

Food-web and climate-related dynamics in the Baltic Sea: present and potential future applications in fish stock assessment and management

MICHELE CASINI, CHRISTIAN MÖLLMANN, AND HENRIK ÖSTERBLOM

Abstract

The human influence on marine ecosystems is being recognized as a basis for extending the horizons of management. Historical anthropogenic influence has involved a wide variety of factors, including the effects of fishing on the dynamics of individual resource species. More inclusive complexity includes the interactions among species, and their interactions with other aspects of their biotic and physical environment. In this chapter, we review these elements of complexity for the central Baltic Sea. This ecosystem has a long history of human influence and its own special characteristics, due to its geographic location, geomorphic traits, and socio-political context. More and more of the complexity of this ecosystem is being recognized as scientists add to the wealth of documentation regarding the influence of surrounding terrestrial activities, monitor the dynamics of component populations, establish the effects of weather and climate, and illuminate the relationships among the various elements of the ecosystem. There is a great deal of historical information to characterize the changes that have occurred, not only among the various species making up the ecosystem, but also at the ecosystem level. Some of these have involved regime shifts, in part owing to climatic factors. Such

significant changes involve more than one of the ecosystem's trophic levels as well as physical features such as salinity, temperature, and oxygen concentration. We begin to understand some of the complexity of ecosystems when we recognize that such factors are not alone, however, and realize that trophic cascade dynamics and feedback loops are also involved. Of particular importance for fisheries management is the clarity with which we have observed, documented, and explained some of the effects of fishing, not simply as an influence on individual resource species, but on the ecosystem as a whole. Some of these ecological aspects are currently used in fish stock assessment and management in the central Baltic Sea, but recently acquired additional knowledge could be potentially used in the future to reach the goal of a sustainable exploitation of fisheries resources in this area.

Introduction

Human activities influence marine ecosystems in multiple and interactive ways (Jackson *et al.* 2001, Hughes *et al.* 2003, Halpern *et al.* 2008). Not only has commercial fishing a substantial impact on ecosystem structure and function by removing target fish biomass (Folke *et al.* 2004, Frank *et al.* 2005), but it also influences non-target species and habitats (see e.g., Browman *et al.* 2004). In addition, fish stock dynamics are influenced by variations in climate, introduced species, and water quality (Daskalov *et al.* 2007). The Baltic Sea is situated in a region where human impacts on the marine ecosystem have been substantial for over a century (Österblom *et al.* 2007, Eero *et al.* 2008). Extensive seal hunting, nutrient runoff from agriculture and municipalities, toxic compounds with a significant impact on top predators, high fishing mortality resulting from commercial and recreational fishing, and changes in climate, all have influenced this semi-enclosed sea. The Baltic is a particularly sensitive sea, being characterized by low salinities whose annual variations can have a large impact on species abundance, composition, and distribution (Voipio 1981). At the same time, as it is severely impacted by human activities and hydro-climatic conditions, it is also a sea with clear political boundaries. All nine bordering countries (except Russia) are part of the European Union (Fig. 1.1), leading to a common policy framework being available for joint action. The framework includes the Common Agriculture Policy, the Common Fisheries Policy, the Water Framework Directive (EC 2000) and the Marine Strategy Directive (EC 2008). These policies and directives all have a substantial impact on the sectors influencing the marine environment. The Marine Strategy Directive, in particular, has laid the foundation for integrating these tools toward the

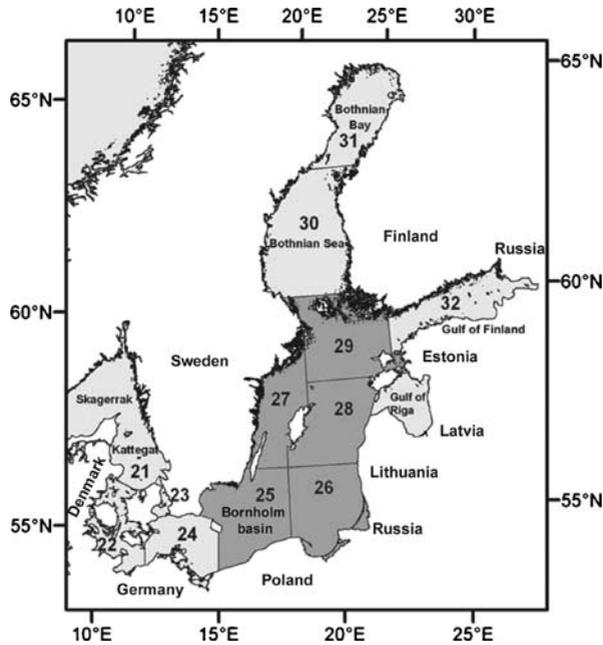


Fig. 1.1. Map of the Baltic Sea. The central Baltic Sea (Baltic Proper) is marked in dark gray.

end of sustainable management of European seas. Management in the Baltic Sea is already ahead of the timetable laid out in the directive. The Helsinki Commission (HELCOM), the international governing environmental body for the Baltic Sea (also including Russia) has developed a joint action plan (the Baltic Sea Action Plan: HELCOM 2007), addressing several of the relevant issues. Nevertheless, much remains to be done. There is however a relatively strong political will in the region to address marine issues and the Baltic can thus be said to be well poised to become a pilot area for implementing an ecosystem approach in a European context.

In this chapter, we treat the concept of ecosystem-based management for fisheries (EBMF) focusing on its ecological aspects (food web and climate impact). In other words, EBMF is handled by taking into consideration the effects of fisheries on the ecosystem, *and* the effects of ecosystem on exploited fish and fisheries. We shortly present an account of the existing knowledge of the Baltic Sea ecosystem functioning and how this knowledge is currently used in fish stock assessment and fisheries management advice. Furthermore, we propose the potential use of additional information in the forthcoming assessment and management activities. We focus on the central Baltic Sea (the so-called Baltic Proper) because of the more detailed knowledge of this region if compared

with other areas of the Baltic Sea. However, other areas will be also taken into consideration for comparison and completeness.

Current ecosystem knowledge

This section describes briefly the present knowledge of the general ecosystem functioning and specific ecological links in the Baltic Sea. The information provided here is based on data from the recent three decades (1974–2008), this choice being dictated by the fact that stock assessment data in the Baltic Sea are available for all the three main species – cod (*Gadus morhua*), herring (*Clupea harengus*), and sprat (*Sprattus sprattus*) – only during this period.

Fish stock dynamics

In general, a high cod population is accompanied by low sprat population (ICES 2009a), since sprat is the main fish prey for cod. During periods of low cod biomass, a consequence of adverse hydro-climatic conditions and/or fishing, sprat is released from cod predation (Casini *et al.* 2008). During the last three decades, following the collapse of the cod stock, the sprat stock increased fourfold, shifting the Baltic from being cod-dominated to being sprat-dominated (Fig. 1.2A). However, the sprat population is also favored by mild weather which supports sprat egg production and survival (Nissling 2004) and larval growth (Baumann *et al.* 2008) as well as the development of the main prey for larval sprat, the copepod *Acartia* spp. (Voss *et al.* 2003, Alheit *et al.* 2005). On the other hand, the decrease of the herring population during the past three decades is likely due to the synergistic effects of high fishing pressure (ICES 2009a), eutrophication-related degradation of coastal spawning grounds (Cederwall and Elmgren 1990), and decrease in mean body growth (Casini *et al.* 2010a; see next section) (Fig. 1.2B).

