacteria and microzooplankton – the so called microbial loop. Some of this energy remains in the microbial loop, some sinks to the benthos, and some is consumed by zooplankton.

Although very little data exist on bacteria and microzooplankton in the NES LME, the microbial foodweb is believed to be extremely important in the energy flow on Georges Bank (*38*).

The third route of energy produced by phytoplankton is consumption by zooplankton. Traditionally, this energy route has been the most studied, and the NEFSC has been monitoring zooplankton abundance and species composition since the 1970s. These monitoring efforts involve deploying small (61 cm diameter), fine meshed (333 µm) nets 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 per year with approximately 120 stations over the whole ecosystem; these surveys are designed to capture seasonal and annual trends, but not smaller-scale variability.

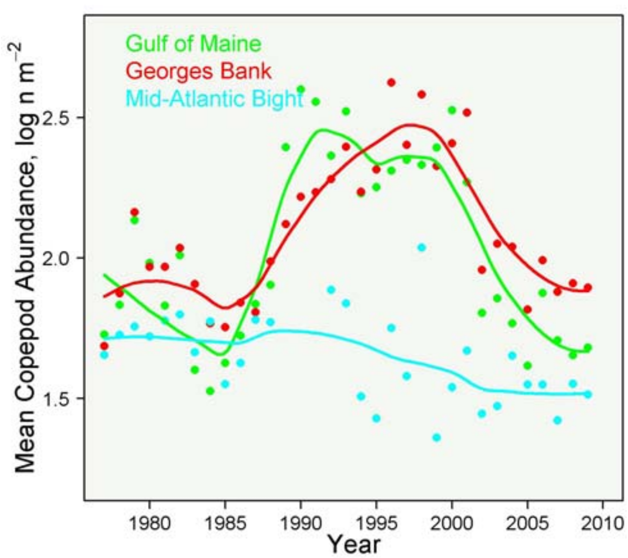
One measure of zooplankton abundance is the volume of material collected in the net, termed zooplankton biovolume. This relatively simple indicator is related to the amount of zooplankton biomass. The time series of zooplankton biovolume among the ecoregions are relatively consistent, suggesting large-scale coherence in zooplankton throughout the NES LME (Figure 4.9). The trends in Georges Bank zooplankton biovolume are similar to those in both the Mid-Atlantic and Gulf of Maine, reflecting its position between the other ecoregions, while trends in the Mid-Atlantic and Gulf of Maine zooplankton biovolumes are the most dissimilar, reflecting their spatial separation. In the early years of the time series, there was a marked drop and recovery in zooplankton abundance with variable but near constant values through the late 1980s, 1990s, and 2000s. Data from 2010 were low, but within the range of interannual variability during the 1990s and 2000s.

Figure 4.9 Time series of zooplankton biovolume. Anomaly values are presented, which represent the annual average of monthly anomalies.



Another measure related to secondary production is the number of copepods in the ecosystem. Copepods are microscopic animals related to lobsters and crabs and are the primary grazers on phytoplankton and microzooplankton. These small animals are the primary food source for forage fishes (e.g., herring and mackerel) and for young groundfishes (e.g., cod, haddock). They are also an important food source for many baleen whales including the endangered North Atlantic right whale (*Eubalaena japonica)*, which feeds primarily on a lipid rich copepod species – *Calanus finmarchicus*. The mean number of nine copepod species in the Gulf of Maine and on Georges Bank generally follows the trends in total zooplankton biomass with relatively low numbers in the mid-1980s and relatively high numbers through the 1990s (Figure 4.10). However, the numbers of copepods exhibit a marked decline in the 2000s, while total zooplankton biomass (Figure 4.9) exhibited only a moderate decline.

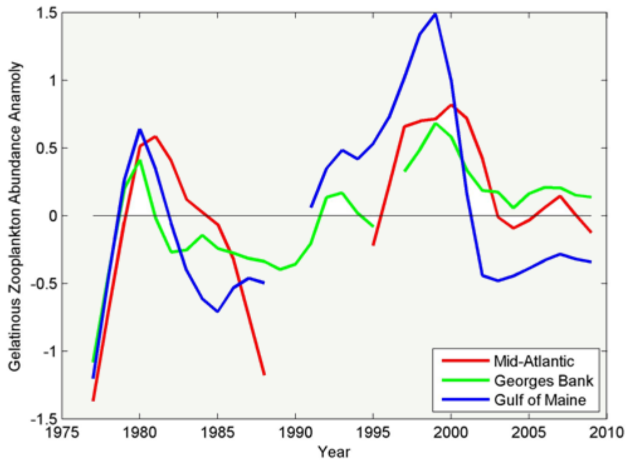
Figure 4.10 Time series of total copepod abundance. Annual averages are presented.



The time series of copepods in the Mid-Atlantic exhibit a very different pattern, with variable but generally decreasing numbers throughout the time series.

Recent work has found that the composition of the zooplankton community has changed over time (*39*). Specifically, several species of small copepods increased in abundance in the 1990s resulting in an increase in total copepod abundance. The community composition changed again around 2000 consistent with the drop in copepod abundance. Individual copepod species can serve as indicators of these broader changes in overall species composition. As an example, in the Gulf of Maine, *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.

Figure 4.11 Time series of abundance for gelatinous zooplankton by Ecological Production Unit. Anomaly values are presented, which represent the annual average of monthly anomalies.



Increases in the abundance of gelatinous zooplankton have been recently observed in many marine ecosystems, possibly signaling an important change in overall system structure in these regions. Zooplankton sampling conducted by the NEFSC does include gelatinous zooplankton (including siphonophores, hydrozoa, coelenterates, ctenophores, and salps). Although the collection and identification of these organisms can be problematic and the sampling gear is not designed specifically to collect gelatinous zooplankton, there is value in examining the time series of abundance (Figure 4.11). Abundances of gelatinous zooplankton were apparently high in the early 1980s and low during the remainder of the 80s. Abundance then increased in the 1990s and decreased in the 2000s. These trends are largely coherent among the ecological production units.

Other species of macrozooplankton are routinely monitored by NEFSC. Trends in abundance for the overall Northeast Shelf system for arrow worms (chaetognaths), krill (euphausiids), two types of sand fleas (amphipods), and planktonic sea squirts (appendicularians or larvaceans) indicate generally increasing trends over time (Figure 4.12). Chaetognaths are predators of other zooplankton species (including some fish larvae) while euphausiids and amphipods are important prey of a number of species including fish, marine mammals, and seabirds.

The patterns in the phytoplankton community and copepod community are linked (Figure 4.13). Comparing phytoplankton data from the CPR with copepod data from the small nets shows that trends in species composition are similar through time. A dominant phytoplankton trend can be described based on multivariate statistical analysis of the time series of phytoplankton species from the CPR in the Gulf of Maine (*36*). A similar dominant zooplankton trend can be

Figure 4.12 Time series of Other Zooplankton species in the Ecological Production Unit. Anomaly values are presented, which represent the annual average of monthly anomalies.

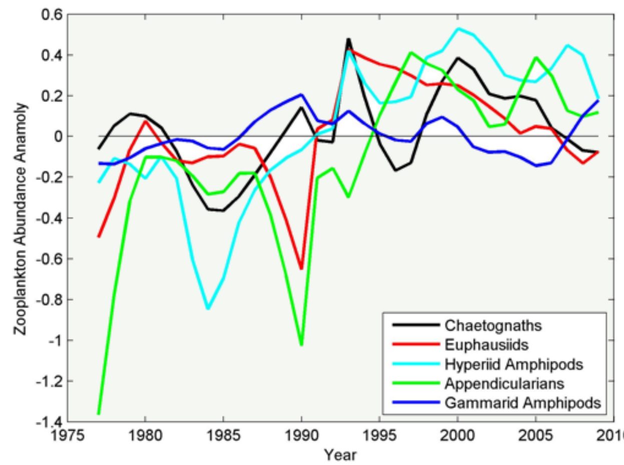
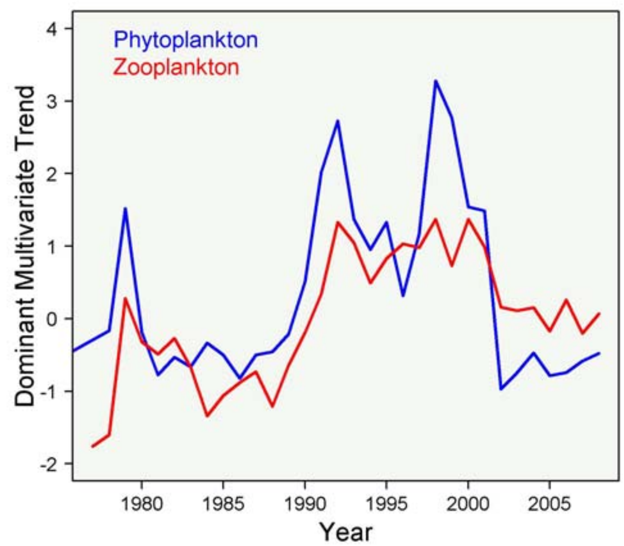


Figure 4.13 Time series of abundance the dominant trend in phytoplankton species composition and zooplankton species composition. The phytoplankton data is from the Continuous Plankton Recorder in the Gulf of Maine eco-region and the zooplankton data is from the net survey in the Georges Bank ecoregion.

