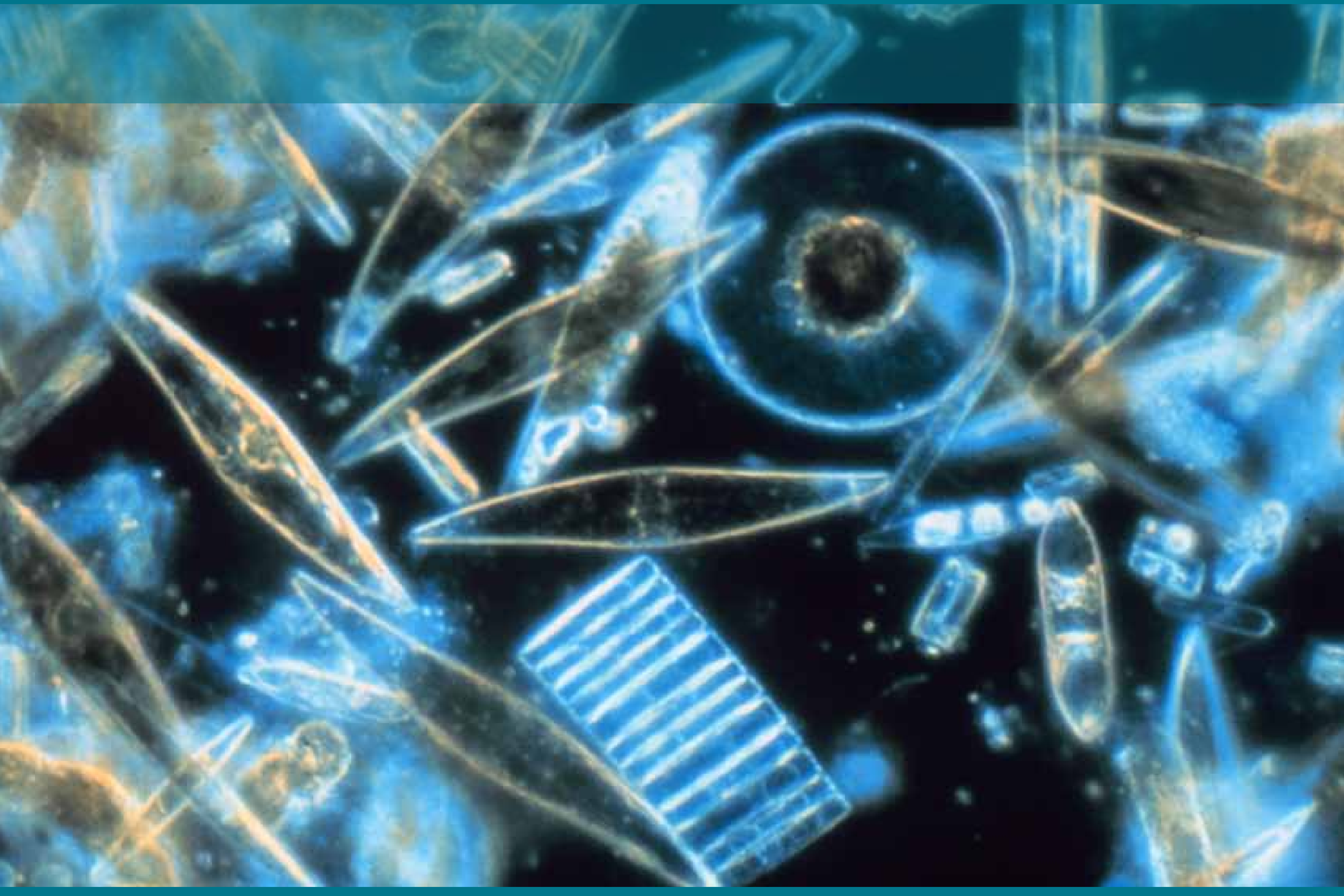
PRIMARY AND SECONDARY PRODUCERS



State of the Scotian Shelf Report

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CONTENTS

1 ISSUE IN BRIEF

Primary and secondary productivity are the foundational processes of the oceanic food web and are the essential building blocks of the entire ecosystem. **Phytoplankton**, comprising single-celled microscopic algae and cyanobacteria, are the major **primary producers** in the upper layers of the ocean. They remove carbon dioxide from the atmosphere, convert sunlight into biologically-available energy, and release oxygen. Phytoplankton provide a vital food source for ocean life and contribute approximately half of the world's primary production (Field et al. 1998). The most common measure of phytoplankton biomass is chlorophyll *a* concentration.

Zooplankton, which are **secondary producers** and primary consumers, are small animals that graze on phytoplankton, various protists, and other particulate matter. In turn, zooplankton fuel higher trophic levels by serving as prey for secondary consumers, such as other invertebrates and fish. The most important zooplankton species on the Scotian Shelf in terms of biomass is the copepod, *Calanus finmarchicus*, whose various life history stages are essential food sources for larval, juvenile and adult fish. *Euphausiids* (krill), especially *Meganyctiphanes norvegica*, are also an important food source for fish. Both *C. finmarchicus* and krill are also consumed by seabirds and baleen whales on the Scotian Shelf (DFO 2000). Members of the microbial community (bacteria) are, however, the dominant secondary producers in terms of their mass and contribution of energy to the ecosystem. These, like zooplankton, subsist off primary production provided by the first trophic level, although this microbial secondary production leads only to a small amount of energy that can be transferred to higher trophic levels, such as to commercially harvested groundfish.

LINKAGES

This theme paper also links to the following theme papers::

- Trophic Structure
- Climate Change and its Effects on Ecosystems, Habitats and Biota
- Ocean Acidification
- Invasive Species

This theme paper looks at the linkages between the primary and secondary producers and other aspects of the Scotian Shelf marine environment. Driving forces include environmental variability and climate change. These drivers affect the timing of ecosystem events and productivity (Figure 1). Changes in phytoplankton and zooplankton abundance may in turn affect other marine organisms, such as fish, seabirds, and marine mammals. Recently, an analysis reported a century-scale decline in phytoplankton biomass at the large ocean-basin scale

of the North Atlantic; however in shelf regions, the trend has switched from negative to positive since about 1980 (Boyce et al. 2010). Evidence of a decline, at the half-century time scale, is not present on the Scotian Shelf where a phytoplankton biomass index has increased in recent decades (McQuatters-Gollop et al. 2010). The trophic structure of the Scotian Shelf is further described in *Trophic Structure*. Due to the variable nature of the ocean, in addition to human activities, it is prudent to monitor the trends of these vital components, primary and secondary production, of the Scotian Shelf ecosystem.