The period considered here is characterized by low abundance of aquatic mammals, resulting from declines observed through most of the 1900s due to human activities (Österblom *et al.* 2007). Therefore, the potential effect of a large population of aquatic mammals on the fish community is not well understood. However, a modeling work by Österblom *et al.* (2007) predicted that in the presence of seals and harbor porpoises, as in the first half of the 1900s, both cod and clupeid populations could be maintained low by predation, at least at low levels of system productivity.

Overall ecosystem change

Recently, Integrated Ecosystem Assessments (IEA) have been conducted for the central Baltic Sea (ICES 2008a) revealing a regime shift in the pelagic ecosystem during the late 1980s and early 1990s (Möllmann *et al.* 2009; Fig. 1.3),

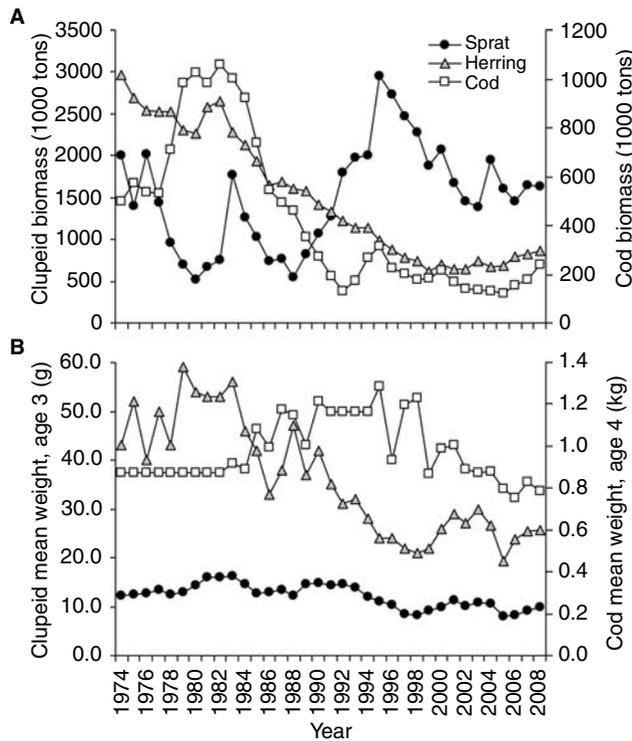


Fig. 1.2. Trends in total biomass and mean weight in the stock of sprat (whole Baltic Sea, SDs 22–32), herring (central Baltic stock, SDs 25–29, excl. Gulf of Riga) and cod (Eastern Baltic stock, SDs 25–32). Data from ICES 2009a.

similar to events detected in several North Pacific and North Atlantic marine ecosystems (e.g., Hare and Mantua 2000, Link *et al.* 2002, Beaugrand 2004, Choi *et al.* 2005, Weijerman *et al.* 2005). Two regimes (1974–1987 and 1994–2005) were identified, characterized by the opposite dominance of cod and sprat (see above), as well as the zooplankton species *Pseudocalanus* spp. and *Acartia* spp. (MacKenzie *et al.* 2008, Möllmann *et al.* 2008). Furthermore, a change in the dominance of phytoplankton from diatoms to dinoflagellates has been indicated (Wasmund *et al.* 1998, Alheit *et al.* 2005).

The central Baltic Sea regime shift occurred in a transition period (1988–1993) characterized by low salinity and oxygen conditions as well as high temperatures and nutrient levels, eventually forcing the biotic part of the ecosystem into a new state (Möllmann *et al.* 2009). In addition to the physical and chemical conditions, unsustainable cod fishing pressure during the late 1980s contributed to the overall ecosystem changes, favoring the cod decrease and the

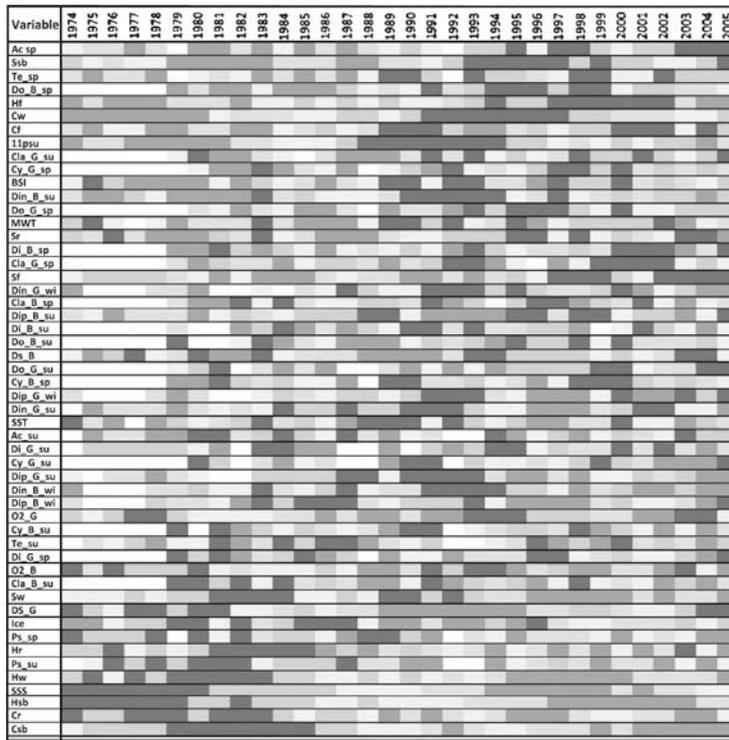


Fig. 1.3. Traffic-light plot representing the development of the central Baltic Sea ecosystem; time-series transformed into quintiles and sorted according to PC1; red represents high values while green represents low values of the respective variable. Modified from Möllmann *et al.* (2009). This figure is also reproduced in the color plate section.

consequent increase in sprat population, with further indirect changes down the food web (Casini *et al.* 2008, Möllmann *et al.* 2008; see next section). The integrated ecosystem assessment also provided indications that the observed changes can be described as a discontinuous regime shift where feedback loops stabilize the new regime which then represents a true alternative stable state (Scheffer *et al.* 2001, Scheffer and Carpenter 2003, Collie *et al.* 2004, Bakun and Weeks 2006). Plausible explanations for this phenomenon are the existence of trophic cascades, threshold dynamics, and prey-to-predator feedback loops (Casini *et al.* 2008, 2009, Möllmann *et al.* 2008, 2009; see below).

Ecosystem effects of fishing - trophic cascades and other indirect effects

An increasingly observed phenomenon involved in the reorganization of marine ecosystems is trophic cascading which involves a domination of

top-down controls (Strong 1992). These processes have been shown in a wide variety of marine ecosystems (Pace *et al.* 1999; see also Casini *et al.* 2008 and references therein). Also in the Baltic Sea, large changes at the top of the food web (e.g., in the cod stock) have been shown to trigger chains of events propagating down the food web, leading to a number of direct as well as indirect effects on other trophic levels of the ecosystems.