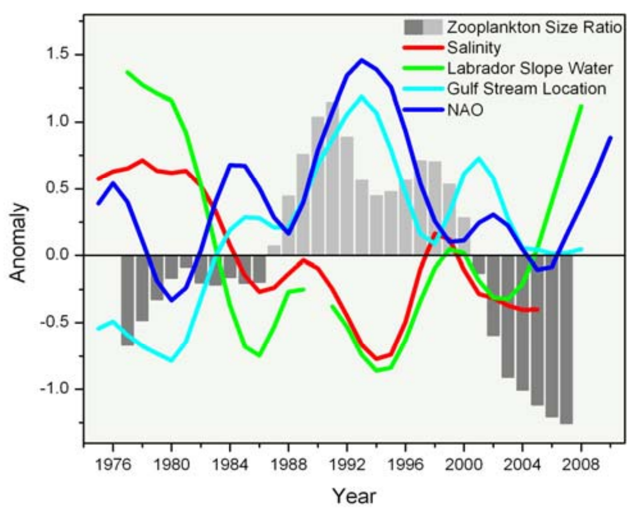


described based on a similar multivariate statistical analysis of the time series of zooplankton species from the research vessel surveys (*39, 40*). Changes in these trends represent changes in community composition among phytoplankton and zooplankton. Both phytoplankton and zooplankton communities show changes in 1990 and 2000, indicating close coupling among the lower trophic levels. Understanding the cause of this coupling is an important regional research need.

Climate Drivers, Physical Pressures, and Zooplankton Community Structure

The link between lower trophic levels and both climate drivers and physical pressures remains unclear. At the decadal scale, a relationship appeared to be emerging between the NAO, location of the Gulf Stream, Labrador Slope Water supply, salinity and a measure of zooplankton community structure (Figure 4.14). This chain of drivers, pressures, and state responses was taken to indicate that the NES LME is affected significantly by remote climate forcing (*24*) and that this forcing impacts lower trophic levels. However, in recent

Figure 4.14 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 Pseudocalanus spp*.) compared to large copepods (*C. finmarchicus*).

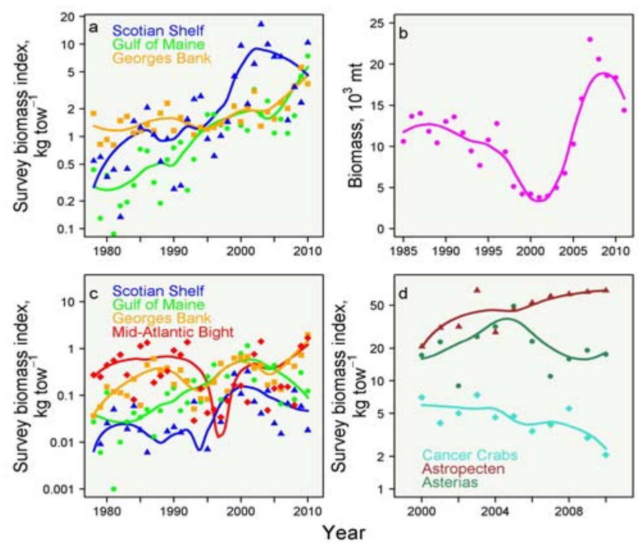


years there is evidence that these relationships may be breaking down (*41*) thus the specific processes that result in changes in phytoplankton and zooplankton community structure remain unresolved.

5 Benthic Invertebrates

Benthic organisms primarily live on the ocean floor or within the bottom sediments. As noted earlier, these animals play an important role in energy transfer within marine systems by consuming a broad range of benthic biomass and subsequently becoming important prey items for fish and other upper trophic level animals. Benthic invertebrates such as mollusks and corals filter phytoplankton and suspended detritus from the water column, while other groups, including many crustaceans and certain species of marine worms, scavenge on the organic content of sediments and detritus that fall to the

Figure 5.1 Biomass indices for (a) American lobster from NEFSC autumn bottom trawl surveys on the Scotian Shelf, Gulf of Maine and Georges Bank, (b) Northern Shrimp based on stock assessment results, (c) crab species based on NEFSC bottom trawl surveys, and (d) Cancer crabs and selected echinoderm genera based on NEFSC scallop surveys.



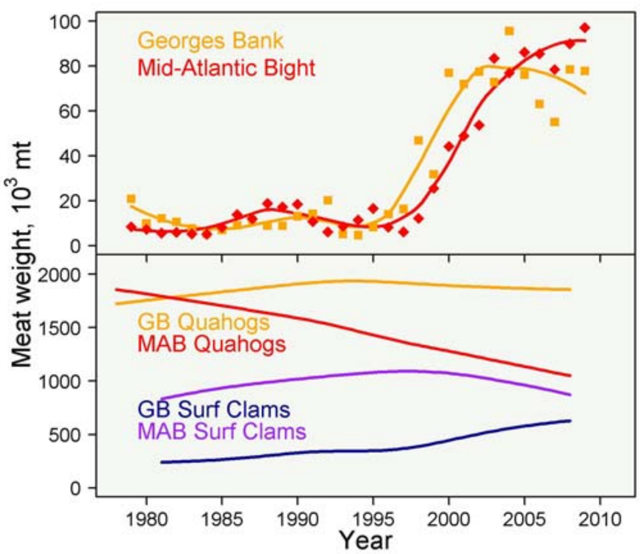
seafloor. As such, many benthic organisms serve as important conduits to couple pelagic and benthic habitats. Other benthic organisms such as sea stars are predators on mollusks and other benthic species. In total, over two thousand species of benthic invertebrates have been identified on the Northeast Continental shelf, although most are relatively rare. Benthic invertebrates such as lobsters, crabs, scallops, clams and sea urchins support important commercial and recreational fisheries, including some of the highest valued fisheries in the region.

Temporal Trends of Selected Species

Population trends are available only for selected commercially and recreationally important benthic species based on directed research vessel surveys and/or stock assessments. Additionally, a few ecologically important species that have been specifically sampled on the NEFSC scallop survey also have available time series. Some of the more prominent benthic biomass trends throughout the NES LME include increases in American lobster *(Homarus americanus),* sea scallop (*Placopectin magellanicus),* and sea stars (*Astropecten americanus*) populations, and decreases in ocean quahog (*Arctica islandica)* and Atlantic surfclam (*Spisula solidissima,*) populations, especially in recent years.

The NEFSC autumn bottom trawl survey indicates that American lobster biomass has increased dramatically in the Gulf of Maine (Figure 5.1a). The lobster biomass

Figure 5.2 Biomass trends of sea scallops from the NEFSC scallop survey, and biomass trends of ocean quahogs and Atlantic surfclams from stock assessment models.



index for Georges Bank has also increased somewhat in recent years, although the increase is not of the same magnitude as seen in the Gulf of Maine. These increases are likely due to high recruitment and low commercial fishing exploitation rates (*42, 43*). On the Scotian Shelf, lobster biomass appears to have peaked during the early 2000s, and has since declined in abundance (Figure 5.1).

Northern shrimp (*Pandalus borealis)* have undergone dramatic population fluctuations in the Gulf of Maine due to variability in recruitment and regulatory changes in fishing effort (Figure 5.1b). Based on a recent assessment (*44*), northern shrimp biomass decreased sharply in the 1990s, quickly rebounded to a high in 2008, and may have declined in recent years. The period of sharp biomass increase from 2002 to 2007 was likely due to strong 2001 and 2004 year classes, as well as moderate 2003, 2005, and 2007 year classes (*44*). Ouellet et al. (*45*) found that recruitment for northern shrimp was most successful during years of high sea surface temperatures during or following hatching, and early, prolonged phytoplankton blooms with high chlorophyll *a* concentrations, which could explain the 2001 and 2007 year classes. These estimates may in fact be biased low given that the estimates do not include predation, which is known to strongly influence shrimp dynamics (*46*).

The NEFSC autumn bottom trawl survey biomass indices of an aggregated assemblage of crab species, including the commercially harvested deepsea red crab *(Chaceon quinquedens),* jonah crab *(Cancer borealis),* rock crab *(Cancer irroratus),* and lady crabs *(Ovalipes spp.)* have shown increases in biomass during the early 2000s, followed by sharp declines in the Scotian Shelf and Gulf of Maine regions in recent years (Figure 5.1c). Aggregated crab biomass indices on Georges Bank and in the Mid-Atlantic Bight have been highly variable over the time series of the NEFSC autumn bottom trawl survey but may be increasing in recent years (Figure 5.1c). This increase in aggregated crab biomass in the Mid-Atlantic Bight region contrasts with trends from special samples taken on NEFSC scallop surveys from 2000-2010, which indicate that Cancer crab biomass in the Mid-Atlantic Bight may be declining, especially in recent years (Figure 5.1d). This discrepancy is likely due to differences in sampled crab species assemblages, survey variability, and gear differences between the two surveys.

Two groups of sea stars were also sampled in the Mid-Atlantic Bight on the NEFSC scallop surveys: *Astropecten* and *Asterias* (including *A. forbesi, A. Vulgaris,* and *Leptasterias tenera*). Over the last decade, it appears that *Astropecten* are generally increasing in density and expanding into shallower water on the continental shelf while *Asterias* densities have fluctuated with lows in 2002 and 2007 to a high in 2005 (Figure 5.1d). These sea stars are known to prey on benthic invertebrates, especially bivalves, and are thought to limit the range of sea scallops to waters less than 80 m depth in the Mid-Atlantic Bight (*47*). Therefore, the increases seen in *Astropecten* populations could impact sea scallop abundance in areas of overlap or prohibit further expansion of sea scallop distributions. Furthermore, *Astropecten* are generalist predators so the observed increases in density and range expansion may have unknown impacts on other benthic species and associated food webs.

Sea scallops are currently the highest valued fishery in the NES LME and have increased dramatically in biomass since the mid-1990s on both Georges Bank and in the Mid-Atlantic Bight, as seen in the biomass estimates from the 2010 assessment (Figure 5.2; (*48*)). This dramatic increase is related to the implementation of effective management measures including reductions in fishing effort, constraints on crew size, and gear restrictions (*49*). Sea scallop populations have also benefitted from the establishment of long-term closed areas on Georges Bank in late 1994 and rotational closures in the Mid-Atlantic Bight over the past decade. In particular, the areas where mobile fishing gear has been prohibited may have enabled a general recovery of the benthos through reductions of disturbance, which may have particularly benefited sea scallops due to their relatively sessile nature. In recent years, biomass trends for sea scallops have become more variable, with declines on Georges Bank during the period of increased fishing access (Figure 5.2). Since then, recruitment has improved, biomass has accumulated, and sea scallop biomass is currently at a high level in both regions.

