

Fisheries in boreal ecosystems

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Northern boreal shelf ecosystems are characterized by relatively few dominant species with strong interactions. The environment is highly dynamic, with strong impacts from oceanographic events that have major influences on fish stocks by altering recruitment, growth, and migration patterns. Excessive catches of one species may lead to the collapse of an important predator or prey in the system and may cause changes in the growth and survival patterns of other species in the food web. Four ecosystems – the Barents Sea/Norwegian Sea, the Bering Sea, the Iceland/Jan Mayen area, and the Newfoundland Shelf area – are compared and the impacts of climate and fishing are discussed on the basis of the recent literature.

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Introduction

Northern boreal shelf ecosystems are intermediate between the deep Arctic water masses in the Polar Sea and temperate water masses of the Atlantic or the Pacific. They are important fishing grounds and are generally characterized by few dominant species, which interact strongly. Currents that exchange water between the polar and temperate regions affect the boreal shelf areas, and changes in the global circulation system have major impacts on fisheries yield. Bordering the Arctic, several boreal fish communities are also strongly affected by seals.

Large-scale changes in species composition and abundance have been noted in many boreal ecosystems, such as the Bering Sea (National Research Council, 1996), Icelandic waters (Vilhjalmsson, 1997a), Norwegian Sea–Barents Sea (Hamre, 1994), and Newfoundland (Lilly, 1994; Carscadden and Nakashima, 1997). Changes have occurred not only in stocks that were fished but also in non-target species. Discussions about the possible drivers of change revolve around the relative importance of climate-driven change and changes induced by fishing.

For example, during 1900–1950 the temperature in Icelandic and Greenlandic waters rose, possibly leading to increases in local stocks of herring (*Clupea harengus*) and appearance of several new species. From 1950 onwards, and especially during the 1960s, the climate cooled, resulting in water of lower salinity near Iceland.

At the same time, both the local and the Norwegian spring-spawning herring that used to feed and over-winter near Iceland disappeared from Icelandic waters (Vilhjalmsson, 1997b). Simultaneously, large fishing pressure on Norwegian spring-spawning herring in the face of declining recruitment possibly contributed to its collapse (Hamre, 1990).

In each of the boreal ecosystems of the world, timing and magnitude of the climate- and the fishing-induced stress differed. Thus, there exists the potential for cross-system comparison of these factors and the resulting changes. From such a comparison, we may learn about the nature of the climate-driven changes in these systems and adjust our assessment and fishing strategies accordingly to prevent dramatic stock collapses.

We start this process of boreal-system intercomparison by describing the general oceanographic features, species abundance trends, climate indices, fishing removals, and fishery control rules that have been operating in recent years with reference to four ecosystems: the Norwegian Sea/Barents Sea, the Icelandic Shelf, the Newfoundland Shelf, and the Bering Sea.

The Norwegian Sea/Barents Sea

The Norwegian Sea and the Barents Sea may in some respects be considered one ecosystem because of oceanographic and biological interactions. The Atlantic Current that flows northwards off the Norwegian coast

branches into the Barents Sea. There is also an inflow of Arctic water and a shelf that is seasonally covered by sea ice. Climate variability in this region has been attributed mainly to the amount and characteristics of the inflow of Atlantic water. Historically, there have been large variations in the climate conditions of the Barents Sea, with switching between warm and cold regimes on time frames from 3 to 11 years (Loeng, 1989). The period 1970–1976 was warm, whereas 1977–1982 was cold. Warming occurred again in the late 1980s and early 1990s and there may be evidence of cooling in the late 1990s.

Although the Barents Sea has around 144 species of fish, only about 10 are very abundant. Plankton-feeding fish include adult herring and blue whiting (*Micromesistius poutassou*) in the Norwegian Sea and capelin (*Mallotus villosus*), juvenile herring, and polar cod (*Boreogadus saida*) in the Barents Sea. Main predators include cod (*Gadus morhua*) and a large variety of mammals and birds (Hamre, 1991). Climate-related effects on recruitment and fish growth and movements, fishing strategies, and predator–prey interactions have all been implicated in the population fluctuations observed in herring, cod, and capelin in the last few decades (Hamre, 1994).