Fish-plankton

In the central Baltic Sea, the decrease in the cod stock has been one of the main causes of the zooplanktivorous sprat outburst (Casini *et al.* 2008), which in turn has altered the lower trophic levels. In fact, a species-level trophic cascade has been detected for spring decreasing the population of the copepod *Pseudocalanus* spp. (Möllmann *et al.* 2008), while for summer a community-level cascade appears in reduced total zooplankton biomass and increased phytoplankton biomass (Casini *et al.* 2008). In summer, moreover, the effects of the large sprat stock are also evident in other features of the zooplankton community, as altered species composition, stage composition, and vertical distribution (Casini *et al.* 2009). Herring, on the other hand, seems not to influence the open sea zooplankton (Casini *et al.* 2008), probably because of the omnivorous nature of the bigger individuals and the coastal distribution of the strictly zooplankton-feeding smaller herring. However, the generally lower stock abundance of herring, if compared with sprat, during the past three decades could also partially explain the lower impact of herring on zooplankton resources in this period. See Fig. 1.4 for a simplified conceptual food web of the central Baltic Sea ecosystem.

Fish growth

Sprat and herring growth are heavily affected by density-dependent factors. The drastic increase of the sprat population in the early 1990s caused an abrupt decrease in both herring and sprat weight-at-age (Cardinale and Arrhenius 2000a, ICES 2009a, Casini *et al.* 2010a; Fig. 1.2B) as well as condition (Cardinale *et al.* 2002, Möllmann *et al.* 2005, Casini *et al.* 2006), caused by the strong intra- and inter-specific feeding competition among clupeids. The decrease in herring growth, however, could have been initiated and facilitated by a decrease in salinity and bottom oxygen, affecting respectively one of the main prey items for herring, the copepod *Pseudocalanus* spp. (Möllmann *et al.* 2003, Casini *et al.* 2010a), and the abundance of zoobenthic prey for larger herring. Arrhenius and Hansson (1993) showed, in fact, that a diet constituted of zoobenthos results in increased body growth of larger herring. Fishing activity, which selects larger and rapid-growing individuals, could also have contributed

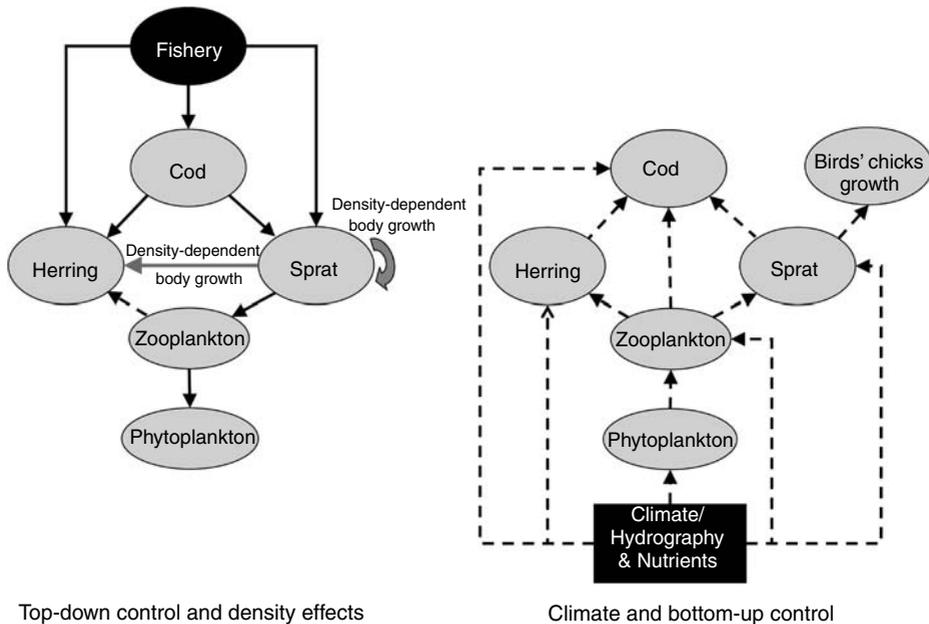


Fig. 1.4. Simplified ecological interactions in the central Baltic Sea. Continuous arrows indicate top-down links, whereas dashed arrows indicate bottom-up (including hydro-climatic effects) links. Top-down and bottom-up (including climate) interactions co-act in shaping food-web structure and dynamics.

to the observed reduction of clupeid mean weight and condition (Rahikainen and Stephenson 2004, Vainikka *et al.* 2009).

Cod growth increased when the stock started to decrease in the 1980s (ICES 2009a; Fig. 1.2B), potentially indicating a density-dependent effect. However, since the early 1990s, cod growth decreased again despite an enduring low stock, this indicating that factors other than direct density-dependence have affected cod growth during the past 15 years.

Top predators: seabirds and mammals

There are indications that changes in fish stock abundance and quality influence marine seabirds. The dramatic changes in the sprat stock during the past three decades, and the related decrease in sprat weight-at-age and condition, appears to have influenced a sprat-feeding seabird, the common guillemot (*Uria aalge*). In the Baltic Sea, the adults of this species feed their chicks almost exclusively with sprat and chicks' weight seems to directly follow changes in sprat condition (Österblom *et al.* 2006; Fig. 1.4). The digestive capacity of the chicks appears ill equipped to deal with what is presumably reduced energy content of their prey. So far, there are no indications that a decrease in weight

has a negative influence on chick survival in the Baltic Sea (Kadin 2007), but the response of chick weight to sprat condition does provide yet another example of how changes in the food web are readily transferred among trophic levels. The possible effects of seabird consumption on fish stocks are currently not well known, but there are indications that marine mammals could have influenced fish stock dynamics in the early 1900s when nutrient levels were very low (Österblom *et al.* 2007). However, there are no indications that mammals (primarily gray seals) at current levels of abundance influence fish stocks directly to any detectable extent.

Threshold dynamics and feedback loops

Apart from the general concurrent effects of bottom-up (including climate) and top-down processes, it has been shown that the relative strength of these two opposite forms of ecosystem dynamics and regulation can vary in the Baltic Sea (Casini *et al.* 2009, 2010a). For instance, a mechanistic investigation of the food web showed that the central Baltic Sea ecosystem can be found in two alternative configurations, in which either hydro-climatic forces or top-down processes, respectively, are the main regulators of zooplankton dynamics (Casini *et al.* 2009). Whether the ecosystem is in one configuration or the other depends on the abundance of the highly influential planktivore sprat, whose dynamics are in turn heavily affected by cod biomass (Casini *et al.* 2009) (Fig. 1.5). Similar threshold-like shifts have been observed in herring growth, being either climate- or density-dependent depending on the level of the sprat population (Casini *et al.* 2010a). This emphasizes the importance of large predatory fish in the maintenance of ecosystem functioning and resilience.