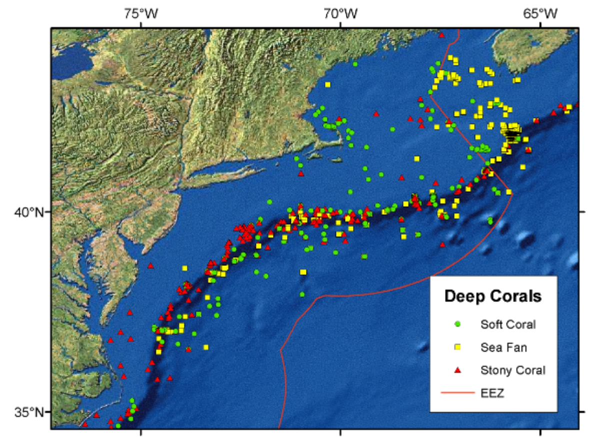
Recent declines in biomass for both ocean quahogs and Atlantic surfclams have been most pronounced in the southernmost region of the NES LME. Ocean quahog biomass from Southern Virginia through Long Island has declined steadily by about 46% from 1978 to 2008 (*50*) (see Figure 5.2). Similarly for Atlantic surfclam in the Mid-Atlantic Bight region, biomass estimates aggregated from Delmarva and New Jersey stocks in a recent assessment show a sharp decline of about 66% from 1996 to 2008, after a general increase in biomass by about 24% during 1981 to 1995 (Figure 5.2; (*51*)). The declines for ocean quahog biomass are due to low productivity and fishing. Recent declines in Mid-Atlantic Bight surfclam biomass are also due to fishing, as well as poor survival after settlement and slow growth, perhaps caused by warm water conditions (*52*). Population estimates for ocean quahog biomass on Georges Bank, as aggregated from Georges Bank and Southern New England stocks, also indicate a slightly declining population trend over the last decade and a half (Figure 5.2), following an increase since 1978 (*50*). Atlantic surfclam biomass on Georges Bank, including biomass from Georges Bank and Southern New England (*51*), increased gradually from 1981 until the mid-1990s and has increased further through 2008 (Figure 5.2).

Other Benthos: Deep Corals

Deep corals are sessile animals that are important in certain deep sea benthic communities, providing structure for fish and invertebrates of higher trophic levels. Although there are no known coral reefs in the northeast U.S. waters, deep corals can be found from shallow waters to 6,000 m depth, and are most common at depths of 50-1,000 m on hard substrate.

The current status of deep coral populations is generally unknown because population trends are not available. However, concerns have been raised about the damage that mobile, bottom-tending fishing gear, especially bottom trawls, may cause to these fragile, slow growing and low recruitment animals. Other potential threats to deep corals include offshore oil and gas drilling, wind farm or other alternative energy installations, as well as ocean acidification due to global warming. To help ensure the protection of deep corals, the New England Fishery Management Council led the development of a new Habitat Closed Area south of Georges Bank, which prohibits the use of bottom trawls and bottom gillnets in the area.

Figure 5.3 Known distributions of hard corals, soft corals and sea fans in the northeastern U.S. and Canadian Gulf of Maine waters. Sea pens and black corals are not included. Canadian data courtesy of Fisheries and Oceans Canada, Bed ford Institute of Oceanography. EEZ is the exclusive economic zone.



Stony corals most often inhabit deep, rocky substrate and are often found on sea mounts and along the continental margin from the outer edges of Georges Bank south to Cape Hatteras (Figure 5.3). Most soft corals and sea fans are primarily deepwater species that occur at depths greater than 500 m in submarine canyons and on seamounts, although certain species occur throughout shelf waters to the continental slope (Figure 5.3). Sea pens are generally found on the continental slope between 200 and 4,300 m, although two species have been found at depths of less than 30 m off of the North Carolina shelf. Overall, deep corals likely provide important habitat, however more research is needed to determine population trends and ensure the conservation of these species.

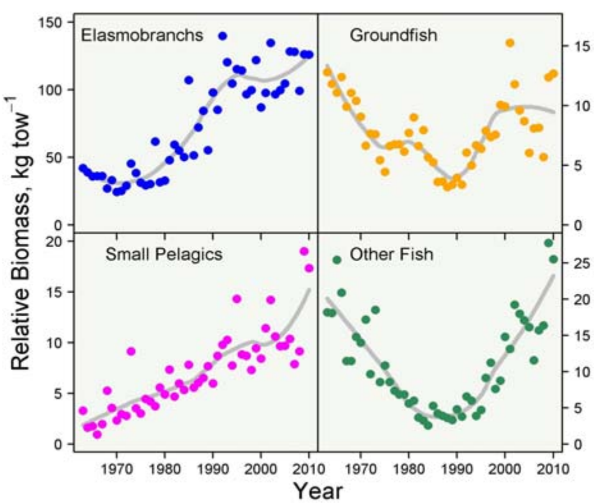
6 Fish Communities

Here we provide a community-level perspective on changes in fish populations over time to complement more traditional species-based approaches (compare to assessments at http://www.nefsc.noaa.gov/sos/). We focus on species groups aggregated in different ways including taxonomic affinities and associated fishing practices, habitat, and diet or trophic level. Integrative measures can provide 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.

Trends for Aggregate Species Groups

Often, broadly defined taxonomic groups are targeted by different components of the fishing fleet. Here we consider four such groups including groundfish (the traditional target species for the bottom-trawl and gillnet fleets), small elasmobranches (skates and dogfish), small pelagic fishes (principally herring and mackerel), and other fish. The small elasmobranches were primarily caught incidentally in groundfisheries until markets for these species were further developed in the 1980's. The small pelagic fishes have long supported important commercial fisheries (including some of the oldest in the

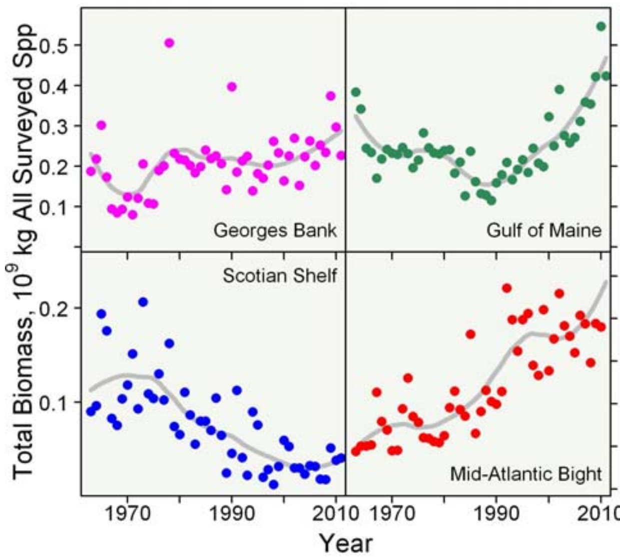
Figure 6.1 Mean catch (kg) per tow caught in NEFSC bottom trawl surveys by species group.



United States) and are often targeted using specialized gear. Many of the species included in the other fish category are taken as incidental catch but some, notably monkfish, have emerged as extremely valuable components of the overall fishery.

An examination of trends in each of these groups over the entire shelf region based on NEFSC research vessel surveys points to dramatic increases over time in the small elasmobranch and pelagic fish components. In contrast, an initial decline and subsequent recovery is evident for the groundfish and other fish categories (Figure 6.1). These patterns are related to targeted harvesting practices that resulted in sharp declines in bottom-dwelling fish. The subsequent implementation of

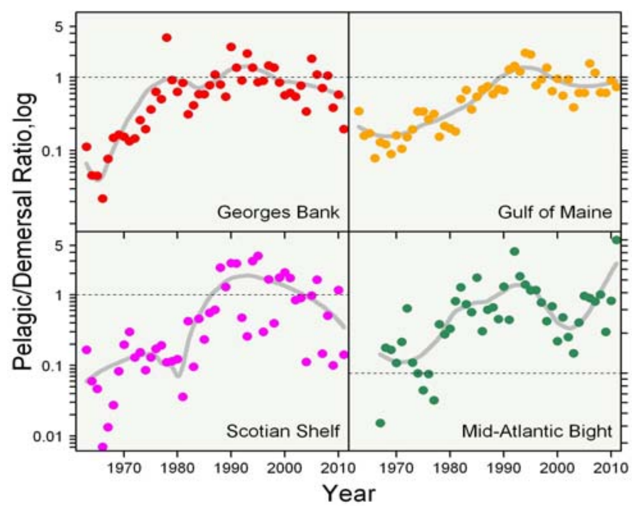
Figure 6.2 Total fish biomass estimates NEFSC bottom trawl surveys disaggregated by region.



more stringent management measures in the 1990s have resulted in recovery of at least some of the groundfish species.

Partitioning total biomass based by each of the ecological production units shows distinctive differences among regions with large recent increases in the Gulf of

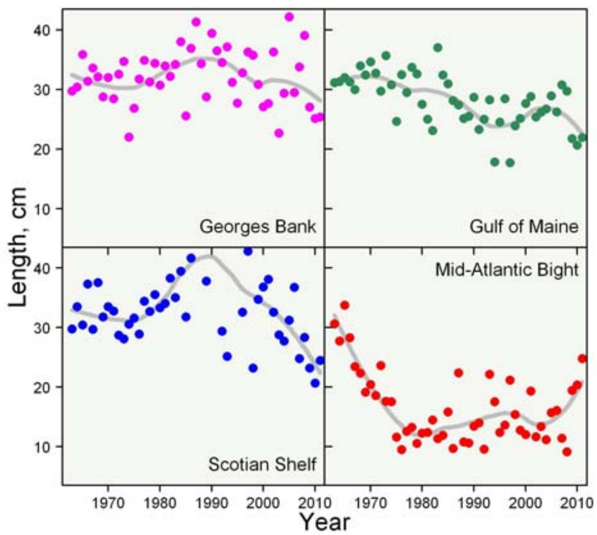
Figure 6.3. Ratio of pelagic to demersal fish biomass caught in NEFSC bottom trawl surveys in each ecoregion.