Historically, Norwegian spring-spawning herring has had the largest biomass of these three dominant species, with a spawning stock that may have peaked at about 25 million tonnes after a long period of good recruitment in the 1930s. During the end of the declining stock trend in the 1950s, which was marked by poor recruitment, fishing mortalities of adults and juveniles increased sharply and the stock collapsed in the late 1960s (Hamre, 1990). After the collapse, inflows of herring into the Barents Sea stopped. This cessation apparently boosted the local capelin stock and gave rise to a large increase in catch. Capelin biomass was high in the 1970s, with stock levels of around 5–6 million tonnes, but fishing and recruitment failure owing to predation by cod and juvenile herring are implicated in the collapse in the mid-1980s (Gjosaeter, 1998). Changes in the migration patterns of herring and capelin also occurred during these periods (Dragesund *et al.*, 1997). The capelin recovered because of a rich 1989 year class, only to collapse again after the rich 1991 and 1992 year classes of herring entered the area. At present, there is little herring in the Barents Sea and the capelin stock has started recovering again.

A combination of a few cold years after 1975 that may not have been favourable for recruitment, plus high exploitation rates, caused a decline in the cod stock down to around 1 million tonnes in 1983 (Fig. 1). The late 1980s and early 1990s were warm and stock biomass increased. Low individual growth rates of cod in the mid-1980s are thought to be due to the low biomass of both herring and capelin (Bogstad and Mehl, 1997).

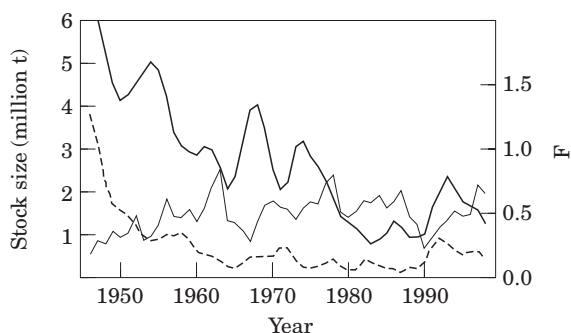


Figure 1. Stock history of North-east Arctic cod: total stock biomass (thick line), spawning-stock biomass (broken line), and fishery mortality (F) for age groups 5–10, weighted by population size (thin line).

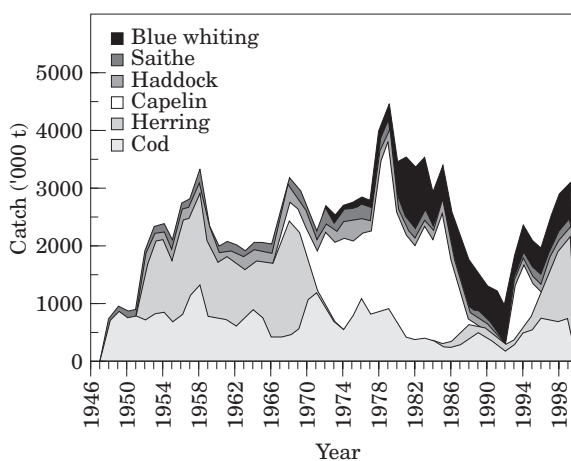


Figure 2. Catches of the six most important fish species in the Norwegian Sea/Barents Sea.

These unexpected decreases in cod growth resulted in higher fishing mortality rates than were anticipated. Cod cannibalism increased with the decreased abundance of alternative prey and seabirds and marine mammals were also strongly affected. Low chick production of common guillemots (*Uria aalge*) and puffins (*Fratercula arctica*) are linked to the lack of juvenile herring, while the winter kills of thousands of common guillemots in 1986–1987 are attributed to the capelin collapse.