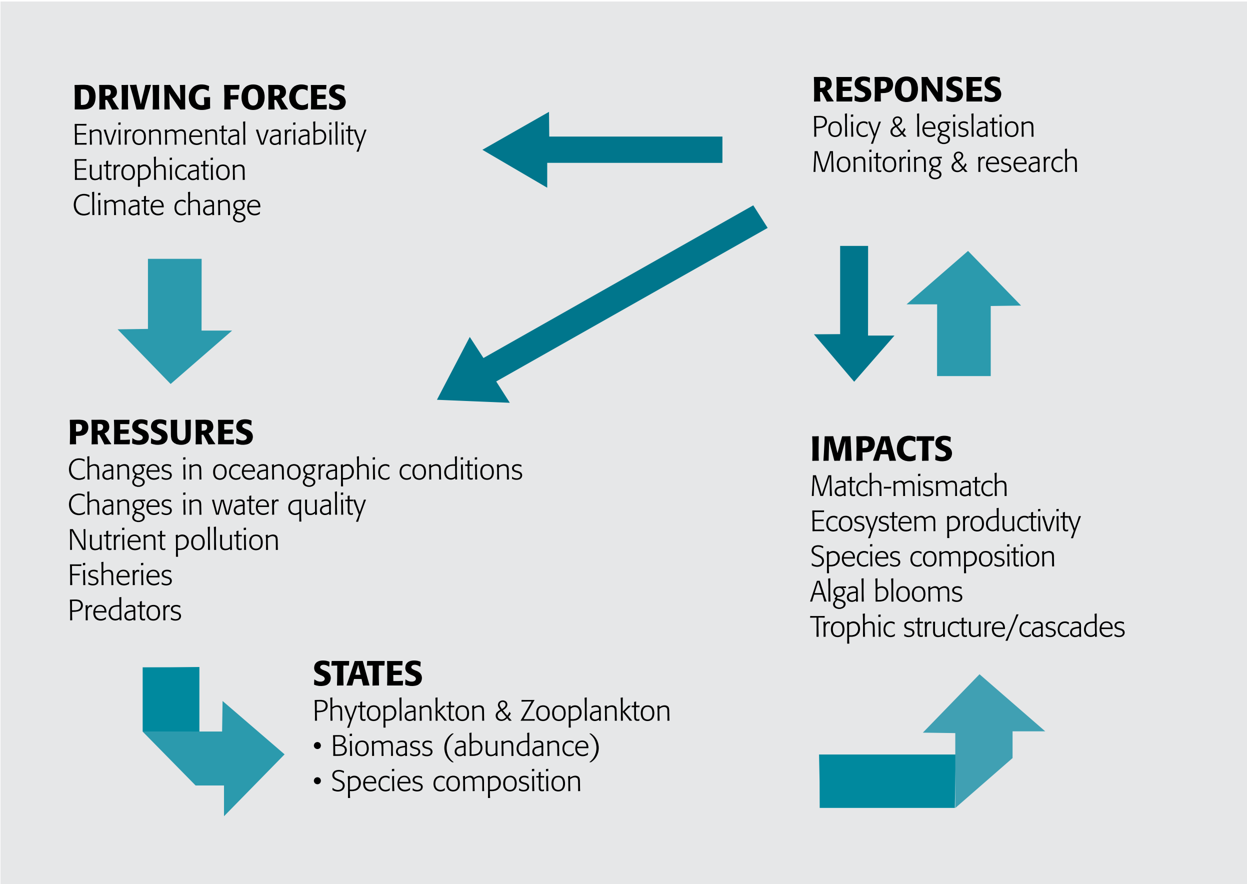
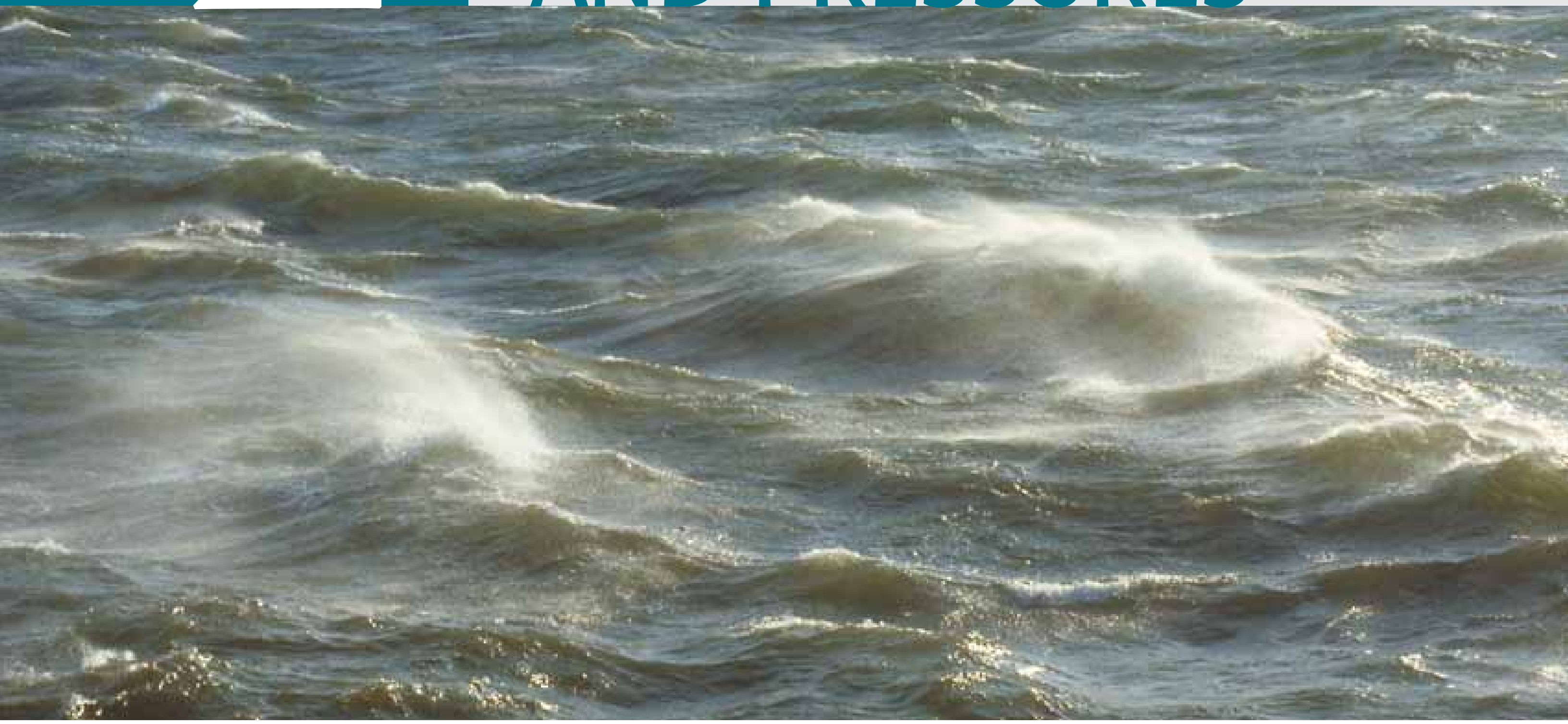


Figure 1: Driving forces, pressures, state, impacts and responses (DPSIR) to primary and secondary productivity on the Scotian Shelf. In general, the DPSIR framework provides an overview of the relation between different aspects of the environment, including humans and their activities. According to this reporting framework, social and economic developments and natural conditions (driving forces) exert pressures on the environment and, as a consequence, the state of the environment changes. This leads to impacts on human health, ecosystems, and materials, which may elicit societal or government responses that feed back on all the other elements.

2 DRIVING FORCES AND PRESSURES



2.1 NATURAL ENVIRONMENTAL VARIABILITY

2.1.1 Oceanographic Processes

The 12-month seasonal cycle is driven by the earth orbiting around the sun. The annual phytoplankton cycle on the Scotian Shelf begins in spring as energy from the sun increases during the changing of the seasons from the winter solstice to the spring equinox. At the same time, surface warming begins to stabilize the water column which has been intensely mixed over the winter. With stable stratification, phytoplankton receive both sufficient sunlight and nutrients to initiate exponential population growth. In general, diatoms (Figure 2) have evolved to take competitive advantage under these conditions of rapid growth and thus constitute the bulk of phytoplankton biomass in the spring bloom. Predictably, dissolved nutrients

decrease from their peak concentration in winter to supply the demand of phytoplankton growth. With the exhaustion of winter nutrients by the spring bloom, a summer flora develops that is able to use nutrients regenerated within the ecosystem itself by the resident bacteria. Large patches of summer phytoplankton are not unusual occurrences on the Scotian Shelf (Figure 3). Summer culminates in the autumn equinox when water temperature reaches its annual maximum, accompanied by a high numerical abundance of small phytoplankton cells, which may or may not rival the bulk biomass earlier developed in the spring bloom by a much lower numerical abundance of large phytoplankton cells. In winter, phytoplankton communities appear inactive, but in some coastal settings under unusual physical and meteorological conditions that permit net growth, sporadic winter blooms of well-adapted species associations may appear.

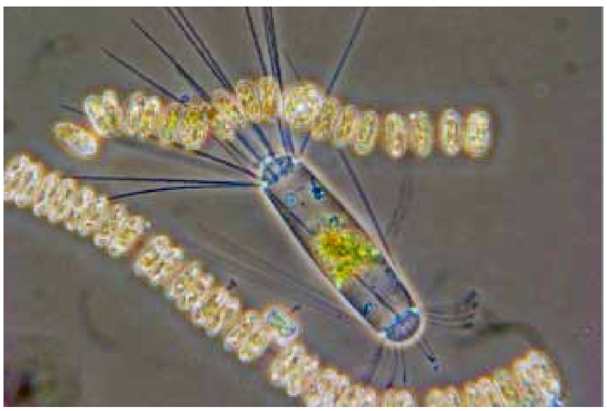


Figure 2. The diatoms *Corethron criophilum* and *Thalassiosira* sp. (chains) in the marine phytoplankton of Atlantic Canada waters (Source: K. Pauley, DFO Maritimes, Ocean and Ecosystem Science Division).

The Scotian Shelf is a naturally dynamic and variable ecosystem and the climate of the eastern

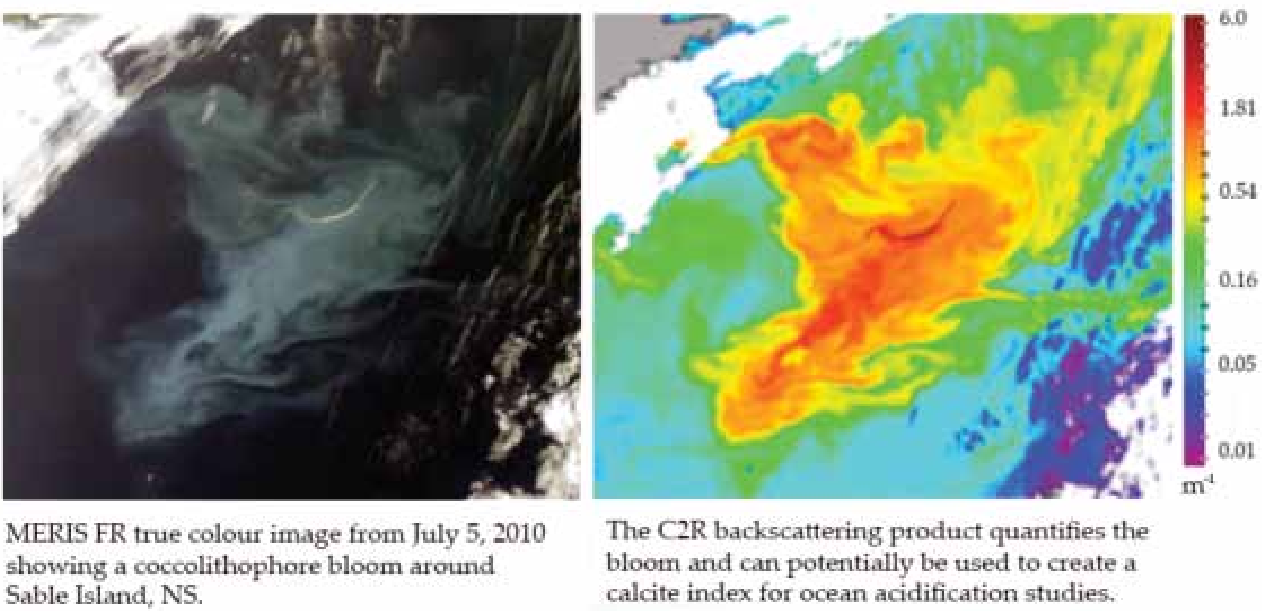


Figure 3. A bloom of coccolithophore phytoplankton on the Scotian Shelf in July 2010 (Source: C. Caverhill, DFO Maritimes, Ocean and Ecosystem Science Division).