Maine and the Mid-Atlantic Bight, slight increases on Georges Bank, and an overall decline on the Scotian Shelf (Figure 6.2).

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 as cod, haddock, and flounders are found in near-bottom waters or are associated with the seabed. In contrast, pelagic fish species such as herring and mackerel are typically found higher in the water column. An index of the ratio of pelagic to demersal fishes provides important insights into relative

Figure 6.4 Mean length (cm) of all finfish species caught in NEFSC bottom trawl surveys disaggregated by region.

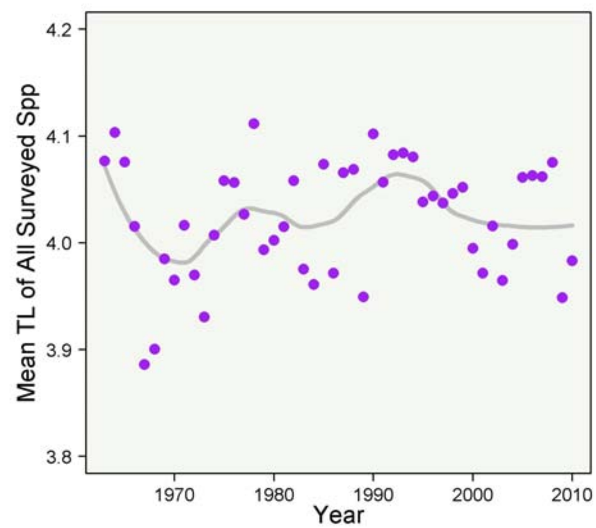


changes in these two major groups of fishes and, therefore, pathways of energy flow (*53, 54*). At a coarse level, this ratio indicates where energy is processed in the ecosystem. In the 1960s, the demersals were dominant throughout the northeast continental shelf. This was followed by a more even ratio in the 1970s to early 1980s reflective of declines in demersals and increases in pelagics in each of the ecological production units (Figure 6.3). In the 1990s, the pelagics dominated fish biomass before declining in the early 2000s (*55, 56*). While pelagics have declined, their abundance remains greater than demersals, and thus the pelagic to demersal ratio has remained above one in recent years.

Average Size

We can also characterize the fish community and species of commercial and ecological significance with respect to their average size (*53, 54*). An indicator of overall mean length, taken from the lengths of all finfish species caught in fishery-independent surveys, reflects changes in the size composition of the entire fish community. Georges Bank has remained relatively stable in terms of the average fish size over four decades (Figure 6.4). Decreases in average size are evident in the other ecoregions but with different timing in the onset of the declines (Figure 6.4). The decrease in mean size has been relatively continuous in the Gulf of Maine since the inception of the NEFSC surveys. In contrast, the Scotian Shelf exhibited an increase until the early 1990s after

Figure 6.5 Average trophic level of all finfish species caught in NEFSC bottom trawl surveys.



which sharp declines were evident. The Mid-Atlantic region showed initial declines followed by a stabilization at low mean size. Average size has recently rebounded slightly in this area. How these general patterns may change as fishes continue to shift their distribution (*57*) will remain an intriguing factor to evaluate.

Mean Trophic Level

The "trophic level" (TL) 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 (*58*). We can determine the trophic level of a species from examining its diet. It is then possible to determine the mean trophic level in the sampled fish community by weighting the trophic levels of individual species by their abundance (biomass) and averaging over all species. The mean trophic level is an indicator of how much energy is transferred to species feeding higher up in the food web. The mean trophic level of fish 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 (Figure 6.5).

Condition Factor

We note that declines in condition factor, or individual fish weight in relation to fish length, have been observed for numerous fish stocks in the Northeast US. Recently, trends in condition factor were analyzed for 40 finfish stocks caught in the NEFSC autumn bottom trawl survey (1992-2010), and sexes were analyzed separately for species whose growth rate differ by sex. Most of fish stocks and sexes (43 of the 66 combinations) were found

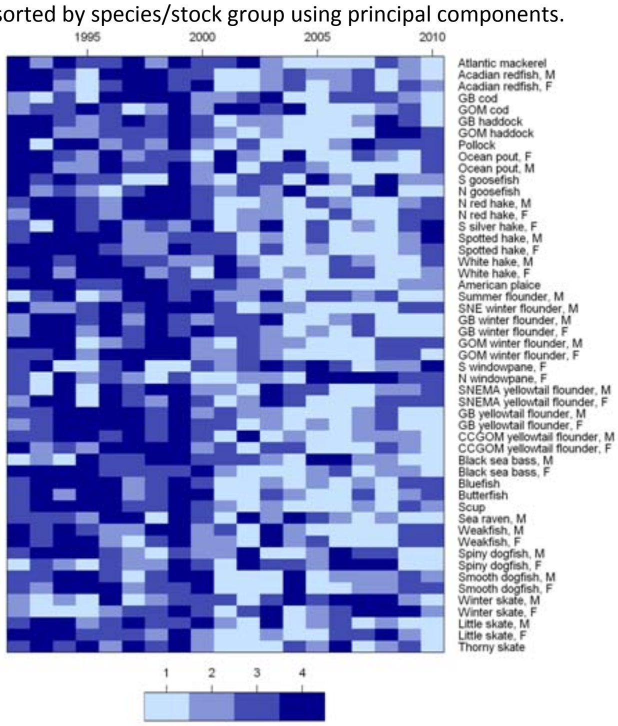


Figure 6.6 Change in condition presented as normalized time series from high (dark blue) to low (light blue) condition, and sorted by species/stock group using principal components.

to have significant trends in condition factor over the time series, and of these, only females of the Northern windowpane flounder stock showed a significant increase in condition factor (Figure 6.6). Changes in condition factor can be due to fishing pressure, competition, or environmental changes. However, further analysis showed that abundance or bottom temperatures did not appear to be driving the observed decreases in fish weight. Similar changes in condition have been noted for fish in Atlantic Canada. The overall change in fish condition is important because the productivity of fish stocks and expected yield depend on growth and condition. Further, the reproductive output of fish stocks is linked to their condition, potentially affecting egg production and recruitment.

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 6.7). The preferred temperature of the community was calculated by weighting the mean preferred temperature

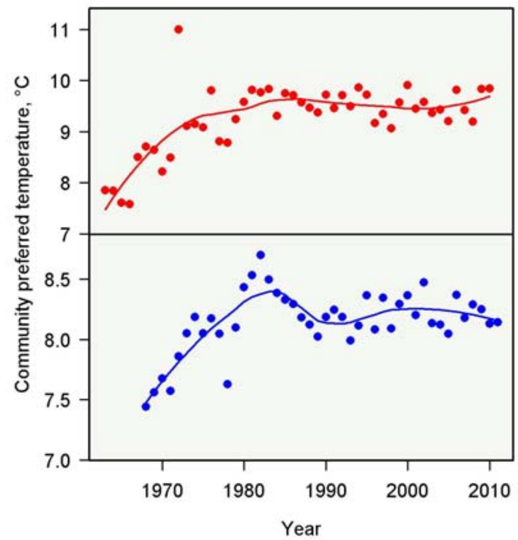


Figure 6.7 Change in the composition of fish communities on the Northeast Continental Shelf as indicated by weighted temperature preferences (the average preferred temperature of the species multiplied by the relative importance of the species measured by its biomass). For autumn (upper panel) and spring (lower panel).

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.

Mean preferred temperature of the fish community increased over both the fall and spring bottom trawl time series from the 1960s to the early 1980s and then either increased slowly (autumn; Figure 6.7 upper panel) or declined from a peak in 1982 (spring; Figure 6.7 lower panel). 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 initially shifted poleward over the first two decades of the survey such that the area occupied by warm-water species was greater than the area occupied by cold-temperate species. This pattern then leveled off in the last two decades (Figure 6.7) .

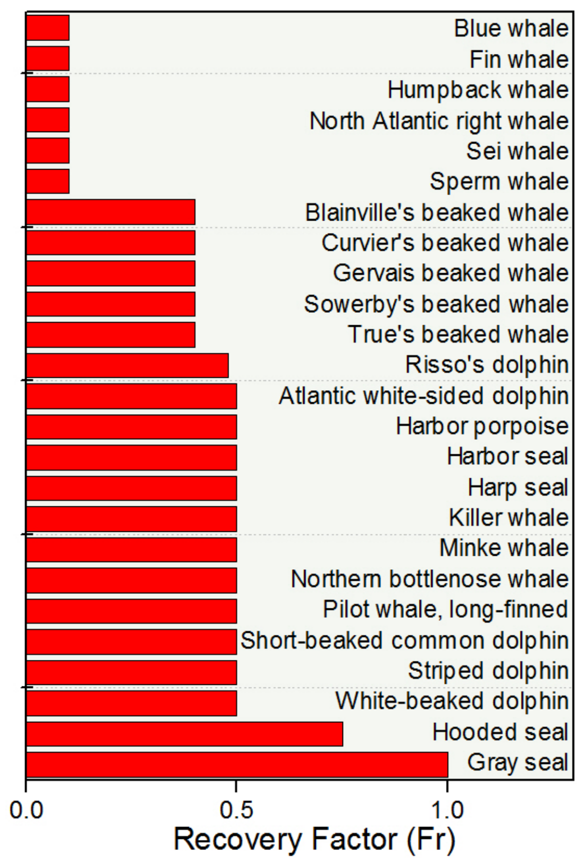
7 Protected Species

Special considerations are required for species that are threatened or endangered by human activities even when these species are not directly targeted by the fisheries. Legal mandates and authorities for protection of these species fall primarily under the Marine Mammal Protection Act, the Endangered Species Act, and other pieces of legislation including the Magnuson-Stevens Fishery Conservation and Management Act and the Migratory Bird Treaty Act.