Catches of the main fish species in the Barents Sea/Norwegian Sea ecosystem are shown in Figure 2. Herring catches were high until the 1970s, when the stock collapsed. Subsequently, capelin catches increased and remained high up to the mid-1980s. In 1990, the consumption by cod was for the first time taken into account when setting the capelin quota for the next year (Tjelmeland and Bogstad, 1993). At present, capelin catch has been resumed at low levels. Herring catches are at the pre-collapse level and managed under a fixed fishing mortality rate ($F=0.15$) combined with a catch

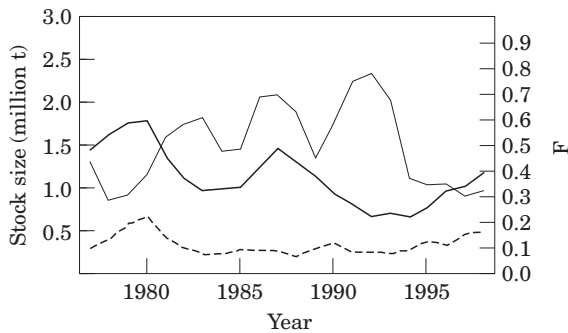


Figure 3. Stock history of Icelandic cod: total stock biomass (thick line), spawning-stock biomass (broken line), and fishery mortality for age groups 5–10, weighted by population size (thin line).

ceiling of 1.5 million tonnes (ICES, 1999a). Cod catch increased in the mid-1990s and is managed at $F=0.42$. Historically, harp seals (*Phoca groenlandica*) have also been harvested, with catches over 100 000 animals in the 1950s and early 1960s. Catches in the last 20 years have been around 40 000 animals, but high unintentional catches in fishing nets along the Norwegian coast occurred in 1987. This coastal invasion of harp seals is thought to have resulted from the collapse of the capelin stock.

The Icelandic Shelf

The Icelandic Shelf region is influenced by the flow of warm Atlantic water from the south and cold low-salinity water from the north (Stefansson *et al.*, 1997). Inter-annual variability in the strength of the flow of Atlantic Water into this area is large and parts of the northern shelf may be much warmer in particular years. There was an extended warm period from the 1950s to early 1960s. The period from 1965 to 1971 was cold and subsequent years alternated between cold and mild conditions, with the early 1990s showing mainly average conditions to the north of Iceland (Jakobsson and Stefansson, 1998).

Although many demersal fish species inhabit these waters, cod makes up a large part of the catch and is the most important predator in the system. Total and spawning-stock biomass declined throughout the 1980s and is showing an increasing trend since 1995 (Fig. 3). Recruitment has been below the long-term average since the late 1980s. In 1997 and 1998, recruitment of age-3 cod was close to average. Other demersal species include Greenland halibut (*Reinhardtius hippoglossoides*), haddock (*Melanogrammus aeglefinus*), saithe (*Pollachius virens*), Atlantic wolffish (*Anarhichas lupus*), redfish (*Sebastes marinus marinus*), and several pleuronectids. Capelin, which has been fished since 1964, is an important prey of several of these demersal species (Pálsson,

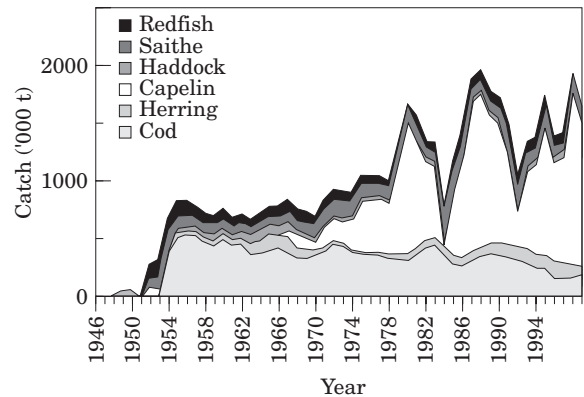


Figure 4. Catches of the six most important fish species in the Iceland/Jan Mayen area.