As said before, a high cod population seems to be very effective in controlling sprat population via predation pressure. In turn, a high sprat population could potentially influence cod recruitment via predation on cod eggs (Köster and Möllmann 2000, Köster *et al.* 2001) and competition with cod larvae for zooplankton resources, especially the copepod *Pseudocalanus* spp. (Möllmann *et al.* 2008, Casini *et al.* 2008; Fig. 1.6). These prey-to-predator feedback loops, strengthened when the sprat abundance is high, may possibly contribute to cod recruitment failure even in periods of favorable hydro-climatic conditions for cod recruitment (Casini *et al.* 2009). Therefore, a high sprat stock may decouple cod recruitment from abiotic forcing and maintain the food web in a new stable state – a state which may be difficult to reverse without strong management action (Möllmann *et al.* 2008, Casini *et al.* 2009). Further evidence for a new “stable state” comes from a stage-structured biomass model for the cod–sprat interaction (Van Leeuwen *et al.* 2008). This study indicates that the lack of cod recovery in the 1990s–2000s could be explained by a stunted size

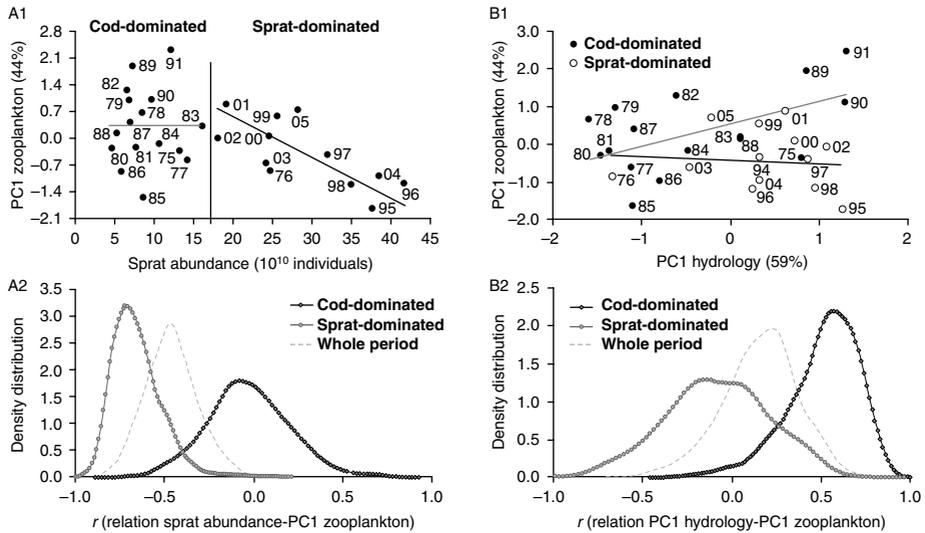


Fig. 1.5. Alternative dynamics of the central Baltic Sea ecosystem related to the dominance and subsequent collapse of the cod population. When cod dominate the system, the low sprat population is not able to significantly affect zooplankton, which is therefore driven by hydrological conditions. This situation drastically changes in situations of low cod biomass, when predation by the high sprat population replaces hydrology as the main regulator of zooplankton. The alternative dynamics are illustrated by changes in the relationship between sprat abundance and zooplankton (A1, A2), and between hydrology and zooplankton (B1, B2) in the scenarios of cod- and sprat-dominance. The vertical dashed line represents the ecological threshold separating the two scenarios. Modified from Casini *et al.* (2009).

distribution of the prey (i.e., sprat) providing insufficient food of the most suitable size for juvenile cod to grow and reproduce (Fig. 1.6). The low condition and energy content of sprat and herring in periods of low cod stock may also constitute a further mechanism hindering cod recovery via affecting cod body growth. However, beside these ecological feedback loops, it must be kept in mind that cod recruitment is also strongly affected by the parental stock size and age-structure, heavily shaped by fishing (Cardinale and Arrhenius 2000b).

Ecological knowledge currently used in stock assessment and management

Assessment

Little ecological knowledge is used currently in the assessment and short-term forecasts of Baltic Sea fish stocks (Table 1.1), although more

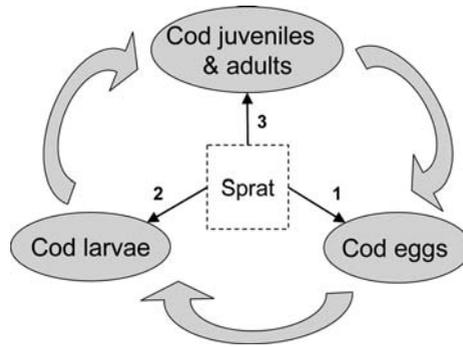


Fig. 1.6. Prey-to-predator feedback loops between cod and sprat. When the cod stock is high, the sprat stock is kept low by predation. For low cod stocks, the abundant sprat stock could hinder cod recovery by predation on cod eggs (1) and food competition with cod larvae (2). Moreover, the consequent lower condition (due to density-dependent processes) and changed size distribution (emergent Allee effect) of cod prey species (sprat and herring) would decrease, respectively, (a) the energy content of cod prey, and (b) the amount of prey of a suitable size for juvenile cod (3). These two last processes could explain the decrease in cod growth since the beginning of the 1990s. During the past two decades, after the drop of cod, the increased sprat stock has produced a drastic decline in both sprat and herring body growth.

information is available if compared with the vast majority of other marine ecosystems.

Multi-species assessment models (previously Multi-Species Virtual Population Analysis, MSVPA; currently Stochastic Multi-Species model, SMS; ICES 2009a) have been used since the mid 1970s to estimate predation mortality of cod on herring and sprat, as well as cannibalism within the cod population, in the central Baltic Sea. Predation mortality by cod has been commonly used also in single-species stock assessment for herring and sprat (ICES 2009a).

The North Atlantic Oscillation (NAO) winter index has been used in the forecast of the sprat year-class strength (ICES 2006), following the study by MacKenzie and Köster (2004) which found a significant correlation between sprat recruitment and spring sea temperature, the area of Baltic ice coverage, and the NAO. Temperature is important for sprat recruitment acting directly on egg survival (Nissling 2004) and indirectly enhancing the spring production of the main food for the larvae (Voss *et al.* 2003).

Temperature and the biomass of the copepod *Eurytemora affinis* are used in the prediction of herring year-class strength in the Gulf of Riga (ICES 2009a). This planktonic species is considered to be crucial for herring recruitment in this area, owing to the fact that it is the main prey for larval herring. Higher

Table 1.1. *Ecosystem information currently used and potentially usable in stock assessment, forecasts, and management for the central Baltic Sea.*

	Ecosystem knowledge used in assessment/forecasts	Ecosystem knowledge used in advice	Future ecological aspects potentially usable in assessment/forecasts	Ecosystem knowledge potentially usable in advice and management
Cod	Cannibalism (Multi-species models)	Regime shift, previous Biomass Reference Points (B_{pa} , B_{lim}) abandoned	Prey-to-predator feedback loops	Prey-to-predator feedback loops
Sprat	Cod predation (Multi-species models) North Atlantic Oscillation	Regime shift, previous Biomass Reference Points (B_{pa} , B_{lim}) abandoned Cod predation	Density-dependent growth (inter- and intra-specific) (also in S-R models)	Density-dependent growth (inter- and intra-specific)
Herring	Cod predation (Multi-species models) Zooplankton (GoR) Temperature (GoR)	Cod predation	Density-dependent growth (inter- and intra-specific) (also in S-R models)	Density-dependent growth (inter- and intra-specific)
All			Seal predation Hydrology (S-R models)	Seal predation Hydrology Ecological thresholds Spatial patterns Ecological indicators

S-R, stock–recruitment.

GoR, Gulf of Riga

water temperature in spring favors the development of this copepod, but also a longer spawning period and a more even distribution of herring spawning activity. After mild winters the abundance of zooplankton is also higher, thus ensuring better conditions for the feeding of herring larvae (see also Cardinale *et al.* 2009).