Marine Mammals

Marine mammal species listed as endangered that occur in the Northeast U.S. Continental Shelf Large Marine Ecosystem (NES LME) include the blue, humpback, North Atlantic right, fin, sei, and sperm whales. The status of the western North Atlantic right whale is of particular concern. This population is currently thought to number around 400 individuals. They are highly susceptible to both collisions with ships and entanglement in fixed fishing gear, resulting in serious injuries and deaths. Current efforts to reduce these risks include sighting surveys for whales during times when they are congregated, wide dissemination of whale locations to mariners, restrictions on the configurations of fixed gill net, lobster and other pot gear, deployment of disentanglement teams, and support for researchers working on new gear and sensing technologies that could further reduce these risks.

Figure 7.1 Relative Status (expressed as Recovery Factor (Fr) of Marine Mammal populations known to occur on the Northeast U.S. Continental Shelf. The Fr ranges from 0 to 1).



The relative status of marine mammal species found on the Northeast Continental Shelf is depicted in Figure 7.1 (D. Palka, NEFSC, personal communication). The plot shows the estimated recovery factor (Fr) for these species (Fr ranges from 0 to 1 with 1 indicating a complete recovery). While many cetacean species are classified as low to moderate with respect to recovery, seal species have increased. Grey seals and harbor seals increased dramatically over the last several decades with potentially important implications. Seals prey on some fish species and in some areas conflict has arisen over predation by seals on commercially important fish species.

Table 7.1 Current status of sea turtle species found on the Northeast Continental Shelf under Endangered Species Act designations.

Species	***ESA status***
Leatherback	Critically endangered
Kemp's Ridley	Critically endangered
Hawksbill	Critically endangered
Olive Ridley	Endangered
Green sea turtle	Endangered
Loggerhead	Threatened

Sea Turtles

Five species of threatened or endangered sea turtles can be found in the NES LME including green, hawksbill, Kemp's Ridley, leatherback, and loggerhead turtles. The Endangered Species Act listing for each of these species is provided in Table 7.1. Threats to sea turtles include disruption of nesting sites, incidental capture in fishing gear, and ship collisions. The latter two impacts are of concern for species occurring in the NES LME.

The distribution of many sea turtles follows well-defined oceanographic features, including fronts associated with the Gulf Stream. These fronts are also important habitat for large pelagic fishes, and there are consistent spatial patterns of incidental takes of sea turtles in the longline fishery off the edge of the shelf. These takes have been substantially reduced both through closures and development of modified hooks.

Seabirds

The National Marine Fisheries Service's marine stewardship role also includes responsibility for the protection of seabirds and other migratory birds. This responsibility is supported by both domestic and international directives to gain a better understanding of seabird bycatch and ways of reducing incidental takes of seabirds. Seabirds were historically hunted for food and for plumage and many species declined precipitously due to over-exploitation. By-catch in fishing operations and threats to nesting areas for some species are currently of greatest concern. The species with the largest number of takes are shearwaters and petrels followed by loons and gulls. The fisheries that were most responsible for these by-catches were bottom otter trawls and scallop dredges, followed by the drift gillnet and finally the midwater paired otter trawl. The red-throated loon (*Gavia stellata*), red-necked grebe (*Podiceps grisegena*), greater shearwater (*Puffinus gravis*), northern gannet (*Morus bassanus*), thick billed murre (*Uria lomvia*), razorbill (*Alca torda*), black guillemot (*Cepphus grille*) and the Atlantic puffin (*Fratercula artica*) have been identified as species at risk due to fisheries bycatch (Marie St. Martin, CUNY, personal communication).

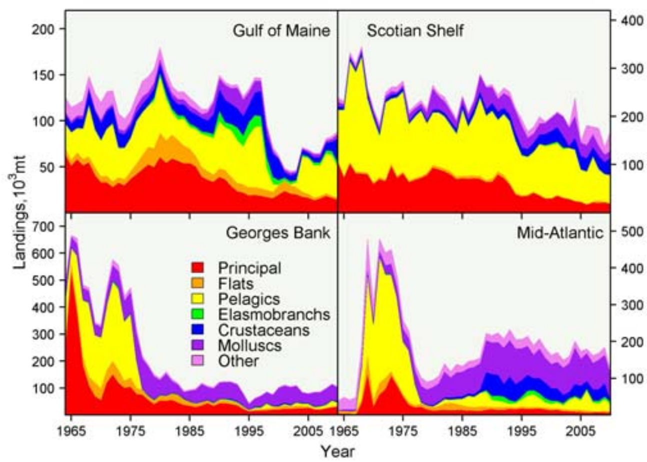
8 Anthropogenic Factors

Trends in Landings

The NES LME has historically produced some of the world's most productive fisheries. While overall landings have declined, the four EPUs have exhibited different trends (Figure 8.1). Landings peaked in the mid 1960s through the mid 1970s on Georges Bank and the Mid-Atlantic during a period of heavy fishing by foreign distant water fleets. Landings from Georges Bank peaked in 1965 at ~670,000 mt, but by 1985 they were at 14% of the peak. For the latter part of the time series, landings have been level around 100,000 mt. Similarly, the Mid-Atlantic peaked in 1971 around 480,000 mt. After a low point of ~90,000 mt in 1979, landings increased to ~231,000 mt in 1993 but have showed a steady decline since then. The two northern ecoregions have shown much different trends. Landings from the Gulf of Maine were relatively stable until a sharp decline in pelagics (Atlantic herring and Atlantic mackerel) in the late 1990s. Since 2003, total landings in the Gulf of Maine have been increasing. Within the Scotian Shelf EPU, landings have steadily declined since the mid 1960s. Of these regions, the Mid-Atlantic currently exhibits the highest volume of landings.

Principal groundfish landings, which include Atlantic cod, haddock, red hake, silver hake, pollock, and monkfish, peaked at ~381,000 mt in 1973 in the NES LME. Groundfish landings have continued to decline since the mid 1970s due to severe overfishing and, more recently, to regulatory intervention that has limited landings in order to rebuild depleted stocks; currently they are a minor component of total system removals. By 1995, principal groundfish landings were at 25% of their peak. Once a major portion of the landings, they are now fourth behind pelagics, molluscs, and crustaceans.

Figure 8.1 Landings by EPU for the NES LME. Landings are disaggregated by species group. The groups represented are: principal groundfish (Atlantic cod, haddock, pollock, silver hake, red hake, white hake, red fish, and monkfish), flatfish (i.e. summer flounder, winter flounder, yellowtail flounder), pelagics (i.e. Atlantic herring, Atlantic mackerel), elasmobranchs (i.e. spiny dogfish, winter skates), crustaceans (i.e. American lobsters, red crab), molluscs (i.e. Atlantic scallops, ocean quahogs), and other. Note: inshore trap landings of lobster not represented.

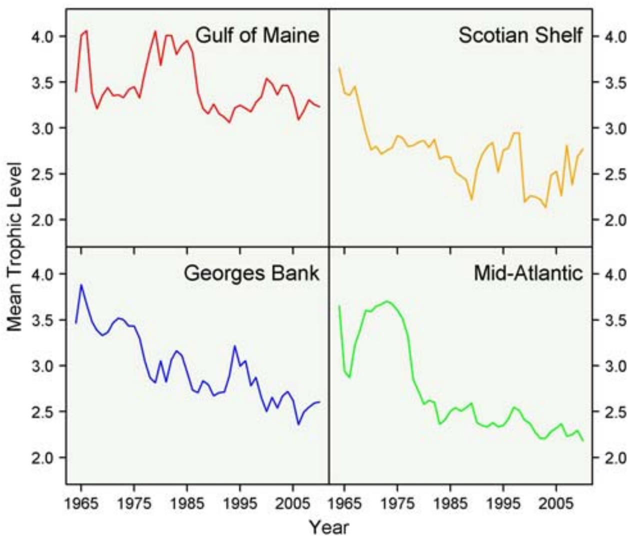


By 1984, landings of small pelagic fishes reached 988,000mt in 1973 but declined to about 31% of this peak value due to the collapse of the Georges Bank component of the herring stock complex and a severe decline in Atlantic mackerel. Recovery of the Atlantic herring and mackerel stocks during the late 1980s and sustained landings of Atlantic menhaden are responsible for relatively robust landings, averaging about 360,000 mt from 1977-2010. 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 8.1). 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 8.1).

Trophic Level of the Landings

It has been recognized for some time that a substantial level of depletion of large piscivorous fish has occurred on a global basis during the last 40-50 years of fishery exploitation (*58-60*). Depending on the region, this has in some cases resulted in the loss of important predators, the shortening of food chains, and/or the simplification of marine ecosystems. Measuring this effect is not easy, but several metrics have been proposed for assessing these impacts, including trophic level of catch (*58*) and catch-per-unit-effort of biotic community biomass (*59*). These metrics are among those designed to measure the overall impact of fishing on large regions of the global oceans.

Figure 8.2 Mean trophic level of the catch by EPU for the NES LME.

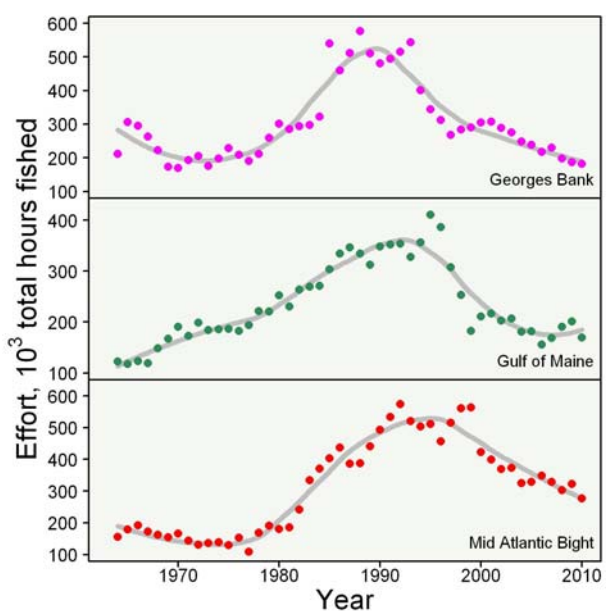


The mean trophic level of landings (TLL) was calculated for the NES LME during 1960-2010 to monitor possible changes in the trophic structure in the region. This method accounts for the trophic level of each species in the landings, weighted by the total landings of each species in a given year. The 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 the major change (described earlier) in the composition of the landings. The higher TLL in the 1960s reflects the representation of cod, haddock, and silver hake in the ICNAF (International Commission for the Northwest Atlantic Fisheries) fishery, while the decline in the 1970s reflects the high proportion of small pelagic fishes in catches by the distant water fleets of that era (Figure 8.2). Further declines in the 1980s reflect the dominance of surf clams, ocean quahogs, and Atlantic menhaden in the landings, in conjunction with continued declines in groundfish by the U.S. industry after the imposition of extended jurisdiction (the 200 mile limit) in 1977 and the imposition of the Hague Line in 1984. 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, Atlantic sea scallops, and steady landings of Atlantic menhaden (Figure 8.2). These results differ from those based on research vessel surveys (see Figure 6.5) in that the survey estimates do not include shellfish, and 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, suggesting a much more simplified ecosystem at present and a focus on landing species that are at a much lower trophic level.