Scotian Shelf is influenced primarily by outflow from the southern Gulf of St. Lawrence together with a lesser input of cold and low-salinity Labrador Current, while the central Scotian Shelf receives inputs of warm water from beyond the shelf-break, which mix with shelf water and flow southwest to the western Scotian Shelf. The waters of the Scotian Shelf typically form layers of varying temperature and salinity which vary by season and region (Breeze et al. 2002). The physical oceanography of the Scotian Shelf is further described in *The Scotian Shelf in Context*.

2.1.2 North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is the dominant meteorological pattern driving North Atlantic climate over a five- to ten-year time scale. It is indexed by the sea level atmospheric pressure difference between the Azores and Iceland. High NAO leads to severe winters over the Labrador Sea, Labrador Shelf and Grand Banks. Cold and fresh conditions prevail on the Newfoundland-Labrador Shelf, the eastern Scotian Shelf and the Gulf of St. Lawrence. The opposite response (warm and salty conditions) is seen on the central and western Scotian Shelf and in the Gulf of Maine. Low NAO leads to mild winters in the Labrador Sea and Grand Banks, with a result that warm and salty conditions prevail on the eastern Scotian Shelf, with opposite conditions on the central and western Scotian Shelf (Petrie 2007). For phytoplankton on the Scotian Shelf, greater intrusion of offshore Atlantic slope water brings more nutrients during the high NAO phase. During low NAO phase, there is greater intrusion of Labrador Slope water, which is colder, fresher, lower in nitrate, and higher in oxygen than Atlantic Slope water.

2.1.3 Atlantic Multidecadal Oscillation

The Atlantic Multidecadal Oscillation (AMO) is the variation in North Atlantic sea surface temperature (SST) between cool and warm phases, each lasting for 20–40 years with a difference of about 0.5°C between extremes. The AMO is thought to be coupled with oscillations in the atmosphere and related to slow changes in the overturning circulation of the Atlantic Ocean. For the Scotian Shelf, even the longest record of plankton observation from the Continuous Plankton Recorder (CPR) is too short to evaluate plankton responses to this mode of variability.

2.1.4 Sea Surface Temperature

During the last two decades water temperatures were relatively cool from 1987–1993 and 2003-2004 and relatively warm in 1999–2000 (Worcester and Parker 2010). Phytoplankton biomass (measured as chlorophyll *a*, Chl-a, concentration, Figure 4) is generally higher in regions with cold surface waters, since cool temperatures are gener-

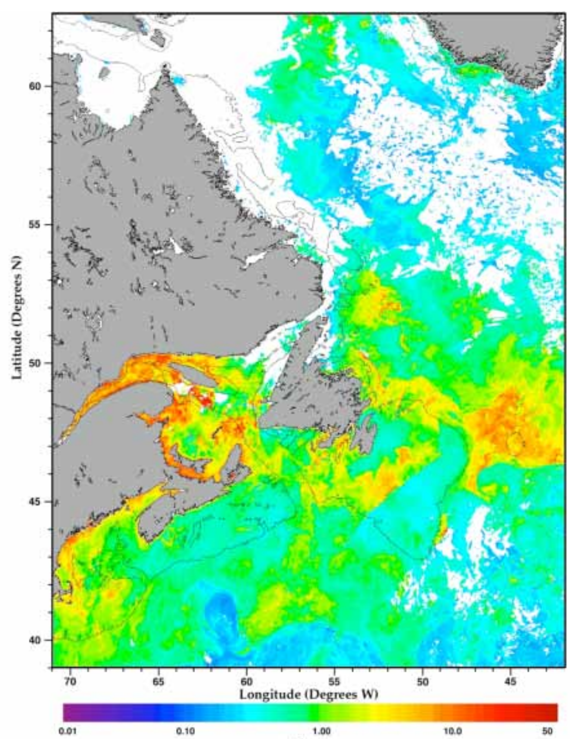


Figure 4. A composite of Chlorophyll a concentration, in milligrams per cubic metre (mg m^{-3}), in Atlantic Canada from April 16 through to the 31, 2012 (Source: BIO 2013).

ally associated with deeper mixing and higher nutrient levels. In ecosystems like the Eastern Scotian Shelf, where ocean currents cause upwelling and cool sea surface waters, phytoplankton biomass is often high. Decadal trends in the intensity and duration of the Scotian Shelf's spring bloom show that it started earlier in the 1990s and 2000s than in the 1960s and 1970s (Sameoto 2004, Head and Pepin 2010b). One possible reason is that less stormy winter weather may have led to less intense mixing of the water column during the winter and thus allowed for earlier stratification during the spring (Zwanenburg et al. 2006). Strong seasonal cycles for Chlorophyll *a* and SST have been demonstrated for the entire Northwest Atlantic continental shelf, although there is no obvious relationship between them at seasonal or annual time-scales on the Scotian Shelf (Maillet 2010).

2.2 ANTHROPOGENIC STRESSORS

2.2.1 Eutrophication

In inshore regions of the Scotian Shelf, the possibility of sustained addition of nutrients such as nitrogen and phosphorus at concentrations significantly above natural levels (i.e., eutrophication) could lead to significant changes in the phytoplankton community. Large populations of certain phytoplankton species, such as those responsible for nuisance algal blooms, can be toxic or otherwise harmful to other organisms in the ecosystem and a risk to human health (Breeze et al. 2002). Two of the main drivers of eutrophication are agricultural runoff (i.e., fertilizers) and combustion of fossil fuels (creating the greenhouse gas nitrous oxide, N_2O) (Vitousek et al. 1997). However, for the Scotian Shelf offshore of the nearshore embayments, there is no evidence of significant nutrient enhancement (Yeats et al. 2010). This is not surprising since the nutrient fields on the Scotian Shelf are mainly affected by physical oceanographic processes such as mixing and transport (advection). Additional human activities contributing to eutrophication are detailed in *The State of the Gulf of Maine Report: Eutrophication* (Liebman et al. 2012) and additional sources of marine pollution are mentioned in *The Scotian Shelf in Context*.

2.2.2 Climate Change

Temperature, Salinity and Stratification

Climate change is arguably the most important driving force of long-term change in primary and secondary productivity, not only on the Scotian Shelf but worldwide. It is expected to influence water temperature, climate regimes, ocean currents, and increase the ocean's acidity. Rising sea surface temperatures might be related to apparent declines in phytoplankton at the century time scale in large ocean basins (Boyce et al. 2010). On the Scotian Shelf and in other regions of the North Atlantic however, trends suggest otherwise (see section 3.1.1) (McQuatters-Gollop et al. 2011). As temperatures continue to rise, the oceans may become less dynamic resulting in a more stratified system (i.e., less mixed) with a diminished capacity to deliver nutrients to phytoplankton (DFO 2009a). Stratification on the Scotian Shelf has increased since 1960, with especially high values in the 1990s (Worcester and Parker 2010, Hebert et al. 2012). However, the possibility that this stratification is influenced by changes in both salinity and temperature means that simple predictions based solely on temperature change may have large uncertainty. The phytoplankton composition may also gradually shift to smaller individuals as waters warm (Moran et al. 2010), but smaller average cell size is not a diagnostic feature of any single driver. Additional nutrients provided by increasing eutrophication could boost phytoplankton productivity in the coastal zone, which together with a warmer and a less dynamic water column might give an increased risk for reduced water quality (such as hypoxia: low dissolved oxygen) (Liebman et al. 2012).

The Scotian Shelf is a transition zone where the southward flow of cold, fresh sub-polar water interacts with the northward flow of warm, salty sub-tropical water, but it is also affected by freshwater outflow from the St. Lawrence Estuary, which exerts a strong influence on water characteristics. Thus, climate change drives stratification by affecting both temperature and salinity. On the eastern and central Scotian Shelf, salinity exerts dominant control on stratification, but on the western Scotian Shelf, the effects of temperature and salinity are more equitable. In areas where there is a long term trend of increasing stratification, the change is most clearly observed in the summer and autumn, and not so clearly in the spring when the phytoplankton bloom is usually most intense (Brickman 2011).

In addition, under climate change, it can be expected that sea ice coverage will decrease, both in spatial extent and in occupied volume. This might have a direct effect by lengthening the growing season for phytoplankton in those limited areas of the Shelf where ice is normally expected (extreme eastern edge and Cabot Strait), but also an indirect effect, since reduced sea ice in waters upstream from the Scotian Shelf (e.g., the Gulf of St. Lawrence and Labrador Shelf) will influence the salinity downstream on the Scotian Shelf.

As the climate changes, the net changes in salinity across the Scotian Shelf are uncertain because of counteracting tendencies. On the one hand, melting Arctic ice and more freshwater discharge in northern regions and the Gulf of St. Lawrence will reduce salinity; on the other hand, a northward shift of more saline subtropical waters will increase it.

The impacts of climate change on the Scotian Shelf are further described in *Climate Change and its Effects on Ecosystems, Habitats and Biota*.