Management

Recently, there has been a great deal of international work (at EC and ICES levels) with the objective of improving the management of Baltic Sea fish

stocks (ICES 2007, 2008b, 2009b). In these frameworks, the consideration of ecosystem dynamics (species interactions and hydro-climatic effects on stocks) has occupied an increasingly crucial role. It is of particular note that there has been an increasing awareness of the fact that appropriate Biological Reference Points for one species (e.g., cod, herring, or sprat) cannot be defined without considering the state of the other two species (ICES 2008b). Likewise, long-lasting shifts in hydro-climatic conditions cannot be overlooked (ICES 2009b). Both processes (trophic interactions and hydro-climatic effects), acting either independently or in synergy with each other, may change the productivity of single species and, in turn, affect stock-recruitment relationships and the way the stocks respond to fishing (Lindegren *et al.* 2009).

For the stocks in the Baltic Sea, management advice is given by ICES based on estimated Biological Reference Points. Fish stocks are then managed by the European Commission, primarily by issuing annual regulations in the form of TAC (Total Allowable Catch). However, the regime shift observed in the Baltic Sea in the early 1990s (see above) has produced a change in the use of the Biological Reference Points since 2008 (ICES 2008a). As a matter of fact, following analyses performed by different ICES expert groups (ICES 2007, 2008b, 2009b), it was decided to abandon the Biomass Reference Point for the Eastern Baltic cod stock (ICES 2008c) and Baltic sprat stock (ICES 2009a), because they were calculated using data collected under different ecological circumstances compared with those observed currently. In fact, in contrast to the previous ecosystem conditions, the circumstances after the early 1990s became more favorable for the sprat stock (e.g., higher temperature and lower predation by cod) and unfavorable for the cod stock (e.g., lower salinity and deep water oxygen levels as well as higher sprat stock), thus rendering the previously estimated Biological Reference Points invalid for these stocks (Table 1.1). Therefore, a multi-annual management plan for cod has been adopted since 2008 (EC 2007), having a certain fishing mortality of $F = 0.3$ as a target to be reached by reducing the TAC step by step every year. At the moment, this management strategy seems to have produced the desired effects (there has been a significant increase in cod biomass over the past two years; ICES 2009a), showing that the regulation of commercial catches is crucial to restoring and maintaining a healthy cod stock. Likewise, the development of a multi-annual management plan for sprat and herring, in which multi-species considerations and ecosystem effects would occupy a crucial part, is in progress (ICES 2009b).

Potential future use of ecosystem knowledge in stock assessment and management

A large amount of ecological information is available for the Baltic Sea ecosystem that has the potential to be used in fish stock assessment and

management (Table 1.1). Generally, including environmental drivers could improve the fit of the Stock–Recruitment (S–R) relationship, and could be used to enhance the short- and medium-term forecasts, for all species (Köster *et al.* 2001, Axenrot and Hansson 2003, MacKenzie and Köster 2004). For cod, for example, the inclusion of salinity has been shown to improve the Ricker S–R model (Heikinheimo 2008). For sprat, a multiple regression model including spawning stock biomass and temperature, ice cover or indices of the North Atlantic Oscillation (NAO), improves the recruitment model (MacKenzie and Köster 2004). The use of these hydro-climatic parameters could also be used to predict sprat recruitment earlier than is now the case at the annual assessment meeting (MacKenzie *et al.* 2008). Biological parameters, and food web-related processes, can also be used to improve recruitment models. For example, there are indications that the weight-at-age of the spawners (a proxy for parental physiological condition), together with temperature, can be used as one of the predictors for central Baltic herring recruitment (Cardinale *et al.* 2009; Table 1.1).

Knowledge of the factors affecting pelagic fish body growth is substantial and detailed in the Baltic Sea. Most of this information, however, rarely has been taken into consideration in stock assessment. Density-dependent growth of herring and sprat for example could be used in short- and medium-term forecasts to provide more precise predictions for biomass and spawning stock biomass of both species (see also ICES 2008b; Table 1.1). In this context, the inclusion of spatial considerations could also be implemented. For example, there are indications that when the cod stock is reduced due to abiotic changes (i.e., decrease in salinity) and fishing pressure, its population aggregates in the southern areas of the Baltic Sea where conditions are more favorable for its reproduction. These conditions trigger an increase in the sprat population prevalently in the northern areas, likely due to predation release, in turn causing a stronger density-dependent effect on clupeid growth in these areas (Casini *et al.* 2010b). This information, along with the knowledge of the natural geographical difference in growth rates of clupeids, could be used in the advice (Table 1.1). The importance of density-dependent mechanisms involving clupeid growth has been also emphasized in view of the potential establishment of an EC multi-annual management plan for pelagic fish (ICES 2009b).

Seal populations (especially gray seals) are currently increasing at a very substantial rate (Karlsson *et al.* 2008), after a decrease during the 1900s due to hunting and pollution (Harding and Härkönen 1999). Modeling work has provided an indication that marine mammals could have influenced fish stock dynamics in the early 1900s when the system productivity was very low (Österblom *et al.* 2007). Therefore, if gray seals continue to increase (Fig. 1.7) and artificial

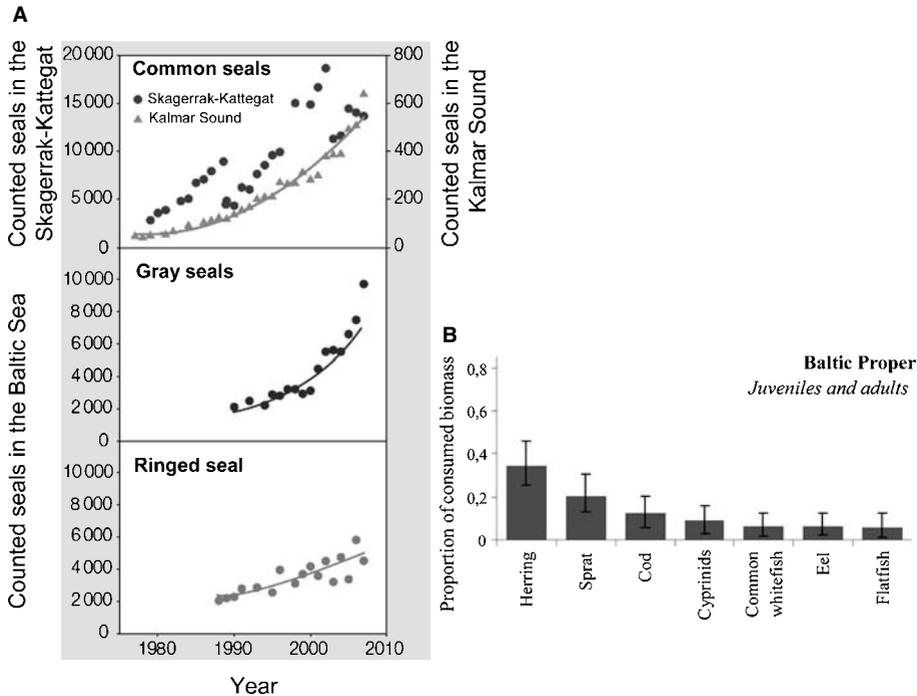


Fig. 1.7. (A) Trends in counted seals in the Skagerrak-Kattegat and Baltic Sea; the Kalmar Sound is the area between the island of Öland and Sweden (modified from Karlsson *et al.* 2008). (B) Diet composition of gray seals in the Baltic Proper (samples collected between 2001 and 2005), presented as the proportion of consumed biomass with 95% confidence limits bootstrapped (based on 2000 bootstrap samples). Species that contribute < 5%, on average, to the consumed prey biomass have been excluded (data from Lundström *et al.* 2010).

nutrient input is substantially reduced (one of the main goals of HELCOM 2007), the effect on the fish community could be substantial (Hansson *et al.* 2007). Under these circumstances, predation mortality by these top predators on cod, herring, and sprat could be taken into account in the assessment of these three species (ICES 2009a; Table 1.1). The potential impact of seals on the fish stocks is exemplified in the Bothnian Sea (ICES SD 30) where it has been estimated that the amount of herring eaten by seals each year is higher than the annual catches of the Swedish fleet in this area (Anna Gårdmark, pers. comm.).