Fishing Effort

The arrival of distant water fleets (DWFs), principally from the former Soviet Union, in the early 1960s resulted in a massive increase in fishing effort in the system. Factory trawlers and associated support vessels were substantially larger than any of the domestic fleet. Following the implementation of the 200 mile limit in 1976-77, most of the foreign vessels were excluded from the Northeast Continental Shelf. A program of fleet modernization for the domestic fishery was undertaken, and standardized fishing effort for both demersal and pelagic fisheries increased from 1977 through the mid-1980s (Figures 8.3, 8.4). Standardized fishing effort

Figure 8.3 Standardized fishing effort (hours fished) for domestic demersal fisheries (otter trawls, gill nets, longlines) by ecoregions principally within US waters.

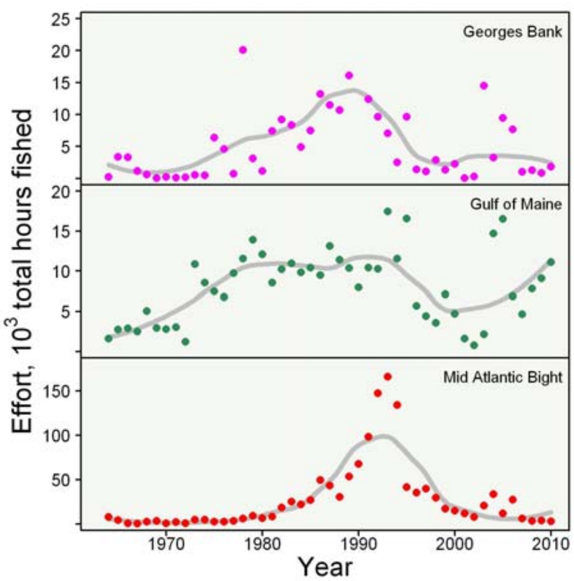


subsequently declined as a result of changing market conditions for some segments of the industry and the effects of management measures to address declines in resource status.

Revenues and Employment

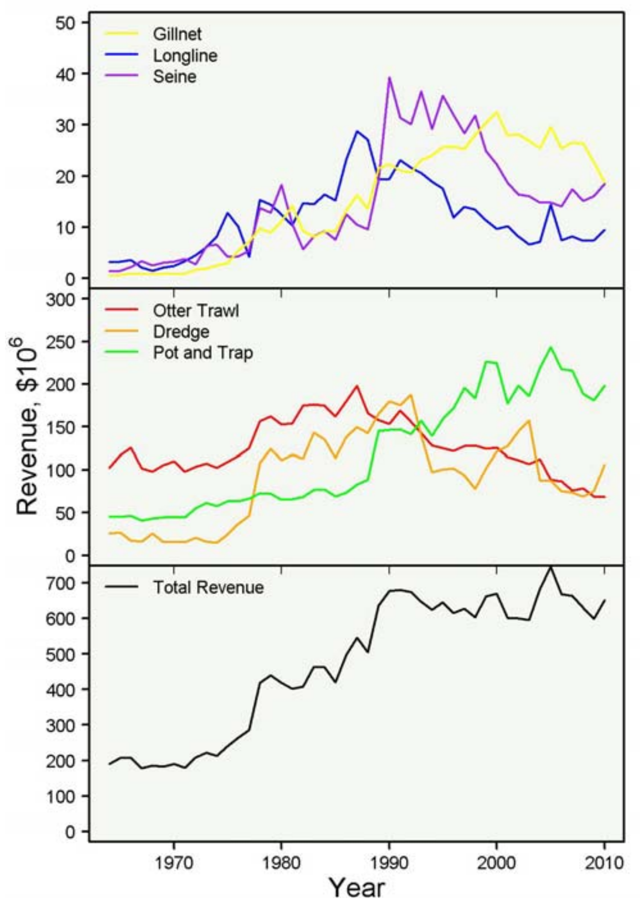
Though commercial fisheries revenues have remained high and stable in the region over the past two decades, this relative stability belies the volatility and change seen in specific fishery sectors. Though always lower revenue sources than some of the other gear types, revenues associated with gillnet, longline, and seine gear types have decreased in recent years from the higher levels seen during the late 1980s and 1990s. Seine and longline revenues however may now be showing the start of an upward trend (Figure 8.5). These gear types currently

Figure 8.4 Standardized fishing effort (hours fished) for domestic pelagic fisheries (purse seines, pair trawls) by ecoregion excluding the Scotian Shelf).



comprise a total revenue stream of approximately $50MM, which represents less than 10% of the total fisheries revenues of the region. Otter trawl and dredge fisheries, while they have remained overall the higher revenue sectors among the gear types, have also declined in recent decades. Note that dredges have showed a less clear-cut picture than otter trawls. Otter trawl revenues were highest during the 1980s exceeding $150MM; however, after declines in stock abundance and structural changes in the fishery itself, otter trawls now account for approximately half that amount. Dredge fisheries peaked at similar revenue levels as otter trawls, but in a later time frame during the early 1990s; these fisheries have also been halved in recent decades. These declines have been offset by pot and trap fisheries, most notably American lobsters, which has increased dramatically in just the past few years. Revenues for pots and traps peaked at nearly $250MM and currently account for a third of the region's fisheries revenues. It should be noted, however, that there is a strong overlap in the

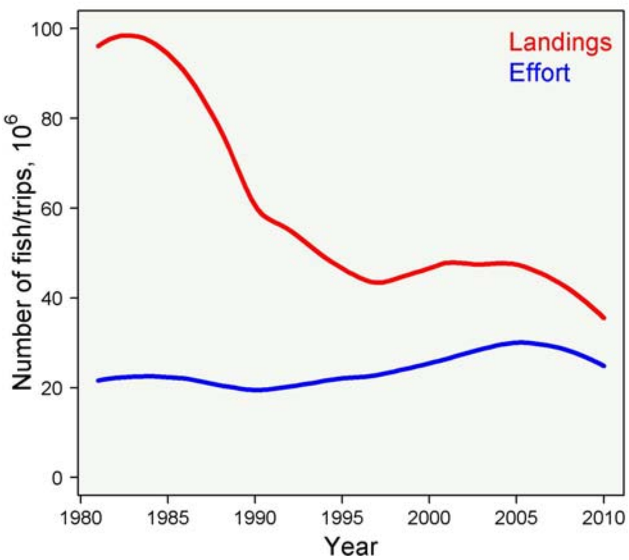
Figure 8.5 Commercial fisheries revenue for six common gear types, and total revenue all gear types. There is a strong overlap in the selectivity of gears, so that the same species are caught by multiple gears. There are a number of trip records with "unknown" gear category which means that the data presented here may only be a subset of the total revenue for each gear category.



selectivity of gears, so that the same species are frequently caught by multiple gears. Further, many of the records contain gear codes of "unknown," meaning that these data are based on subsets of the total revenue actually associated with each gear.

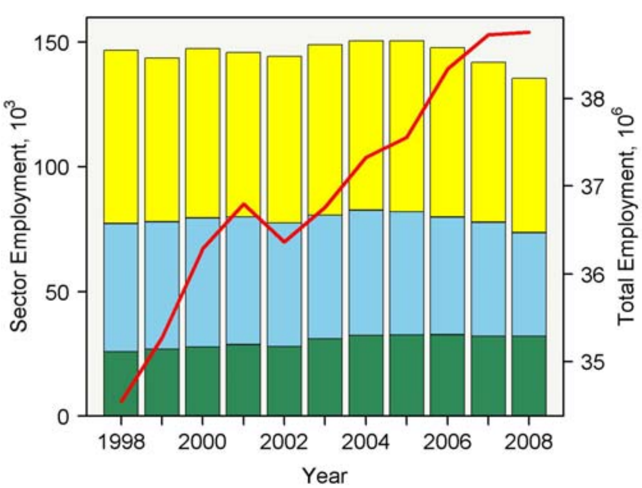
Changes in recreational fisheries reflect some of the same pressures acting on commercial fisheries, where dependency on stressed stocks has resulted in declining landings. The recreational fishery is composed of for-hire vessels (party and charter vessels), private boats, and anglers fishing from shore (shore mode). Data from the last several decades show a general decrease in landings (fish kept), while effort has been increasing (Figure 8.6). This could be because of several factors, including more stringent regulations and lower stock sizes. It is important to remember, however, that recreationally caught fish are sometimes kept (landed) and sometimes

Figure 8.6 Landings (numbers of fish) and effort (number of trips) for recreational fisheries throughout the NES LME (for-hire, private boat and shore-mode).



released. The released fish are not necessarily removed from the ecosystem, though delayed mortality after release has been documented (*61*). Further, keeping fish

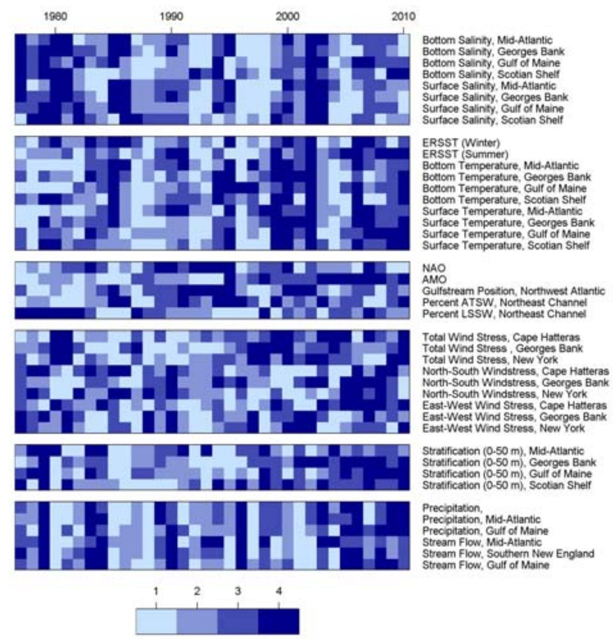
Figure 8.7 Employment by marine related sectors, boating (green), seafood (blue), and shipping (yellow). Total employment for all jobs of the regional economy(red line).



is not the most important factor in the fishing experience for the majority of recreational (as opposed to subsistence) fishermen (*62*). Therefore, increased regulation to further lower landings, though not catch and release fishing, could conceivably be implemented with fairly little disruption to the recreational fishery.