Ocean Acidification

Phytoplankton have an important role in climate systems. By taking up carbon dioxide (CO_2), and by influencing the reflection and absorption of solar energy, phytoplankton significantly affect our global climate. The global increase in atmospheric and oceanic CO_2, attributed to the burning of fossil fuels, is evident in on the Scotian Shelf. There has been a documented decrease in pH (or increased acidity) of approximately 0.1 to 0.2 pH units since 1927 (DFO 2009a). It is not immediately clear what the short-term consequences of ocean acidification will be on primary and secondary productivity. It is possible that increases in CO_2 could stimulate more primary productivity, but if present trends continue, the decreases in pH will negatively affect organisms that build and maintain skeletons requiring calcium in the long-term (DFO 2009a). Organisms that may be vulnerable include members of the phytoplankton (e.g., coccolithophores), microzooplankton (e.g., foraminifera) and larger zooplankton (e.g., pteropods) communities. One zooplankton genus that is relatively abundant on the Scotian Shelf is *Limacina* spp. (Figure 5), which has a calcium carbonate shell that is degraded by low pH (Worcester and Parker 2010). At the moment it is unclear whether the abundance of this or any other organism has yet been affected by the reduction in pH on the Scotian Shelf (Johnson et al. 2012b). Potential impacts of ocean acidification on the Scotian Shelf are further discussed in *Ocean Acidification*.

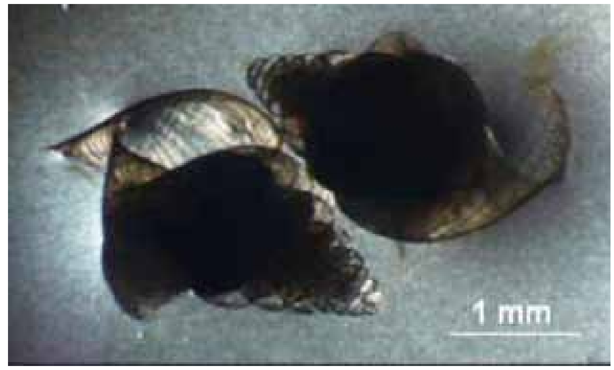


Figure 5. The pelagic mollusc *Limacina limacina* (Source: M. Ringuette, DFO Maritimes, Ocean and Ecosystem Science Division).

3 STATUS AND TRENDS

3.1 PHYTOPLANKTON

3.1.1 Biomass and Abundance

Primary producer biomass is most commonly estimated by examining ocean colour. Because photosynthesis involves the capture of light energy by the green pigment chlorophyll a found universally across species of phytoplankton, its concentration is frequently used as an estimate of phytoplankton biomass. The initiation, duration, and intensity of phytoplankton blooms are reflected by seasonal development in chlorophyll *a* concentra-

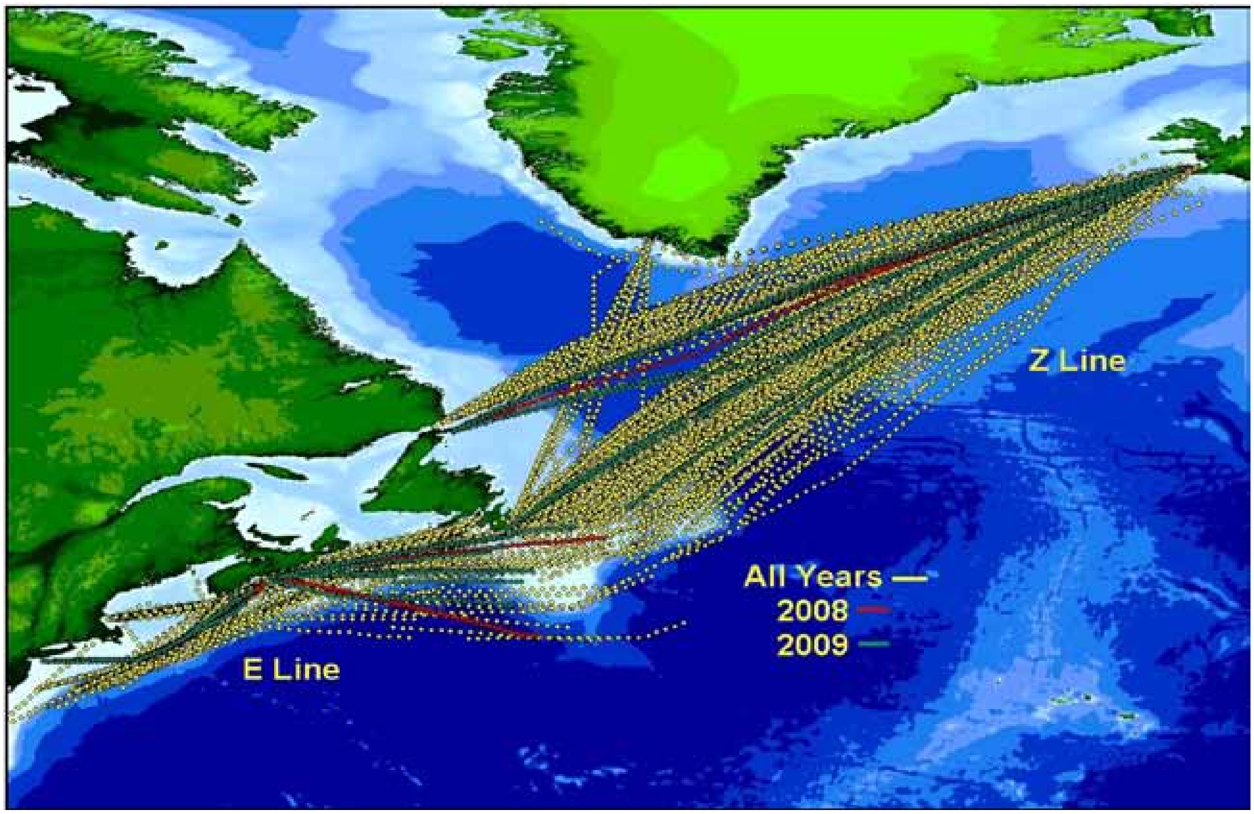


Figure 6. Continuous Plankton Recorder (CPR) lines and stations, 1961 to 2009 (2008 and 2009 highlighted) (from Johnson et al. 2012a).

tion. Two data sources that are commonly used to map the distribution of ocean colour over space and time are the continuous plankton recorder (CPR), which returns a semi-quantitative index of "greeness" (the Phytoplankton Colour Index, PCI), and remote sensing via satellite imagery (e.g., Sea-viewing Wide Field-of-view Sensor, or SeaWiFS and Moderate Resolution Imaging Spectroradiometer, or MODIS), which returns estimates of chlorophyll a concentration in the near-surface layer (Breeze et al. 2002). CPRs are towed by commercial vessels along oceanic trade routes (Figure 6), and have provided a relatively long time series, with irregular sampling on the Scotian Shelf between 1960 and 1976 and more regular (approximately monthly) sampling since 1991. Total phytoplankton biomass is estimated from the CPR samples by the PCI, but information is also obtained on species composition for the larger forms (e.g., Head and Pepin 2010a and 2010b).

In Atlantic Canada there appears to be a positive relationship between annual average chlorophyll concentration and fish yield, with the eastern and western regions of the Scotian Shelf having values that are higher than the Grand Bank, but lower than the southern Gulf of St. Lawrence (Table 1). CPR results indicate

Table 1. Characteristics of nine geographical areas in Atlantic Canada in terms of location, size, annual average indices of productivity (chlorophyll concentration and total fish yield) and long-term mean bottom temperature. Presented from highest to lowest chlorophyll concentration, the Eastern and Western Scotian Shelf are highlighted (adapted from Frank et al. 2006).

Location	Size (km^2)	Chlorophyll ($mg\ m^{-3}$)	Total fish yield ($t\ km^{-2}$)	Bottom water temperature (°C)
Gulf of Maine	53909	2.06	2.702	7.12
Southern Gulf of St. Lawrence	71982	2.06	1.824	1.88
Georges Bank	106903	1.68	1.639	8.74
Western Scotian Shelf	89266	1.67	2.496	6.55
Northern Gulf of St. Lawrence	128986	1.49	1.049	3.18
Eastern Scotian Shelf	149133	1.13	1.361	4.85
St. Pierre Bank	89404	0.81	0.870	2.96
Labrador Shelf/Northern Grand Bank	392068	0.80	1.021	1.17
Southern Grand Bank	180005	0.80	0.589	2.37

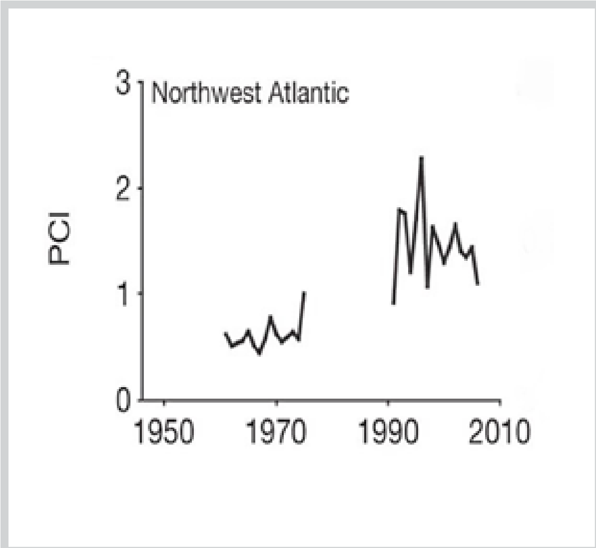


Figure 7. Results from the CPR survey show increasing phytoplankton trends measured by the phytoplankton colour index (PCI) in the Northwest Atlantic (from McQuatters-Gollop et al. 2011).