1997), but particularly of cod. Inter-annual differences in capelin abundance are thought to affect cod growth (Jakobsson and Stefansson, 1998) and a relationship between the two is used in short-term predictions of the cod stock. Climate and feeding conditions influence the timing and location of the capelin spawning migration. Important biological interactions are the predation by cod on capelin and shrimp and the predation by marine mammals (especially seals) on cod.

Recent fish catches in the Iceland/Jan Mayen area are shown in Figure 4. Capelin catches increased from the late 1960s to the present level of 1.0–1.5 million tonnes, interrupted by a brief moratorium in 1982. A constant-escapement management strategy is applied, where 400 000 t of capelin are left to spawn. Cod catches have been declining since the beginning of the 1980s, with a historic minimum of 190 000 t in 1995 (ICES, 1999b). In 1995, a catch rule was introduced by which the catch is limited to 25% of the fishable stock (cod aged 4 years or more), which translates into a corresponding $F=0.44$ for the 1998/1999 fishing year. Under this regime, catches for 1995–1997 have shown a weakly increasing trend. The catches of Icelandic summer-spawning herring and haddock have been more or less stable. Landings of saithe have been gradually reduced to below 40 000 t in 1998 from a peak of about 100 000 tonnes in 1991. Harp seals have also been harvested, but catch numbers have decreased steadily from around 30 000 in the 1950s to less than 10 000 in recent years.

Newfoundland

The eastern shelf of Newfoundland is influenced by two main current systems – the cold, low-salinity Labrador Current from the north and the warm, high-salinity North Atlantic Current from the south. The northern shelf is seasonally ice-covered. Water temperatures have been below normal from around 1980 to the early 1990s,

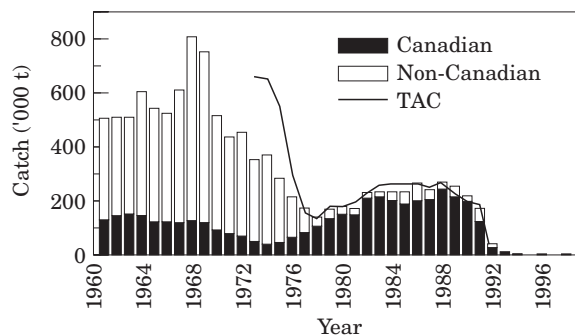


Figure 5. Catches of northern (2J+3KL) cod off Newfoundland by Canadian and foreign vessels. Total allowable catches by year also indicated.

with two very cold periods in the mid-1980s and early 1990s (Lilly, 1994). Temperatures were moderate during 1994 and were above normal in 1996–1998, at least over deep shelf areas.

The Atlantic coast of Canada has about 325 marine fish species, with most of the diversity restricted to shallow waters (2–45 m; Emery, 1978). Historically, cod has been the dominant groundfish species, but at present it is at historical low levels. After an abrupt decline around 1990, the fishery was closed (Fig. 5). The collapse of northern cod and the change in its distribution have been evaluated with respect to a number of factors, including changing climate and capelin abundance (Rose and Leggett, 1988; Lilly, 1994) as well as over-estimates of stock size in combination with high fishing mortality (Myers *et al.*, 1996; Shelton, 1998). However, there is no consensus on the most important factors that caused the decline. Because of the problems in reconciling catch and survey data and in reconciling inshore and offshore survey data, there is no agreed assessment at present. Despite the moratorium on cod fishing and more moderate temperatures in recent years, offshore abundance (Fig. 6) and recruitment do not yet show any improvement. Size-at-age declined during 1983–1985 and in the early 1990s, but is now increasing. Changes in cod growth have been related to water temperature but not to capelin abundance during the early 1990s. Cod serves also as an important prey for harp seals in the northern parts and for grey seals (*Halichoerus grypus*) south of Newfoundland. The impact on the cod stock is not clear, but estimates of predation are high and seals may be impeding stock recovery.