Employment in jobs related to the marine environment represents a small part of the total employment picture of the Northeast United States. However, these employment sectors are pivotal to other industries and to the way of life of many Americans. Overall marine sector employment has been declining, particularly since 2005, in large measure due to changes in the seafood employment sector (including harvest,

Figure 9.1 Climate and physical forcing indicators of change. The series have been grouped according data types. Dark blue indicates high levels of the standardized variates and light blue indicates low levels.

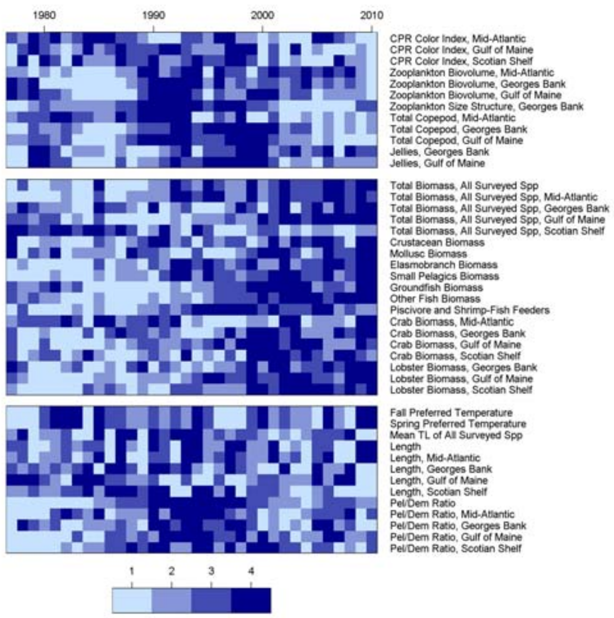


dealer, processing and retail seafood market), more so than either boating (boat building, retail boat dealers, marinas, and marine excursion such as whale watch, party/charter fishing, and harbor cruises) or shipping (including ship building, shipping, harbor operations, and other shipping-related services) (Figure 8.7). These changes in seafood sector employment may be attributed to multiple causes: shifting demographics in fisheries participation, movement of processing to other areas, and greater efficiency in fisheries operations that has reduced the need for certain jobs. Given that processors source their product from all over the world and are only partially dependent on fish from the local ecosystem (*63, 64*) indicating that 86% of all seafood eaten in the U.S. is imported, changes in processing employment are only loosely connected to the conditions in the NES LME. The actual shipping component of the shipping sector is also only extremely loosely connected to the local ecosystem, as is some of the ship building and harbor operations.

9 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. After partitioning the variables by ecological production

Figure 9.2 Biotic ecosystem indicators of change. The series have been ordered using a Principal Components Analysis to group variables showing similar patterns. The series have been grouped according data types. Dark blue indicates high levels of the standardized variates and light blue indicates low levels.

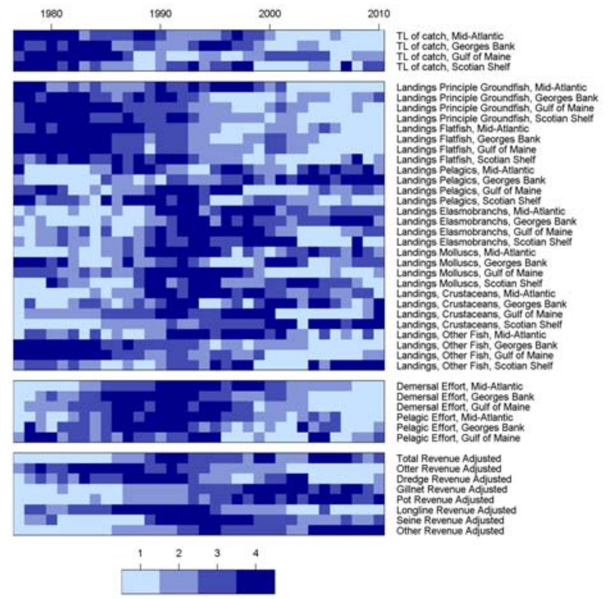


units, the analysis uses 42 metrics of climate and physical change (Figure 9.1), 44 indicators of biotic state (Figure 9.2), and 46 indicators of anthropogenic drivers and pressures (Figure 9.3) to characterize change in ecological state on the northeast shelf. Here our objective is to illustrate the general patterns of change for the three major index categories at a glance. Later in this section, we focus on selected metrics in greater detail.

We transformed each of the index 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 from high to low for each series and constructed graphical arrays representing time trends for each series in each of the three major categories identified above (Figures 9.1-9.3)

The array of climate and physical metrics clearly reveals the increase in temperature (reflected in the research vessel survey data and the AMO) stratification, and precipitation, particularly in the last decade (Figure 9.1). A general spatial coherence in these changes is also

Figure 9.3 Human-related indicators of change. The series have been grouped according data types. Dark blue indicates high levels of the standardized variates and light blue indicates low levels.



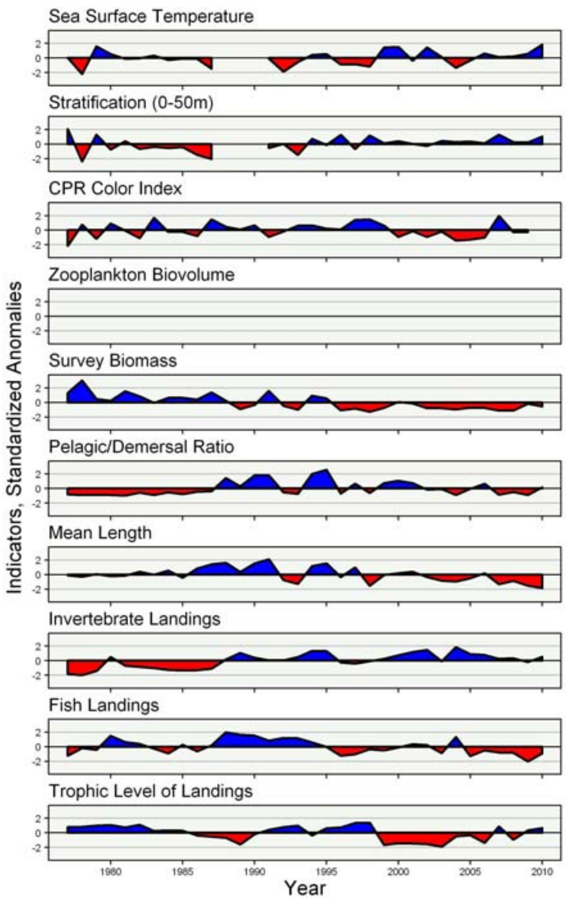
evident among the four ecological production units. Patterns in other variables are more diffuse but do show a general decline in salinity and an increase in precipitation, again particularly in the last decade.

Consideration of the ecosystem state variables reveals the general decline in the CPR color index over the last decade. In contrast, we observe an increase in zooplankton-related metrics during the period 1990-2000 (Figure 9.2).

For the fish community we observed increases in biomass in the aggregate assemblages of most species groups and areas (although the Scotian Shelf ecoregion did show contrasting trends for some biomass metrics (Figure 9.2). Coherence was generally high among the other three ecological production units. The ratio of pelagic to demersal fish peaked in during the mid 1990s and then declined. We note a generalized decline in the size-related metrics.

The metrics related to human-related activities show a strong decline in the mean trophic of the catch and in groundfish landings (Figure 9.3). 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. Recent declines for landings of the small pelagics are related to sharply reduced exploitation rates. Effort levels for demersal and pelagic fisheries peaked from the mid 1980s to the the mid- 1990s and then declined under increasingly stringent regulations (Figure 9.3) .

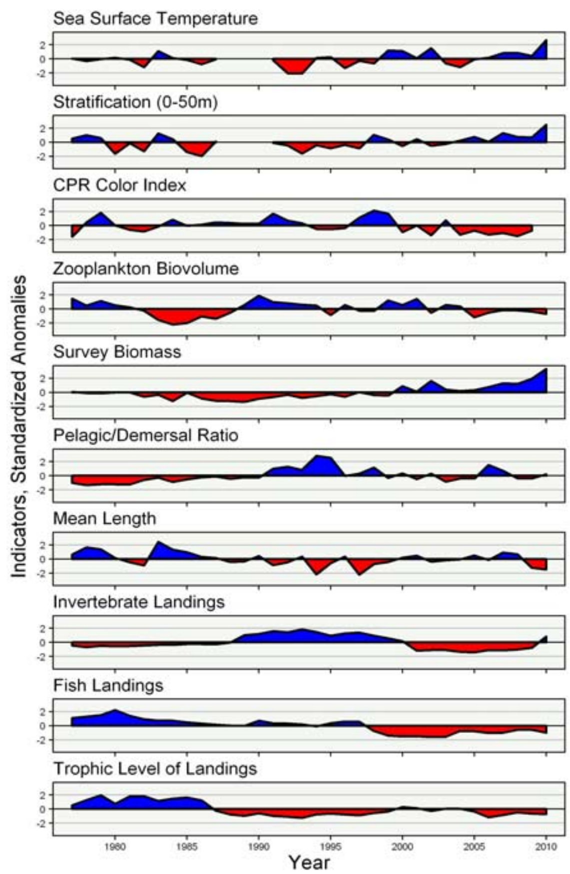
Figure 9.4 Relative change in selected indicators for the Scotian Shelf Ecological Production Unit. Note: inshore trap landings of lobster not represented in the invertebrate landings category.