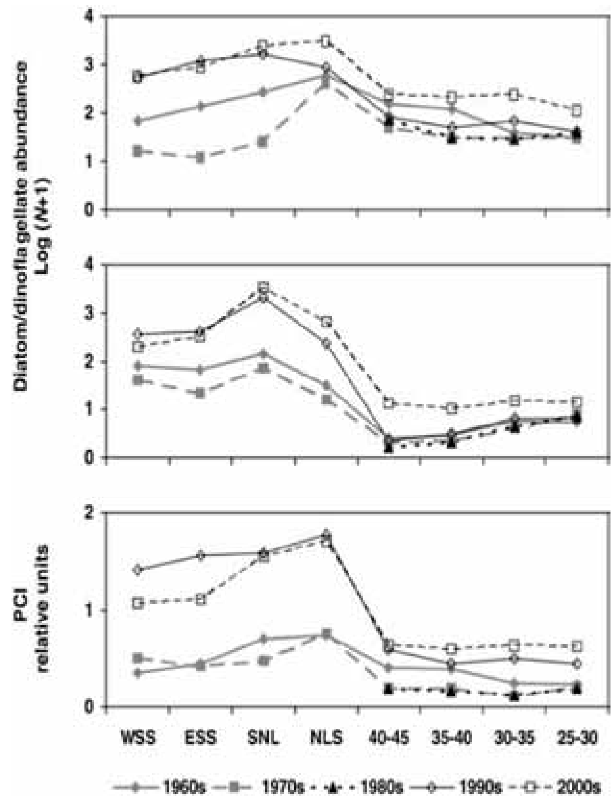


Figure 8. Decadal annual average abundances of three measures of primary producer biomass: diatoms (top panel), dinoflagellates (middle panel), and the phytoplankton colour index (PCI, bottom panel) in eight regions of the Northwest Atlantic. The eight regions are the Western Scotian Shelf (WSS), the Eastern Scotian Shelf (ESS), the South Newfoundland Shelf (SNL) and the Newfoundland Shelf (NLS), as well as four regions east of the NLS. The eastern regions are defined by their longitudinal limits (e.g., 40°– 45° W is bounded by 40° W and 45° W) (from Head and Pepin 2010b).

that the PCI and abundance of larger phytoplankton species in the Northwest Atlantic Ocean and on the Scotian Shelf were higher in the 1990s and 2000s than in the 1960s and 1970s (Figures 7 and 8), with the bloom occurring earlier (Head and Pepin 2010b). Monitoring by Fisheries and Oceans Canada (DFO) throughout the water column at a fixed station off Halifax since 1999 has shown considerable variability in the magnitude of the spring chlorophyll *a* peak, with a maximum of > 900 milligrams per cubic metre (mg m^{-3}), in 2007, and a minimum of 127 mg m^{-3}, in 2011 (Figure 9, Johnson et al. 2012b).

The 10-year time series (2003-2012) of satellite remote sensing observations (Figure 10) show warming trends on both the western and eastern Scotian Shelves, which are strongly driven by the very warm year of 2012. Over these 10 years, there is little indication of directional change in chlorophyll concentration on the western Scotian Shelf. In contrast, a slight positive trend can be discerned on the eastern Scotian Shelf (Figure 10B).

3.1.2 Composition

Over 300 different taxa (or groupings) of plankton (phyto- and zooplankton) have been identified in the CPR samples from the Scotian Shelf (Breeze et al. 2002). The structure and composition of the phytoplankton community has not been described in detail and is typically reported as the sum of abundances of two dominant groups, diatoms (which have shells made of silica) and dinoflagellates (which can swim using flagella) (Worcester and Parker 2010). The spring bloom is typically dominated by diatoms. Dinoflagellates rarely dominate the

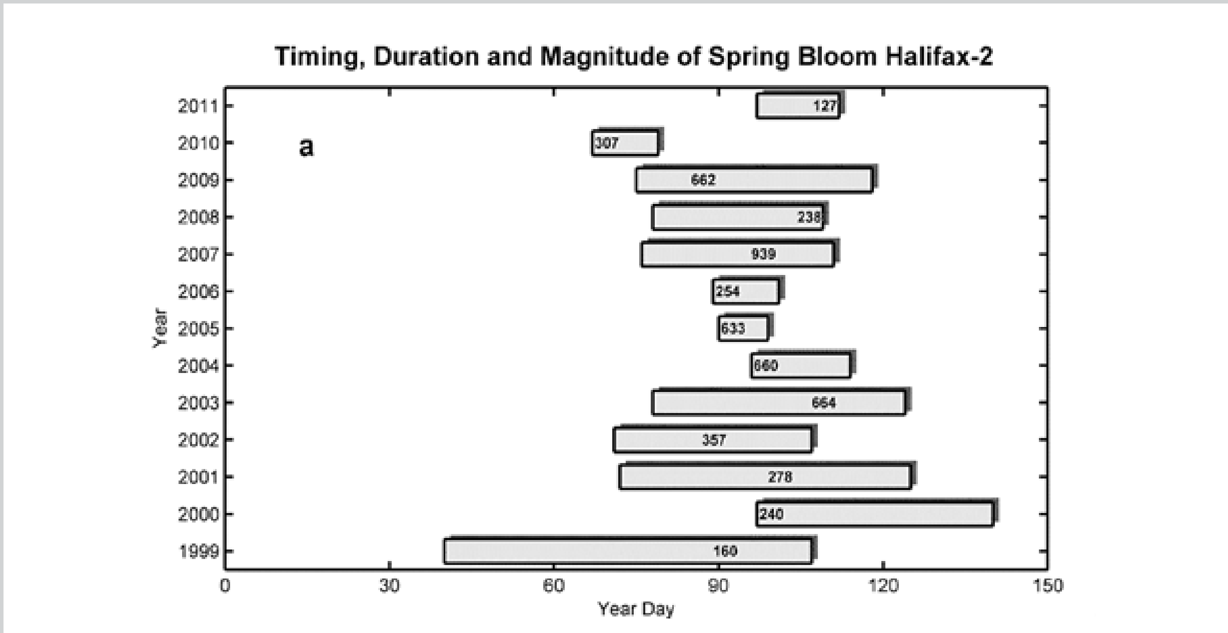


Figure 9. Timing (based on 40 milligrams of chlorophyll per metre squared [mg CHL m^{-2}] threshold for determining start and end of the bloom), duration (horizontal bars) and magnitude (numbers in bars, mg CHL m^{-2}) of the spring phytoplankton bloom at the Halifax 2 fixed station, 1999-2010 (from Johnson et al. 2012b).

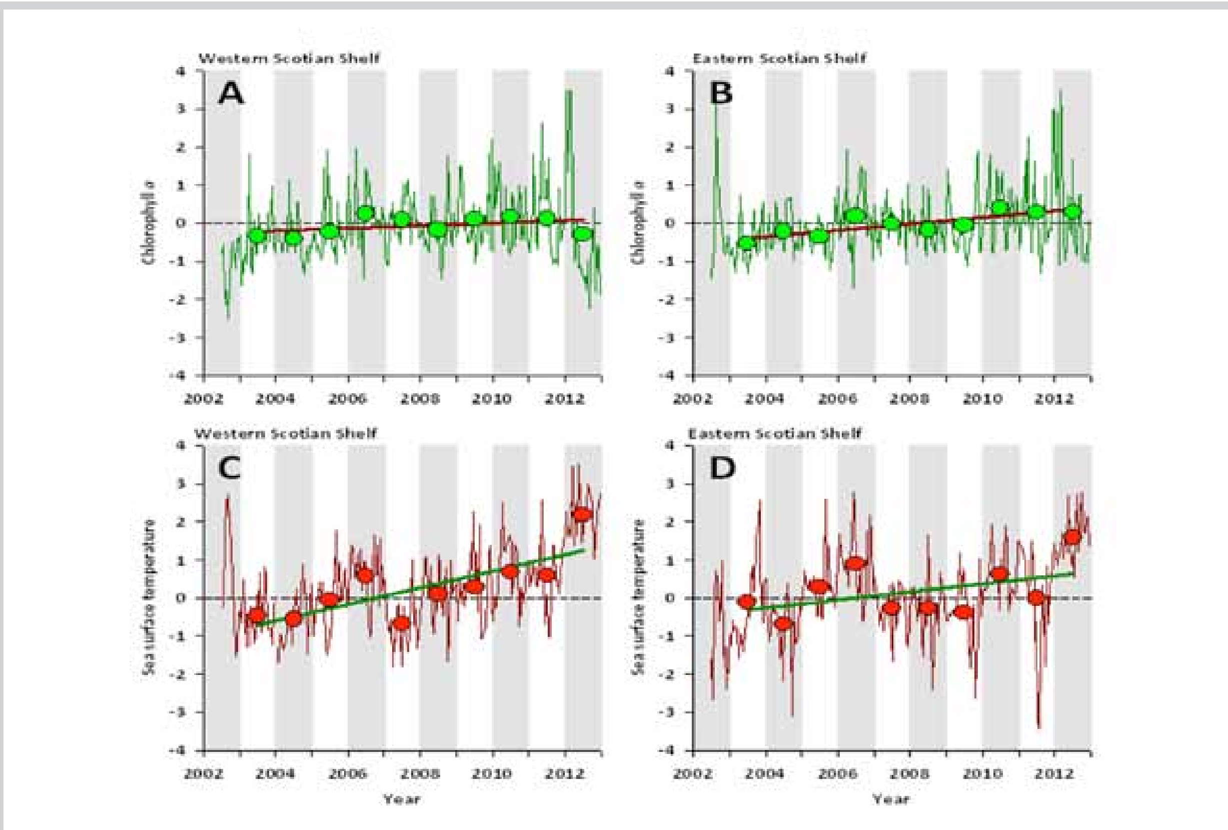


Figure 10. Time-series of surface chlorophyll anomalies (A,B) and sea surface temperature anomalies (C,D) from MODIS bi-weekly composites (thin lines) for the Western Scotian Shelf (A,C) and the Eastern Scotian Shelf (B,D) from 2002 to 2012. Annual average anomalies are indicated by the solid circles, and the 10-year trend is indicated by the thick lines computed by simple linear regression (Source: DFO Maritimes, Marine Ecosystem Section, Remote Sensing Unit).