Herring is restricted mainly to inshore waters, but is not an important planktivore in the region. It is not consumed by cod even when capelin abundance is low (Lilly, 1994). Capelin is the most important prey for cod and also an important forage species for other groundfish (e.g. Greenland halibut; Bowering and Lilly, 1992) and many species of birds and mammals (Carscadden,

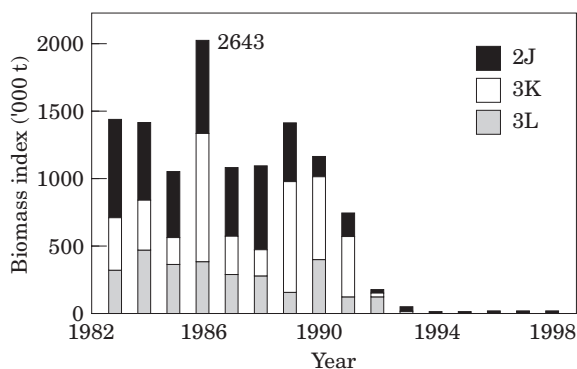


Figure 6. Biomass index of northern cod from autumn bottom-trawl surveys by statistical area (2J, 3K, and 3L).

1984). An offshore capelin fishery started in 1972 but declined sharply after the peak catch (246 000 t) in 1976. Coincident to the decline in offshore fishing, an inshore fishery began in the late 1970s (peak catches around 80 000 t in the 1980s). This fishery decreased sharply in 1991, when acoustic estimates of offshore capelin biomass plummeted while inshore indices did not (Carscadden and Nakashima, 1997). This discrepancy has been attributed to a change in behaviour: capelin was more broadly dispersed in the 1990s, rather than in schools. The decline in population size and change in distribution has been attributed primarily to environmental changes. Cod distribution during this period seemed to match the capelin distribution and capelin continued to be the dominant prey for cod (Lilly, 1994). Decreases in the size of mature capelin and delays in peak-spawning times have also been attributed to below-average water temperatures in the early 1990s.

An $F_{0.1}$ control rule has been used for cod from 1984 to 1988, with projected F-values of around 0.2 and increasing to 0.44 in 1989 and 0.32 in 1990 (Shelton, 1998). Fishery regulations in the 1990s prevented opening of the capelin fishery until females reached a critical size. This kept the fishery closed during 1994 and 1995.

The Bering Sea

The Bering Sea is the world's third-largest semi-enclosed sea and its eastern shelf is the widest continental shelf outside the Arctic Ocean. The exchange of water between the North Pacific Ocean and the Bering Sea is still poorly known. There is a weak slope current at the eastern shelf boundary and three frontal regions on the shelf are associated with the 50 m, 100 m, and 170 m isobaths. The seasonal ice-cover influences the distribution of particular species (National Research Council, 1996). Shifts in climate indicators, such as the Aleutian

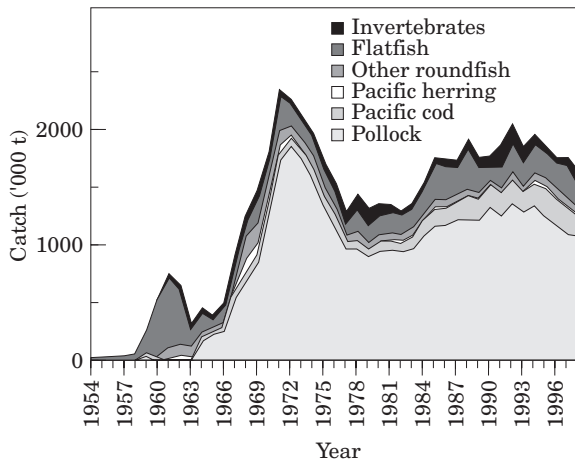


Figure 7. Catches in the eastern Bering Sea by major categories.

low central pressure anomaly (Overland *et al.*, 1998) and sea-surface temperatures (National Research Council, 1996) show interdecadal changes in the climate. The early 1970s was colder than average, while the late 1970s to the late 1980s was warmer than average. Since 1989, there appears to be a shift to more average or cooler-than-average conditions.