As described above, cod recruitment could be hampered by excessively high populations of its main fish prey species (especially sprat) through several mechanisms: (a) predation on cod eggs, (b) competition with cod larvae for common zooplankton prey, (c) decrease in per capita abundance of the preferred prey size when the cod stock is at a low level (caused by a decrease

in growth and fecundity of herring and sprat), i.e., an emergent Allee effect (De Roos *et al.* 2003, Van Leeuwen *et al.* 2008), and (d) decrease in prey (sprat and herring) energy content at high prey abundances (density dependence in clupeid body growth). Currently, the strength of these prey-to-predator feedback mechanisms (Fig. 1.6) on the cod stock are under investigation at national (Fiskeriverket 2008) and international (ICES 2008b, 2009b) levels. If these studies provide evidence for a significant negative effect of sprat on cod population, alternative counterintuitive ecosystem-based management actions, as a relative reduction of the sprat population, could be evaluated. However, the risks associated with an artificial suppression of sprat in the current Baltic ecosystem (e.g., risk of an explosion of jellyfish mass to occupy the open zooplanktivore niche) should be carefully assessed before such a management approach can take place.

The synergistic effect of fishing, food-web dynamics, and hydro-climatic forces implies that advice on fishing mortality should be set taking into consideration the actual internal food-web state and external physical circumstances (Lindegren *et al.* 2009). The occurrence of thresholds in the ecosystem functioning (Casini *et al.* 2009, 2010a) implies that the management must be very adaptive and managers must be supplied continuously with updated information of the ecosystem state and especially of the main driving factors (Table 1.1). Quantitative thresholds, when properly determined, would provide straightforward reference points available for management decisions (Casini *et al.* 2010a).

The information currently used, along with information that is potentially usable, in stock assessment and advice, as discussed above, is extremely relevant to the objective of a sustainable management of the fishery resources. This information, however, also should be integrated with other ecosystem objectives in order to reach the goals set by different policy bodies (see below). For example, the way the harvest of exploited fish stocks is managed has repercussion on all the other components of the food web, including eutrophication symptoms (e.g., risk of algal blooms; Casini *et al.* 2008), and nutrient dynamics (Hjerne and Hansson 2002), crucial aspects in the HELCOM agenda (HELCOM 2007).

Ecological indicators

A further step towards developing an ecosystem approach to the management of marine resources for the Baltic Sea is the translation of the in-depth knowledge on the functioning of the ecosystem into an indicator-based management strategy (Hall and Mainprize 2004, Jennings 2005). Such a strategy includes the definition of strategic goals and ecological objectives which are to a large degree dependent on societal consensus. The available ecological knowledge can then be used to translate the ecological into operational objectives

which are reflected in specific indicators with characteristic reference targets and limits being the basis for management decisions (Jennings 2005). For the central Baltic Sea ecosystem such a strategy can be easily developed given the conceptual knowledge regarding the structure and function of the food web (see above and Fig. 1.3). Based on this conceptual understanding, different kinds of indicators (reflecting pressures, states, and response indicators; see Jennings 2005) can be selected. These can be for a single species targeted by the fishery, but should also reflect community changes (as the size-spectrum in fish communities) or ecosystem-wide reactions (see above; Hall and Mainprize 2004). Indicators of spatial changes occurring at the regional scale can also be evaluated (as suggested already for the central Baltic Sea; Casini *et al.* 2010b). Eventually, a set of indicators can be selected which together may form an early-warning system (Table 1.1). Such an approach would allow the adaptation of exploitation levels to, for example, changes in productivity in order to avoid unintended over-exploitation. Developing such a system requires, however, a thorough testing of the suitability of the combination of many possible indicators and respective reference points and targets. Such an exercise has still to be done for the Baltic Sea ecosystem.

Steps forward in ecosystem management

The ecosystem approach has been heavily promoted as a necessary approach by scientists, and has been incorporated, to varying degrees, in numerous policy documents. Now, politicians and managers are seeking advice from scientists regarding how this approach should be implemented (Rice 2005, Watson-Wright 2005). In the Baltic Sea, there has been a long tradition of systems research, and the understanding of Baltic Sea structure, function, and dynamics has advanced substantially during the most recent years. Ecosystem knowledge about the Baltic Sea is transferred to policy makers along different pathways, depending on the issue at hand, and the management institution asking for advice. In many marine regions, the focus has been on the impacts of fishing on marine ecosystems (e.g., bottom trawling, bycatch of target and non-target species, competition with marine predators). In the Baltic Sea there is also recognition of reciprocity. The dynamics, circumstances, and condition of ecosystems have a clear impact on fisheries (and fish stocks dynamics). Such factors include the status of the marine ecosystem, along with a variety of abiotic factors (nutrient levels, water quality, salinity, temperature, and deep water anoxia). There is thus a clear case for better integration of advice from the fisheries sector and the environment sector, and there are steps to move in this direction, albeit slow. Advice from ICES scientists on sustainable levels of fishing mortality are primarily dealt with by the Ministries of Fisheries (via

the European Commission and stakeholders; Daw and Grey 2005) in a well-established annual cycle (advice on quotas, stakeholder consultations, and Council decisions), whereas issues and objectives related to the environment are handled primarily by the ministries of environment, throughout different HELCOM processes. Ecosystem considerations are increasingly becoming a part of ICES advice (e.g., multi-species assessment of quotas and discussions about reference points due to regime shifts; ICES 2008b) but there is currently no process established to deliver integrated assessments for the Baltic Sea to both the Ministers of Fisheries and Environment. However, the advisory structures within ICES are currently undergoing changes. One major problem is that the sectors influencing the Baltic Sea interact in numerous ways, and it is commonly difficult to separate cause and effect. The Marine Strategy Directive (EC 2008) can potentially promote coherence and consistency between the different policy-setting bodies, but there is a large need of common vision and common strategies shared by all. There are currently no mechanisms in place to deal with potential trade-offs. Potentially, this can be achieved by considering a number of possible trajectories for the future. Such scenario planning, with relevant stakeholders, could provide a mechanism for establishing priorities between potentially conflicting goals and help management bodies around the Baltic Sea find a common strategy. Before moving to an ecosystem approach, however, there is a clear case for starting with the scientific advice already at hand (Mace 2004). All indications from other regions where management is moving towards an ecosystem approach suggest that this approach, taking account of uncertainty and predator demands, results in smaller quotas than are currently implemented. If simple, single-species stock advice is being followed, and if fleet capacity is closer matched to systems capacity – that will be a necessary start. The capacity to implement an adaptive response to dynamic ecosystems with multiple tipping points must be a goal for management beyond those of traditional approaches, as hard as they themselves may be to achieve.

Acknowledgments

We thank Olle Karlsson and Karl Lundström who made Fig. 1.7 available.