community but they contribute significantly to blooms later in the year (Breeze et al. 2002). Many other phytoplankton taxa are known in these waters (Li et al. 2011), but there are no long-term time series records for most of them. Over the past decade, the annual average chlorophyll concentrations at the Halifax station have been relatively stable with diatoms dominating in winter and spring (>75% of the total count), and flagellates and dinoflagellates in summer and fall (sum >60% of the total count) (Johnson et al. 2012b). Diatom and dinoflagellate abundances, and the PCI were higher in the 1990s and 2000s than in the 1960s and 1970s (Figure 8), with the increases in diatom abundance and the PCI occurring mainly in the January to March period (Figure 11). In addition, in the past decade, there has been a general increase in the abundance of

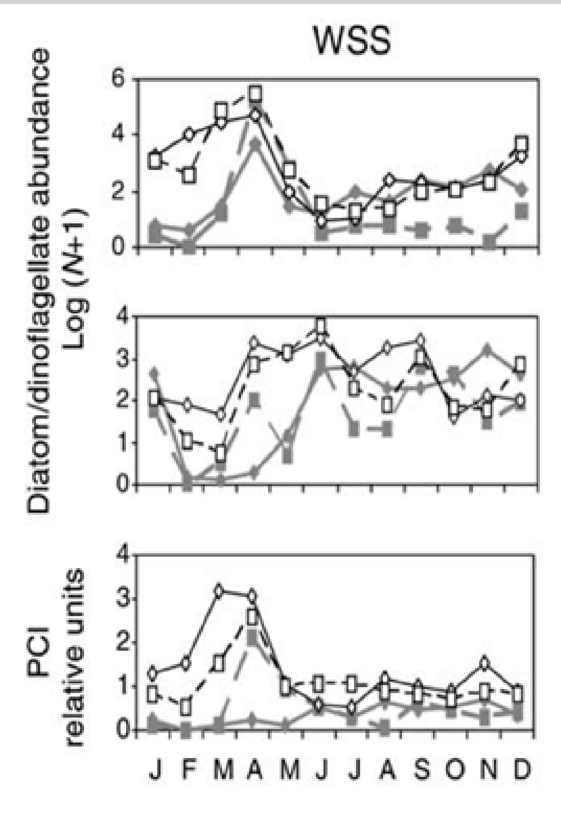


Figure 11. Seasonal cycles, by decade, of the abundance of diatoms (top row) and dinoflagellates (middle row) and the PCI (bottom row) for the Western Scotian Shelf (after Head and Pepin 2010b).

the smallest members of the phytoplankton assemblage, known as picophytoplankton, across broad reaches of the Scotian Shelf, and particularly in the nearshore Bedford Basin (O'Brien et al. 2012).

3.2 ZOOPLANKTON

3.2.1 Biomass and Abundance

Secondary producer (zooplankton) biomass can be measured directly, in sub-samples from net tows, as wet or dry weights, or indirectly by counting individual organisms from net tows (or from CPR counts) then using pre-determined (or published) individual organism weights to calculate total biomass. Zooplankton fall into three main categories according to their body size, microzooplankton, mesozooplankton, and macrozooplankton. Copepods (mesozooplankton) (Figure 12) and euphausiids (krill, Figure 13) (macrozooplankton) make up the largest proportion of zooplankton biomass on the Scotian Shelf and are the most well-studied (Breeze et al. 2002).

As reported above, phytoplankton abundance was relatively low on the Scotian Shelf in the 1960s and 1970s and relatively high in the 1990s and 2000s (Figures 8 and 11). By contrast, abundances for the CPR copepod (zooplankton) taxa Calanus I-IV (mainly juvenile *C. finmarchicus*) and late stage *C. finmarchicus* (*C. finmarchicus* V-VI), which together dominate the mesozooplankton, were higher during the 1960s and 1970s than during the 1990s and 2000s (Figure 14, top panels). As well, the peak in *Calanus* I-IV abundance appeared earlier in the 1990s and 2000s than in previous decades,

Figure 12. The copepod *Calanus finmarchicus*, as copepodite stage 5 in a fat-rich overwintering state (Source: M. Ringuette, DFO Maritimes, Ocean and Ecosystem Science Division).

Figure 13. The euphausiid (krill) *Meganictyphanes norvegica* (Source: M. Ringuette, DFO Maritimes, Ocean and Ecosystem Science Division).

shifting from June-July to May-June (Figure 11) (Sameoto 2004, Head and Pepin 2010b). The abundances of three representative small copepods increased between the 1970s and 1990s (Figure 14, centre panels), while the abundance of euphausiids decreased and that of another taxon representative of macrozooplankton, hyperiid amphipods, increased (Figure 14, bottom panels).

Food (phytoplankton) availability and other environmental variables (e.g., temperature) are likely the most important factors regulating

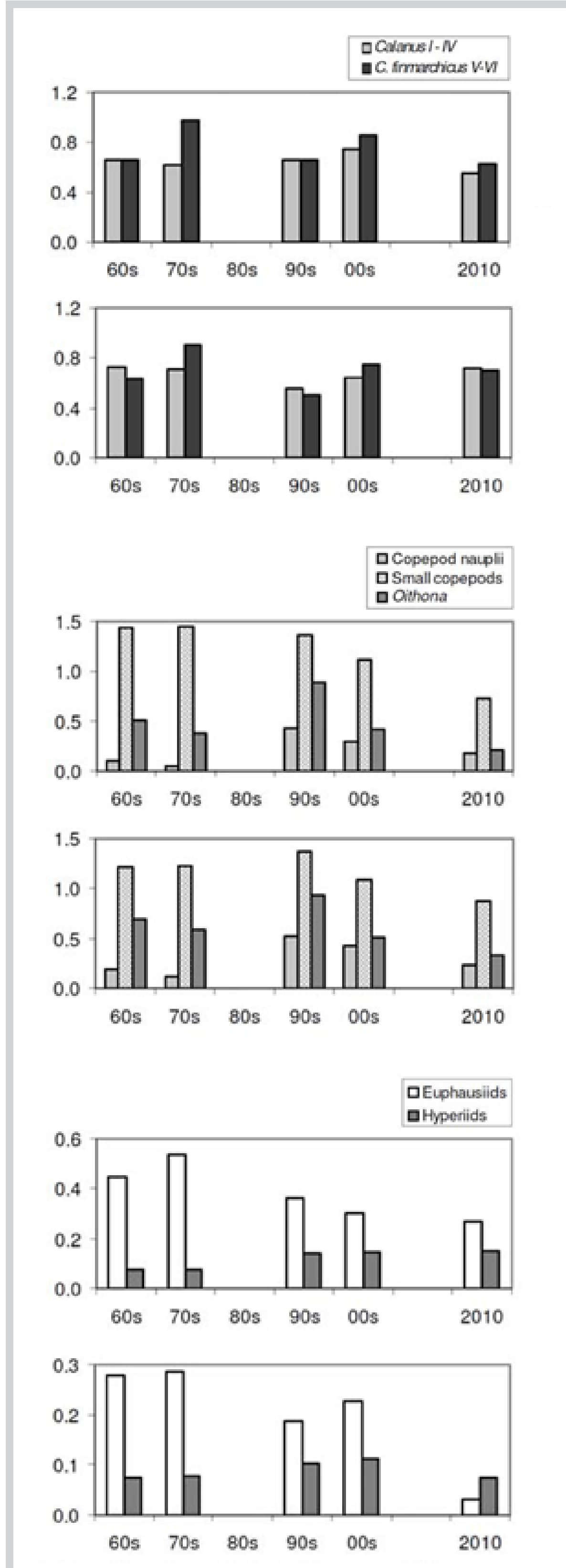


Figure 14. Annual average abundances by decade and in 2010 for selected zooplankton taxa on the Western (top row of each pair) and Eastern (bottom row of each pair) Scotian Shelf (from Johnson et al. 2012b).