The Bering Sea is home to about 300 species of fish, 150 species of crustaceans and molluscs, 50 species of seabirds, and 25 species of marine mammals. Species groups targeted by commercial fisheries include groundfish [walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), and pleuronectids], Pacific herring (*Clupea pallasii*), shellfish (king crabs – Lithodidae), snow and Tanner crabs (*Chionoecetes* spp.), and salmon *Oncorhynchus* spp. (Fig. 7).

Total groundfish biomass since the 1960s has undergone two major periods of fluctuations, with peaks in the early 1970s and early 1980s of around 6 million tonnes and 12 million tonnes, respectively (Bakkala, 1993). Walleye pollock is the dominant groundfish species in the eastern Bering Sea in terms of biomass (Livingston *et al.*, 1999), with recent levels of adult biomass of over 5 million tonnes after an historic high in the mid-1980s (Fig. 8). Stock biomasses of cod (1.3 million tonnes) and herring (100 000 t) are also lower than in the 1980s. Walleye pollock is an important prey for fish, birds, and marine mammals (Livingston, 1993). Cannibalism by adult pollock appears to dominate the sources of mortality on age-0 and age-1 juveniles (Livingston and Methot, 1998; Livingston and Jurado-Molina, *in press*) and explains part of the density-dependence observed in the Ricker type spawner–recruit relationship for this species. Climate variables (e.g. spring air temperatures, ice cover, and wind speed and direction in the outer shelf area where pollock spawn) have also been linked to recruitment variation (Quinn

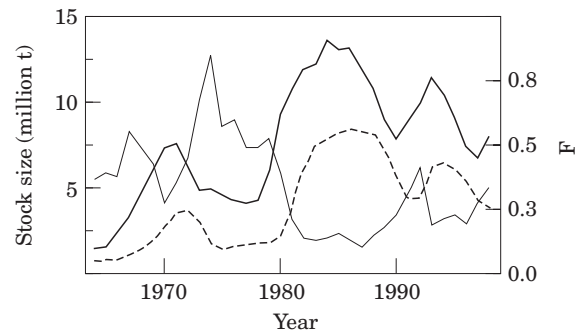


Figure 8. Stock history of eastern Bering Sea pollock: total stock biomass (thick line), spawning-stock biomass (broken line), fishery mortality (F) for age groups 5–10, weighted by population size (thin line).

and Niebauer, 1995; Wespestad *et al.*, *in press*). Shifts in distribution of juveniles have been noted also, with changes linked to inter-annual differences in winds and bottom temperatures (Wespestad *et al.*, *in press*; Wyllie-Echeverria, 1996). Pollock and cod stocks show similar recruitment patterns and the frequency of occurrence of strong year classes has increased after a regime shift in 1976/1977 (Hollowed *et al.*, 1998). Pollock size-at-age varies inter-annually and was particularly low in 1997, a year of anomalously warm conditions and unusual plankton production (Macklin, 1999).

Capelin are distributed in the eastern Bering Sea in cooler waters than pollock and their spatial distribution broadens in cold years (Brodeur *et al.*, 1999). Recently, they have been found in the northern inner shelf areas during summer. However, high abundances had been noted near the outer shelf region of the Pribilof Islands prior to the warm era of the late 1970s.

Walleye pollock comprise most of the groundfish landings in terms of volume (Fig. 7), with catches of around 1 million tonnes per year since around 1970. Herring catches have averaged less than 50 000 t per year. There is at present no commercial fishery for capelin, and beginning in 1998 it was restricted to be a by-catch-only fishery.

Until recently, the allowable catch of eastern Bering Sea pollock was set at the $F_{0.1}$ level (Wespestad, 1993). In 1996, the North Pacific Fishery Management Council approved new definitions of allowable catch and over-fishing levels based on a tiered system, which depends on the amount of information available for a species. Under this system, walleye pollock is managed at the $F_{40\%}$ level (i.e. the fishery mortality rate associated with an equilibrium spawning biomass per recruit is equal to 40% of the equilibrium value in the absence of fishing). This corresponds to an $F=0.29$ projected for 1999. Maximum exploitation rates for herring have consisted of a fixed rule of 20% of the exploitable biomass.