References

- Alheit, J., C. Möllmann, J. Dutz *et al.* 2005. Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. *ICES J. Mar. Sci.* **62**:1205–1215.

- Arrhenius, F. and S. Hansson. 1993. Food consumption of larval, young and adult herring and sprat in the Baltic Sea. *Mar. Ecol. Progr. Ser.* **96**:125–137.
- Axenrot, T. and S. Hansson. 2003. Predicting herring recruitment from young-of-the-year densities, spawning stock biomass, and climate. *Limnol. Oceanogr.* **48**:1716–1720.
- Bakun, A. and S.J. Weeks. 2006. Adverse feedback sequences in exploited marine systems: are deliberate interruptive actions warranted? *Fish. Fish.* **7**:316–333.
- Baumann, H., R. Voss, H.-H. Hinrichsen *et al.* 2008. Investigating the selective survival of summer- over spring-born sprat, *Sprattus sprattus*, in the Baltic Sea. *Fish. Res.* **91**:1–14.
- Beaugrand, G. 2004. The North Sea regime shift: evidence, causes, mechanisms and consequences. *Progr. Oceanogr.* **60**:245–262.
- Browman, H.I., P.M. Cury, R. Hilborn *et al.* 2004. Theme Section: perspectives on ecosystem-based approaches to the management of marine resources. *Mar. Ecol. Progr. Ser.* **274**:269–303.
- Cardinale, M. and F. Arrhenius. 2000a. Decreasing in weight-at-age of Baltic herring (*Clupea harengus*) between 1986 and 1996: a statistical analysis. *ICES J. Mar. Sci.* **57**:1–12.
- Cardinale, M. and F. Arrhenius. 2000b. The influence of stock structure and environmental conditions on the recruitment process of Baltic cod estimated using a generalized additive model. *Can. J. Fish. Aquat. Sci.* **57**:2402–2409.
- Cardinale, M., M. Casini, and F. Arrhenius. 2002. The influence of biotic and abiotic factors on the growth of sprat (*Sprattus sprattus*) in the Baltic Sea. *Aquat. Living Res.* **15**:273–281.
- Cardinale, M., C. Möllmann, V. Bartolino *et al.* 2009. Effect of environmental variability and spawner characteristics on the recruitment of Baltic herring *Clupea harengus* populations. *Mar. Ecol. Progr. Ser.* **388**:221–234.
- Casini, M., M. Cardinale, and J. Hjelm. 2006. Inter-annual variation of herring (*Clupea harengus*) and sprat (*Sprattus sprattus*) condition in the central Baltic Sea: what gives the tune? *Oikos* **112**:638–650.
- Casini, M., J. Lövgren, J. Hjelm *et al.* 2008. Multi-level trophic cascades in a heavily exploited open marine ecosystem. *Proc. R. Soc. B* **275**:1793–1801.
- Casini, M., J. Hjelm, J.-C. Molinero *et al.* 2009. Trophic cascades promote threshold-like shifts in pelagic marine ecosystem. *Proc. Natl. Acad. Sci. USA* **106**:197–202.
- Casini, M., V. Bartolino, J.C. Molinero, and G. Kornilovs. 2010a. Linking fisheries, trophic interactions and climate: threshold dynamics drive herring *Clupea harengus* growth in the central Baltic Sea. *Mar. Ecol. Progr. Ser.* **413**:241–252.
- Casini, M., G. Kornilovs, M. Cardinale *et al.* 2010b. Density-dependence regulates spatial and temporal patterns in the condition of central Baltic Sea clupeids. In press.
- Cederwall, H. and R. Elmgren. 1990. Eutrophication of the Baltic Sea: biological effects. *Ambio* **19**:109–112.

- Choi, J.S., K.T. Frank, B.D. Petrie, and W.C. Leggett. 2005. Integrated ecosystem assessment of a large marine ecosystem: a case study of the devolution of the eastern Scotian Shelf, Canada. *Oceanogr. Mar. Biol. Ann. Rev.* **43**:47–67.
- Collie, J.S., K. Richardson, and J.H. Steele. 2004. Regime shifts: can theory illuminate the mechanisms? *Progr. Oceanogr.* **60**:281–302.
- Daskalov, G.M., A. Grishin, S. Rodionov, and V. Mihneva. 2007. Trophic cascades triggered by over fishing reveal possible mechanisms of ecosystem regime shifts. *Proc. Natl. Acad. Sci. USA* **104**:10518–10523.
- Daw, T. and T. Gray. 2005. Fisheries science and sustainability in international policy: a study of failure in the European Union's Common Fisheries Policy. *Mar. Pol.* **29**:189–197.
- De Roos, A., L. Persson, and H.R. Thieme. 2003. Emergent Allee effects in top predators feeding on structured prey populations. *Proc. R. Soc. Lond. B* **270**: 611–618.
- EC. 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32000L0060:EN:NOT>. Accessed June 2009.
- EC. 2007. Council regulation (EC) No. 1098/2007 establishing a multiannual plan for the cod stocks in the Baltic Sea and the fisheries exploiting those stocks, amending Regulation (EEC) No. 2847/93 and repealing Regulation (EC) No. 779/97. *Official Journal of the European Union* L 248, September 22 2007, pp. 1–10.
- EC. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32008L0056:EN:NOT>. Accessed June 2009.
- Eero, M., F.W. Koster, and B.R. MacKenzie. 2008. Reconstructing historical stock development of Atlantic cod (*Gadus morhua*) in the eastern Baltic Sea before the beginning of intensive exploitation. *Can. J. Fish. Aquat. Sci.* **65**:2728–2741.
- Fiskeriverket. 2008. *Planktivore Management – Linking Food Web Dynamics to Fisheries in the Baltic Sea (PLANFISH)*. First Annual Report 2008.
- Folke, C., S. Carpenter, B. Walker *et al.* 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annu. Rev. Ecol. Evol. Syst.* **35**:557–581.
- Frank, K.T., B. Petrie, J.S. Choi, and W.C. Leggett. 2005. Trophic cascades in a formerly cod-dominated ecosystem. *Science* **308**:1621–1623.
- Hall, S.J. and B. Mainprize. 2004. Towards ecosystem-based fisheries management. *Fish Fish.* **5**:1–20.
- Halpern, B.S., S. Walbridge, K.A. Selkoe *et al.* 2008. A global map of human impact on marine ecosystems. *Science* **319**:948–952.
- Hansson, S., O. Hjerne, C. Harvey *et al.* 2007. Managing Baltic Sea fisheries under contrasting production and predation regimes: ecosystem model analyses. *Ambio* **36**:265–271.