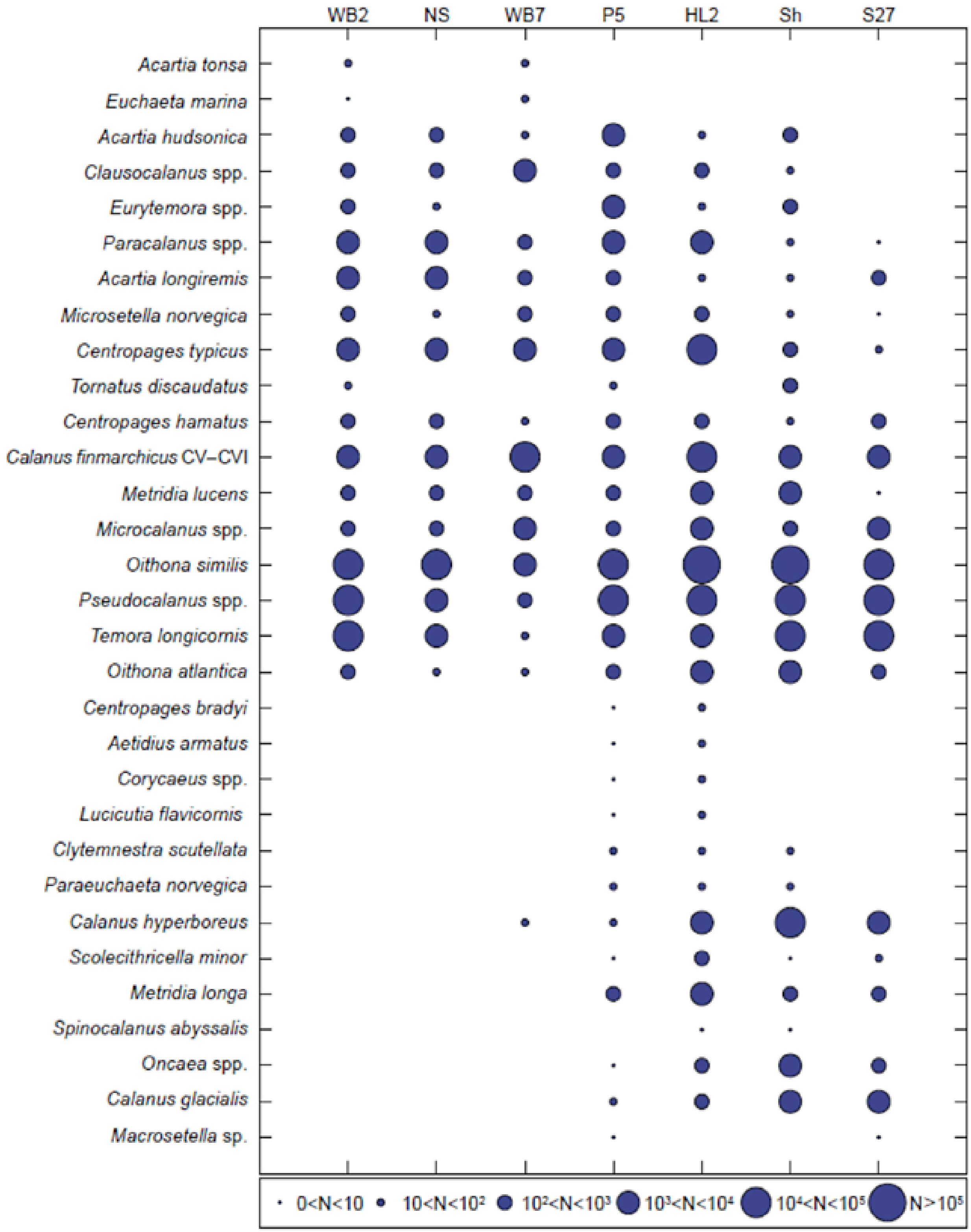


Figure 15. The average annual abundances of the most common copepods at fixed stations in the northwest Atlantic, ordered from southwest to northeast. The seven stations were: NS (western coastal Gulf of Maine) sampled in 2003–2005 and 2007, WB2 (nearshore western Gulf of Maine) sampled in 2003–2007, WB7 (offshore western Gulf of Maine) sampled in 2005–2007, and P5 (Bay of Fundy), Sh (Shediac, western Gulf of St. Lawrence), HL2 (Scotian Shelf), and S27 (Newfoundland Shelf) all sampled in AZMP in 1999–2007 (from Johnson et al. 2010).

zooplankton abundance. For *Calanus* I-IV, their earlier appearance after 1990 may be linked to the earlier occurrence of the spring bloom, and their reduced annual abundance to the "mis-match" (see section 4.1) that has arisen between the seasonal cycles of growth and production for phytoplankton and *C. finmarchicus* (Head and Pepin 2010b). The short-lived smaller taxa appear to have been able to respond to increased phytoplankton (food) levels, although increasing near-surface temperatures (Hebert et al. 2012) may also have contributed to higher growth rates. The causes of the changes in abundance of euphausiids and hyperiid amphipods are not obvious, although it should be noted that the CPR does not sample these taxa very effectively due to their large size and their ability to avoid capture. In addition, it should be noted that the Scotian Shelf is an advective system (flowing and dynamic), where changes in the abundance of long-lived zooplankton species (e.g., *Calanus*) may be influenced by larger climate processes, such as circulation variability related to the North Atlantic Oscillation (NAO) (e.g., Greene and Pershing 2000) and inter-annual variations in the influx of water from the Gulf of St. Lawrence.

3.2.2 Composition

The composition of the zooplankton community has been studied in greater detail than that of the phytoplankton (e.g., Breeze et al. 2002). One species, the copepod *Calanus finmarchicus*, sometimes contributes >70% of the total copepod biomass (Figure 15) (Zwanenburg et al. 2006), and has been the subject of numerous studies, including investigations of its distribution and ecology (e.g., Head et al. 1999, Head et al. 2005, Johnson et al. 2008, Plourde et al. 2009). Despite the dominance of *C. finmarchicus*, the Scotian Shelf has a relatively high diversity of copepod species compared to neighbouring regions (Figure 15). The abundances of individual species may change from season to season and from year to year, but no strong trends are obvious for the 1999-2011 period (Johnson et al. 2012b).

4 IMPACTS

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4.1 CHANGES IN ECOSYSTEM EVENTS (MATCH-MISMATCH)

The Scotian Shelf ecosystem is a dynamic and productive system characterized by high seasonal variability. Phytoplankton and zooplankton production support ocean ecosystems and global fisheries, and climate change is expected to have important impacts on mechanisms regulating productivity. For example, shifts in the timing of seasonal events, such as the spring bloom, could influence trophic interactions on the Scotian Shelf, since they could disrupt the life cycles and productivity of grazers, if the

latter are no longer present at the same time as their prey (Durant et al. 2007). On the other hand, effects may not always be negative. For example, *C. finmarchicus* eggs and larvae are important food items for the larvae of spring-spawned cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) (Zwanenburg et al. 2006). In 1999, when the spring phytoplankton bloom occurred 4 weeks earlier than normal on the Scotian Shelf, *C. finmarchichus* and haddock responded by reproducing earlier than normal, and this was associated with increased survival of haddock larvae and increased recruitment to the fishery (Platt et al. 2003; Head et al. 2005). This "match-mismatch" concept is further discussed in the *Climate Change and its Effects on Ecosystems, Habitats and Biota* theme paper.

4.2 ECOSYSTEM PRODUCTIVITY

In principle, warmer temperatures and less severe weather conditions arising from climate change could stabilize the water column, decrease the supply of nutrients to surface waters, and therefore reduce the productivity of the system (Boyce et al. 2010). However, the situation is likely more complicated. Interannual variation in stratification is also responsive to yearly variation in salinity and it is not immediately clear if warmer temperatures will necessarily lead to less mixing of the Scotian Shelf water column. Recently, it has been the inflows of low temperature and low salinity waters that have driven interannual variability in water-column stability and mixed-layer depth on the Scotian Shelf, causing yearly changes in phytoplankton dynamics and seasonal cycles (Ji et al. 2007). Whether this situation will continue under long-term climate change is unclear, however. In any case, increased water-column stability will result in fewer nutrients reaching surface waters but will also mean phytoplankton spend more time closer to the surface and the sunlight they need for photosynthesis. These counter-effects may largely offset each other on an annual basis but these remain to be more fully examined.

4.3 SPECIES COMPOSITION

The species composition of the zooplankton on the Scotian Shelf may be impacted by climate change effects, operating over large, or local, spatial scales, if there are changes in ocean currents. For example, increased inputs of fresh water from the Arctic during the 1990s and early 2000s apparently enhanced the influx of Arctic Calanus species (*C. glacialis* and *C. hyperboreus*) to the Labrador Shelf and hence, via the Gulf of St. Lawrence, to the Scotian Shelf (Head and Pepin 2010b). As well, varying numbers of warm-water zooplankton species are brought to the Shelf from the south on an annual basis (Johnson et al. 2010). At the local level, assuming climate change leads to warmer temperatures and high levels of stratification on the Scotian Shelf, it is probable that smaller forms will become more dominant in the phytoplankton community, and that this might also influence the structure of the zooplankton community. Ocean acidification, driven by climate change, could also influence the composition of phytoplankton and zooplankton communities directly by impacting those with calcified structures, and indirectly by impacting their predators (e.g., fish) (see *Climate Change and its Effects on Ecosystems, Habitats and Biota* and *Ocean Acidification*). Additionally, the introduction and establishment of invasive species also influences species composition; these impacts are further described in the *Invasive Species* theme paper.

4.4 EUTROPHICATION (BLOOMS)

Increased nutrient inputs to coastal regions (e.g., from farming and other land-use practices) can fuel phytoplankton and macro-algal blooms. As this plant material decays and sinks to the ocean floor, it is utilised by bacteria and other benthic organisms, which can lower the dissolved oxygen concentration in the water rendering it hypoxic (little dissolved oxygen) or anoxic (no dissolved oxygen). There is limited or little evidence that there have been any wide-spread hypoxic or anoxic events on the Scotian Shelf, although the deeper regions of Emerald Basin have reduced oxygen levels and those of the Laurentian Channel are generally regarded to be hypoxic. More study is required on the local and broad-scale effects of eutrophication on the Scotian Shelf (DFO 2012).