We next isolate selected key metrics from each of the ecological production units to highlight major changes more clearly. Our criteria for inclusion were based on earlier analyses indicating the importance of certain metrics for linking drivers, pressures, and ecosystem response (*5*) and previously identified key characteristics of successful indicators. Fulton et al. (*65*) found that high priority should be assigned to species groups characterized by fast turn-over times (phytoplankton, zooplankton, and bacteria), species subject to commercial fishing pressure, and community or ecosystem level metrics. In contrast, indicators based on population-level measures and those that are strongly model-based (e.g., based on network analysis) were found to be less informative. Similarly, Samhouri et al. (*66*) reported that indicators of lower trophic level; high productivity groups; and complementary indicators such as phytoplankton, zooplanktivorous fish, piscivorous fish, and mean trophic level of the catch collectively performed well as indicators of ecosystem change.

Although a full appreciation of the nature of change in the NES LME and its underlying causes is enhanced by considering the full suite of metrics provided in this document, collapsing the whole to a smaller number of integrative measures provides a convenient way of capturing the dominant changes in the system. In the following, we highlight 10 indicators: sea surface temperature, stratification, the CPR color index of phytoplankton abundance, zooplankton biovolume, total fish biomass, the ratio of pelagic to demersal fish

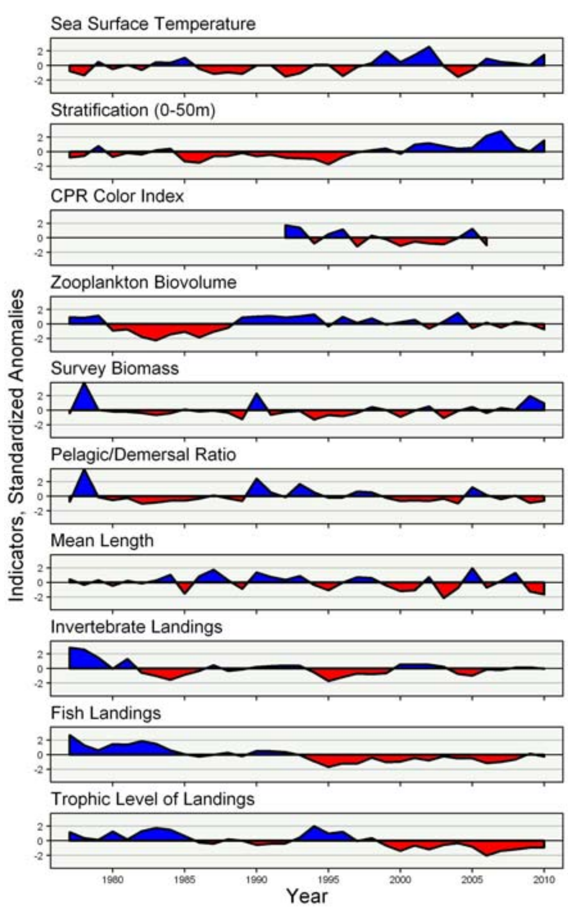
Figure 9.5 Relative change in selected indicators for the Gulf of Maine Ecological Production Unit. Note: inshore trap landings of lobster not represented in the invertebrate landings category.



biomass, mean length of the NEFSC survey catch, invertebrate landings, fish landings, and the mean trophic level of the catch. We again report standardized anomalies for each of these metrics. We also explore in greater detail some of the regional differences that do emerge.

As noted above, increases in sea surface temperature and stratification over the last decade are evident in each of the four regions, indicating a

Figure 9.6 Relative change in selected indicators for the Georges Bank Ecological Production Unit.



commonality in physical forcing throughout the system (Figs 9.4-9.7). The largest relative increases in stratification were found in the most weakly stratified systems where the scope of change is greatest.

The CPR color index of phytoplankton abundance showed variable but generally declining levels on the Scotian Shelf (Fig. 9.4) and the Mid-Atlantic Bight (Fig. 9.7) and more dramatic declines in the Gulf of Maine (Fig. 9.5). The color time series was incomplete for the Georges Bank region (Figure 9.6).

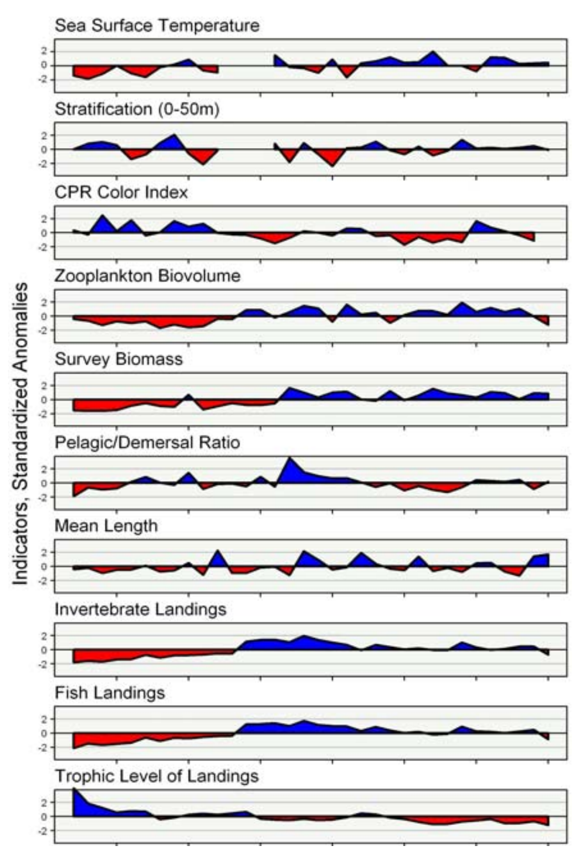
Zooplankton biovolume generally declined in the Gulf of Maine (Figure 9.5) but increased on Georges Banks (Fig. 9.6) and in the Mid-Atlantic region (Fig. 9.6). Estimates were not available for the Scotian Shelf because of irregular sample coverage in this area.

NEFSC survey biomass declined on the Scotian Shelf (Fig. 9.4) but increased in the Gulf of Maine (Figure 9.5) and the Mid-Atlantic (Fig. 9.7) and fluctuated around a relatively stable level with a recent increase on Georges Bank (Fig. 9.6). The pelagic to demersal fish ratio generally peaked in the mid 1990s and has since declined in each of the four Ecological Production Units (Figs. 9.4-9.7).

The mean length of the fish catch expressed as a standardized index declined sharply on the Scotian Shelf (Fig. 9.4) and showed weaker declines or fluctuations around the mean in the other regions (Figs 9.5-9.7).

Strong relative increases in invertebrate landings were observed on the Scotian Shelf and the Mid-Atlantic over the last 2 decades (Figs. 9.4 and 9.7) but declined in

Figure 9.7. Relative change in selected indicators for the Mid-Atlantic Bight Ecological Production Unit. Note: inshore trap landings of lobster not represented in the invertebrate landings category.



the Gulf of Maine (Fig. 9.5) and on Georges Bank (Fig. 6) over the last decade. Fish landings declined in each of the production units except the Mid-Atlantic region (Fig. 9.4-9.7). Finally, general declines in the mean trophic level of the catch were observed in each of the four ecological units.

10 Summary

The NES LME is shaped by both natural and anthropogenic drivers and by complex interactions that affect the biotic community. As a boundary ecosystem between warm and cold temperate ocean provinces, the ecosystem is highly dynamic. Some events such as the annual change in water temperature or the timing of a phytoplankton bloom, which may be critical to the function of the ecosystem, are indeterminately variable, whereas parameters such as the AMO have strong oscillatory behavior that may be used to produce reasonable decadal forecasts of thermal regime. Our notion of what constitutes anthropogenic forcing must be broadened. The status quo of simply viewing anthropogenic effects in terms of single species harvest must be replaced by the explicit incorporation of interactive effects between species (*67*) and cumulative impacts (*55*). We also need to recognize and incorporate climate change into our decision making process to deal with shifting species distributions and associated species interactions (*57*). To meet these challenges, an ecosystem-based approach to management is being adopted, which seeks to increase the accuracy of our management decisions by considering the relevant data streams affecting key management decisions. The ecosystem-based approach must begin with the definition of the ecosystem extent; four putative ecological production units have been proposed in this report. They represent a framework to begin developing ecosystem level management advice. At the same time, the protocols used to develop these production units are flexible and may be adapted for a changing ecosystem and/or the specialized needs of specific management problems.

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Glossary

Catch Per Unit Effort (CPUE): A standardized measure which relates a unit of effort (time, number of tows, number of hooks, etc) for a specific type of gear, to the catch of an organism.

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.

Ecological Production Units (EPU): Subunits of the Northeast U.S. Continental Shelf Large Marine Ecosystem: Scotian Shelf, Gulf of Maine, Georges Bank, and Mid-Atlantic Bight. They were delineated through multivariate statistical analyses on physiographic and phytoplankton data sets. Each of these subunits may also have coastal and shelf break special consideration areas associated with them.

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.

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 ^{o}C, and the temperature during one of the years was 16.2 ^{o}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.

Trophic Level (TL): The position an organism occupies in a food web. Primary producers such as phytoplankton occupy trophic level 1 (TL1). The TL number for each organism is the number of steps it is away from the start of the food web. So zooplankton which feeds on phytoplankton would be at TL2, herring which feeds on zooplankton would be at TL3, etc. Organisms are often assigned trophic levels in between whole numbers as they may eat prey which occupy two or more trophic levels.

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