Table 1. Summary of characteristics (SSB: spawning stock biomass; R: recruitment; C: catch; F fishery mortality) for the dominant gadoid species in the Barents Sea/Norwegian Sea (BN), Iceland/Jan Mayen area (IJ), Newfoundland Shelf (NF), and Bering Sea (BS) ecosystem, with information on trends in climate and the factors affecting gadoid production (P/G: prey abundance affects growth; T/G: temperature affects growth; T/R: temperature affects recruitment; C/D: climate affects distribution of prey; TP/R: top predators affect survival rates).

Species		Trends in SSB and R	C and F	Main prey	Trends in climate	Factors
BN	Cod	Declining SSB (<1 10 ⁶ t) Recent R: low.	C 1997: >750 10 ³ t; strongly reduced thereafter F 1999: 0.42	Capelin	1960s–early 1970s: cool Early 1990s: warm Late 1990s: cooling	C/D P/G T/R
IJ	Cod	Increasing SSB (>300 10 ³ t) R after 1985: below average; in 1997 and 1998 about average	C 1997: 200 10 ³ t F 1999: 0.45	Capelin	1950s: warm 1960s: cold 1970s–1990: mixed	C/D P/G T/R
NF	Cod	Very low SSB and R	Mean C 1977–1991: 212 10 ³ t; 1998: 5000 t	Capelin	1980s–early 1990s: cold 1994–present: moderate	T/G T/R C/D TP/R
BS	Walleye pollock	Declining in 1990s, SSB >5 10 ⁶ t Recent R: low (except 1996)	C 1998: 1.1 10 ⁶ t F 1999: 0.29	Juv. pollock and zooplankton	Early 1970s: cold Late 1970s–late 1980s: warm 1989–present: avg. or cool	T/G T/R C/D

Boreal ecosystems and fisheries management

Although boreal systems comprise hundreds of fish species, very few of these species contribute significantly to the total biomass in the system. Gadoids and their prey seem to be the most dominant members in terms of biomass, and interactions with climate as well as predator/prey interactions strongly influence production (Table 1). At present, the eastern Bering Sea walleye pollock stock appears to be in a healthy state, despite the recent decline in spawning-stock biomass (Fig. 9). Northern cod is in a collapsed state, while the cod stocks at Iceland and in the Barents Sea are vulnerable.

The ecosystem with the most conservative exploitation rates for the dominant gadoid species shows large fluctuations in biomass, indicating that such variations may be expected even when exploitation is relatively low. The difficulties of properly assessing stock size in the face of dramatic changes in distribution, growth rate, and recruitment are reflected in the depressed nature of the gadoid stocks in other areas. These climate-linked shifts in biological characteristics have led in some cases to overly optimistic estimates of trawlable biomass, and thus to unintentionally high exploitation rates. Increased emphasis is being placed on understanding spatial changes in distribution, growth, and abundance and factoring the information into the stock-assessment process.

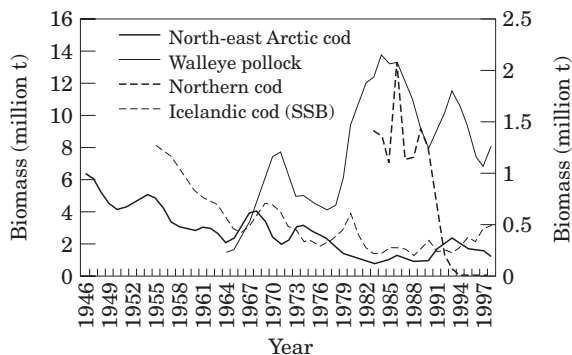


Figure 9. Stock biomass history of some of the main gadoids in four boreal ecosystems: walleye pollock and North-east Arctic cod – left scale; northern cod and Icelandic cod – right scale (SSB: spawning-stock biomass only).