4.5 TROPHIC STRUCTURE

There has been a change in trophic structure, attributed to an ecological cascade, on the Eastern Scotian Shelf. Specifically, the phytoplankton biomass increase in the 1990s, described in Status and Trends (Section 3), was linked to the decrease in the abundance of zooplankton, large-bodied copepods such as *Calanus finmarchicus* in particular. This decrease in zooplankton was in turn attributed to higher predation from forage fishes, which were more abundant due to the apparent overfishing and decline of their large-bodied groundfish predators (Bundy 2005, Frank et al. 2005). Euphausiid (krill) abundance decreased along with the copepods. Euphausiids utilize phytoplankton as food exclusively in their earliest stages, playing an important role on the Scotian Shelf. Like copepods, euphausiids are also preyed upon by juvenile groundfish and pelagic fish (Zwanenburg et al. 2006). The cascade interpretation of the changes in trophic structure on the Scotian Shelf has not been accepted by all of the scientific community, however. Others have argued that while effects may cascade from top carnivores downwards to their immediate prey, any extended impacts on zooplankton, phytoplankton, and nutrients are minor or nonexistent. Instead, it is argued that climate-associated effects provide an alternative explanation to observed changes in the phytoplankton and zooplankton, in both the Gulf of Maine/Georges Bank region (Greene et al. 2008) and on the Scotian Shelf (Head and Pepin 2010b). The potential impact of climate change on the Eastern Scotian Shelf trophic structure and function remains to be further examined. Refer to the *Trophic Structure* theme paper for a more detailed description.

5 ACTIONS AND RESPONSES

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5.1 INTERNATIONAL COMMITMENTS

There is little legislation and policy that directly impacts primary and secondary productivity. A precautionary approach framework (DFO 2009c) has been developed by DFO and is being implemented in all fisheries. The goal of the framework is to estimate reference points and establish baselines for managed stocks. Phytoplankton and zooplankton are not managed stocks, unlike the commercially harvested species at higher trophic levels which are dependent upon primary and secondary productivity. An ecosystem-based management framework has been developed (DFO 2007), which aims to understand ecosystem productivity at the lower trophic levels and to bring this knowledge into policy and management.

Fundamentally, minimizing the impacts of anthropogenic stressors on the Scotian Shelf in an effort to slow climate change driven factors, such as rising water temperatures, would be prudent. One example of how this could be done would be to implement changes in legislation and public policy to reduce greenhouse gas emissions. Relevant legislation and policy are further discussed in *Climate Change and its Effects on Ecosystems, Habitats and Biota*. Additionally, there is legislation to limit nutrient enhancement of the coastal zones as governed by the *Canadian Environmental Protection Act*, 1999, and supported by the *Fisheries Act*, 1985.

In 1995, DFO was considering a proposal to harvest 1000 tonnes of krill. The experimental fishery did not take place due to the important role krill plays in the Eastern Scotian Shelf ecosystem, particularly for herring and the endangered North Atlantic right whale (Harding 1996).

5.2 MONITORING AND RESEARCH

It will be important to continue to monitor primary and secondary productivity using CPR, satellite imagery and *in situ* observations over the short and long-term. Additionally, in view of the importance of temperature and salinity in controlling water stratification and metabolic rates, trends in SST and larger climate processes (e.g., the NAO) will likely become more important as indicators of productivity over time. Further, oceanographic processes such as vertical mixing during late winter-early spring which determines the timing of the spring phytoplankton bloom (Zwanenburg et al. 2006) should also be considered.

Productivity, the foundation of the ecosystem, exhibits a recurrent annual cycle, and DFO's Atlantic Zone Monitoring Program (AZMP) was designed to enable researchers to understand, quantify, and predict ecosystem states. Using data collected at a series of fixed coastal sampling locations, during broad-scale oceanographic and trawl surveys, and via remote sensing, the AZMP has been monitoring and assessing the distribution and variability in temperature and salinity conditions, and concentrations of nutrients and the plankton that they support on an annual basis. There are several methods, with various levels of sophistication, that can be used to estimate the biomass of primary (Table 2) and zooplankton secondary (Table 3) producers.

The Bedford Institute of Oceanography has created a website where maps of ocean colour data (Chl-a mg m^{-3}) are displayed. Maps of sea surface temperatures, measured by remote sensing, are also displayed. Data are available upon request. Temperatures at the surface and throughout the water column are also measured by hydrographic buoys and during oceanographic and research trawl surveys. CPRs were towed during only a few months of the year over the 1960-1976 period, but sampling has been more regular (approximately monthly) for most years since 1991. Satellite observations of ocean colour are dependent on weather (i.e., cloud cover), but are displayed as two-week averages, which have good coverage for most of the region for much of the year. When viewed from space, true water colour (Figure 3, left) is less useful than false colour imagery computed from radiometry (Figure 3, right) as an indicator of phytoplankton biomass. To monitor changes in phytoplankton abundance, examining results from both the CPR and remote sensing together provides a more holistic picture (Head and Pepin 2010a).

Table 2. Common methods, data sources, and approximate time series lengths, for estimating primary producer biomass on the Scotian Shelf.

METHOD	VARIABLE(S) MEASURED	INFORMATION	YEARS
Remote sensing by satellite	Surface chlorophyll *a* concentration, limited information on species composition and size structure	Satellites - CZCS, SeaWiFS, MODIS, MERIS Data sources NASA - http://oceandata.sci.gsfc.nasa.gov/ DFO -http://www.bio.gc.ca/science/new-tech-technouvelles/sensing-teledetection/index-eng.php	1978-1986, 1997-present (AZMP)
Continuous plankton recorder (CPR)	Phytoplankton Colour Index (PCI) semi-quantitative abundances of phytoplankton by species or higher taxonomic order	Recorder towed by sea-going vessels at approximately monthly intervals. Data reside at SAHFOS http://www.sahfos.ac.uk/	1960-1976 intermittently, 1991-present (AZMP)
Secchi disk	Water transparency	Visual estimate using a black and wite disk lowered into the water.	approximately 1900 to present
In situ methods	Chlorophyll *a*, biomass, species composition	Chlorophyll *a* measured on extracts of filters. Direct microscope counts of cells in water samples. Monthly at fixed coastal stations, 4 times per year shelf-wide. Date resides in BIOCHEM (DFO database)	1999-present (AZMP)

Table 3. Common methods, data sources, and approximate time series lengths, for estimating zooplankton secondary producer biomass on the Scotian Shelf.

METHOD	VARIABLE(S) MEASURED	INFORMATION	YEARS
Plankton tows	Species composition and abundance	Oblique plankton net tows (333 micron mesh) year-round. Sampling was on DFO research cruises in the SSIP (Scotian Shelf Icthyoplankton Programme). Data reside in BIOCHEM.	1978-1981
Plankton tows	Species composition and abundance + bulk biomass	Vertically towed plankton nets (200 micron mesh). Sampling is at fixed coastal stations (monthly) and shelf-wide on DFO oceanographic (spring and fall) or research trawl (winter and summer) surveys. Data reside in BIOCHEM (DFO database)	Intermittent pre-1999, regular 1999-present (AZMP)
Continuous Plankton Recorder (CPR)	Semi-quantitative abundances of zooplankton by species or higher taxonomic order	Recorder is towed by sea-going vessels at approximately monthly intervals. Data reside at http://www.sahfos.ac.uk/	1960-1976 intermittent, 1991-present regular (AZMP)
Acoustic surveys	Krill abundance	DFO volume backscattering (200kHz). Data are collected during DFO shelf-wide oceanographic surveys in spring and summer	1984-present

INDICATOR SUMMARY

INDICATOR	DPSIR ELEMENT	STATUS	TREND
Climate change	Driving force	Unknown – There have been small, but measurable, changes, yet it is not presently clear what the short-term impacts may be.	Unknown/Worsening – In the long-term, overall impacts are expected to be negative, i.e., increased SST, however this has yet to be observed or confirmed.
Ocean acidification	Pressure	Fair/Unknown – The Scotian Shelf has become slightly more acidic however it is not presently known if there has been an impact.	Unknown/Worsening – Though pH has decreased this does not necessarily mean that productivity and ecosystem health are negatively affected. It is expected that if current trends continue, some species and ecosystem health will experience declines.
Changes in sea surface temperature	Pressure	Good – Sea surface temperatures support primary productivity.	Unknown/Worsening – If present warming trends continue, it is likely that species and ecosystem health will be influenced.
Timing of phytoplankton blooms	State	Fair – The Scotian Shelf is productive, though the timing of the spring bloom has become earlier.	Unknown – The timing of the spring phytoplankton bloom is earlier, which may eventually have negative implications for the state of the Scotian Shelf.
Chlorophyll *a* concentration	State	Good – Phytoplankton have been abundant in recent decades.	No trend – Generally speaking, the trend indicates ongoing abundance.
Zooplankton biomass (*Calanus* spp.)	State	Good – Zooplankton have been less abundant in recent decades however there is no indication that they are not supporting the food web.	No trend – Generally speaking, the trend indicates ongoing abundance.
Match-mismatch	Impact	Fair – Indications that blooms continue to support larvae and sustain adults.	Unknown/Worsening – Impacts will depend on whether the fish larvae are also early (or late), however being out of phase is typically reported to be negative for fisheries.

Categories for Status: Unknown, Poor, Fair, Good.
Categories for Trend: Unknown, No trend, Worsening, Improving.

Data Confidence:

- Measures of phytoplankton, zooplankton, and temperature are robust. Primary and secondary productivity is variable on the Eastern Scotian Shelf, with decadal trends. While monitoring is necessary as the climate is in flux, there have been subtle changes but no indication of alarm in the short-term.

Data Gaps:

- Canada is in the beginning stages of evaluating the short- and long-term impacts of climate change on the marine environment.

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