Previous work has demonstrated the dependence of recruitment on environment, showing that the probability of high recruitment in cod increases with temperature (deYoung and Rose, 1993; Ottersen and Sundby, 1995), although the causal relation may be indirect, through spatial effects (deYoung and Rose, 1993). However, high temperatures are a necessary but not sufficient condition for good recruitment. Although temperature–recruitment relationships have some predictive value, researchers and managers are still hampered by the inability to predict climate beyond the present. Therefore, management advice that uses

such relationships must include probabilistic analyses of outcomes under various climate regimes.

For all stocks considered, there is strong environmental forcing of recruitment, which indicates that there may be longer periods of similar conditions for recruitment than would occur just by chance, with more or less abrupt regime shifts. If confirmed by a rigorous statistical analysis – which is beyond our scope here – this effect should be included in stock assessment. For many of the stocks, a formal quantification of cannibalism or recruitment success related to spatial effects, with perhaps temperature as a proxy, should be investigated. Also, the impact of climate on production needs to be considered more fully when developing and applying control rules.

When implementing the precautionary approach for boreal systems, it might be necessary to let the biological reference points (Thompson and Mace, 1997; ICES, 1998) vary with environmental regime, as now required by US national guidelines. However, theoretical studies indicate that strategies based on fixed exploitation rate cope reasonably well with environmental changes that affect natural mortality and larval survival (Walters and Parma, 1996). These strategies are now being used for some herring and capelin stocks in boreal systems and represent one way to manage stocks more conservatively in the face of large, environment-driven changes.

The strong predator–prey interactions among exploited fish stocks and the reliance by mammals and birds on these stocks indicate that these factors also need to be considered in implementing an ecosystem approach to fisheries management in boreal ecosystems. The ban on directed fishing for forage fish in some areas and the consideration of predator forage needs before catch is allocated represent ways in which these relationships have been acknowledged in the Bering Sea and Atlantic boreal systems, respectively. Spatial restrictions on harvesting in key feeding areas of mammals are also being implemented in the Bering Sea. Concurrent with the implementation of these management rules has been the development of spatially explicit, multispecies stock-assessment models for several boreal ecosystems (Bogstad *et al.*, 1992; Stefansson and Palsson, 1997, 1998). These models are useful to examine historical changes in species abundance, growth rate and distribution, and in the role that fishing and climate may have had in causing those changes. In some cases, these models are already being used in “comprehensive stock assessment” (Jakobsson and Stefansson, 1998), which goes beyond traditional single-species assessment and includes multispecies considerations and risk analyses as key ingredients.

Furthermore, multispecies interactions have direct effects on biological reference points (Rice, 1997) and these have to be evaluated when considering stock-rebuilding strategies, stock–recruitment relationships, yield per recruit, and recruits per spawner. The last two

estimates can be particularly distorted when fishery mortality is reduced quickly: ignoring multispecies interactions can lead to large overestimates of the yield available at a lower target *F*. More work in this field is required, particularly for boreal systems that exhibit such strong interactions.

Boreal models are still limited in their ability to predict the status of these ecosystems given the uncertainty about the direction and magnitude of future climate change and the inaccurate representation of the biological mechanisms. However, the wasp-waisted character of food webs of boreal seas (i.e. the presence of usually one dominant prey species; Rice, 1995) makes these systems in some senses more tractable for modelling than ones with more complex food webs, even though the lack of alternate prey species makes the models highly sensitive to prey collapse. Advancing these models through improved seasonal and spatial sampling and through further studies on migration and prey switching should be given high priority.

The boreal seas provide a unique laboratory for examining the combined effects of climate and fishing on ecosystems. Further comparisons of their behaviour, with more attention to the nature and magnitude of climate change relative to fishing impacts, and intercomparison of multispecies models for these areas, should lead to better understanding of how to fish these systems in a sustainable fashion.

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