- Harding, K.C. and T. Härkönen. 1999. Development in the Baltic grey seal (*Halichoerus grypus*) and ringed seal (*Phoca hispida*) populations during the 20th century. *Ambio* **28**:619–627.
- Hare, S.R. and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progr. Oceanogr.* **47**:103–145.
- Heikinheimo, O. 2008. Average salinity as an index for environmental forcing on cod recruitment in the Baltic Sea. *Boreal Env. Res.* **13**:457–464.
- HELCOM. 2007. *Helcom Baltic Sea Action Plan*. www.helcom.fi/BSAP/en_GB/intro/ Accessed June 2009.
- Hjerne, O. and S. Hansson. 2002. The role of fish and fisheries in Baltic Sea nutrient dynamics. *Limnol. Oceanogr.* **47**:1023–1032.
- Hughes, T.P., A.H. Baird, D.R. Bellwood et al. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* **301**:929–933.
- ICES, International Council for the Exploration of the Sea. 2006. *Report of the Baltic Fisheries Assessment Working Group (WGBFAS)*, ICES CM 2006/ACFM:24.
- ICES, International Council for the Exploration of the Sea. 2007. *Report of the Workshop on Limit and Target Reference Points (WKREF)*, ICES CM 2007/ACFM:05.
- ICES, International Council for the Exploration of the Sea. 2008a. *Report of the Working Group on Integrated Assessment of the Baltic Sea (WGIAB)*, ICES CM 2008/BCC:04.
- ICES, International Council for the Exploration of the Sea. 2008b. *Report of the Workshop on Reference Points in the Baltic Sea (WKREFBAS)*, ICES CM 2008/BCC:04.
- ICES, International Council for the Exploration of the Sea. 2008c. *Report of the Baltic Fisheries Assessment Working Group (WGBFAS)*, ICES CM 2008/ACOM:06.
- ICES, International Council for the Exploration of the Sea. 2009a. *Report of the Baltic Fisheries Assessment Working Group (WGBFAS)*, ICES CM 2009/ACOM:07.
- ICES, International Council for the Exploration of the Sea. 2009b. *Report of the Workshop on Multi-annual Management of Pelagic Fish Stocks in the Baltic (WKMAMPEL)*, ICES CM 2009/ACOM:38.
- Jackson, J.B.C., M.X. Kirby, W.H. Berger et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. *Science* **293**:629–637.
- Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. *Fish. Fish.* **6**:212–232.
- Kadin, M. 2007. *Post fledging survival and sexual maturation in Common guillemot Uria aalge – the influence of biological and ecological factors*. Degree project thesis, Dept. of Systems Ecology, Stockholm University, Stockholm.
- Karlsson, O., T. Härkönen, and B.-M. Bäcklin. 2008. Populationer på tillväxt. In Viklund, K., Tidlund, A., Brenner, U., and Svahn, K. (eds.), *Havet 2008 – om miljötillståndet i svenska havsområden*. Stockholm: Naturvårdsverket, pp. 91–92.
- Köster, F.W. and C. Möllmann. 2000. Trophodynamic control by clupeid predators on recruitment success in Baltic cod? *ICES J. Mar. Sci.* **57**:310–323.
- Köster, F.W., H.-H. Hinrichsen, M.A. St. John et al. 2001. Developing Baltic cod recruitment models. II. Incorporation of environmental variability and species interaction. *Can. J. Fish. Aquat. Sci.* **58**:1534–1556.

- Lindegren, M., C. Möllmann, A. Nielsen, and N.C. Stenseth. 2009. Preventing the collapse of the Baltic cod stock through an ecosystem-based management approach. *Proc. Natl. Acad. Sci. USA* **106**:14772–14727.
- Link, J.S., J.K.T. Brodziak, S.F. Edwards *et al.* 2002. Marine ecosystem assessment in a fisheries management context. *Can. J. Fish. Aquat. Sci.* **59**:1429–1440.
- Lundström, K., O. Hjerne, S.-G. Lunneryd, and O. Karlsson. 2010. Understanding the diet composition of marine mammals: grey seals (*Halichoerus grypus*) in the Baltic Sea. *ICES J. Mar. Sci.* **67**:1230–1239.
- Mace, P.M. 2004. In defence of fisheries scientists, single-species models and other scapegoats: confronting the real problems. *Mar. Ecol. Progr. Ser.* **274**:285–291.
- MacKenzie, B.R. and F.W. Köster. 2004. Fish production and climate: sprat in the Baltic Sea. *Ecology* **85**:784–794.
- MacKenzie, B.R., J. Horbowy, and F.W. Köster. 2008. Incorporating environmental variability in stock assessment: predicting recruitment, spawner biomass, and landings of sprat (*Sprattus sprattus*) in the Baltic Sea. *Can. J. Fish. Aquat. Sci.* **65**:1334–1341.
- Möllmann, C., G. Kornilovs, M. Fetter, F.W. Köster, and H.H. Hinrichsen. 2003. The marine copepod, *Pseudocalanus elongatus*, as a mediator between climate variability and fisheries in the central Baltic Sea. *Fish. Oceanogr.* **12**:360–368.
- Möllmann, C., G. Kornilovs, M. Fetter, and F.W. Köster. 2005. Climate, zooplankton, and pelagic fish growth in the central Baltic Sea. *ICES J. Mar. Sci.* **62**:1270–1280.
- Möllmann, C., B. Müller-Karulis, G. Kornilovs, and A.M. St. John. 2008. Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascades, and feedback-loops in a simple ecosystem. *ICES J. Mar. Sci.* **65**:302–310.
- Möllmann, C., R. Diekmann, B. Müller-Karulis *et al.* 2009. Reorganization of a large marine ecosystem due to atmospheric and anthropogenic pressure: a discontinuous regime shift in the Central Baltic Sea. *Global Change Biol.* **15**:1377–1393.
- Nissling, A. 2004. Effects of temperature on egg and larval survival of cod (*Gadus morhua*) and sprat (*Sprattus sprattus*) in the Baltic Sea – implications for stock development. *Hydrobiologia* **514**:115–123.
- Österblom, H., M. Casini, O. Olsson, and A. Bignert. 2006. Fish, seabirds and trophic cascades in the Baltic Sea. *Mar. Ecol. Progr. Ser.* **323**:233–238.
- Österblom, H., S. Hansson, U. Larsson *et al.* 2007. Human-induced trophic cascades and ecological regime shifts in the Baltic Sea. *Ecosystems* **10**:877–889.
- Pace, M.L., J.J. Cole, S.R. Carpenter, and J.F. Kitchell. 1999. Trophic cascades revealed in diverse ecosystems. *Trends Ecol. Evol.* **14**:483–488.
- Rahikainen, M. and R.L. Stephenson. 2004. Consequences of growth variation in northern Baltic herring for assessment and management. *ICES J. Mar. Sci.* **61**:338–350.
- Rice, J.C. 2005. Implementation of the Ecosystem Approach to Fisheries Management – asynchronous co-evolution at the interface between science and policy. In Browman, H.I. and Stergiou, K.I. (eds.), *Politics and socio-economics*

- of eco-system-based management of marine resources. *Mar. Ecol. Progr. Ser.* **300**:265–270.
- Scheffer, M. and S.R. Carpenter. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends Ecol. Evol.* **18**:648–656.
- Scheffer, M., S. Carpenter, J.A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. *Nature* **413**:591–596.
- Strong, D.R. 1992. Are trophic cascades all wet? Differentiation and donor control in speciose ecosystems. *Ecology* **73**:747–754.
- Vainikka, A., F. Mollet, M. Casini, and A. Gårdmark. 2009. Spatial variation in growth, condition and maturation reaction norms of the Baltic herring, *Clupea harengus membras*. *Mar. Ecol. Progr. Ser.* **383**:285–294.
- Van Leeuwen, A., A.M. De Roos, and L. Persson. 2008. How cod shapes its world. *J. Sea Res.* **60**:89–104.
- Voipio, A. 1981. *The Baltic Sea. Elsevier Oceanography Series, 30*. Amsterdam: Elsevier.
- Voss, R., F.W. Köster, and M. Dickmann. 2003. Comparing the feeding habits of co-occurring sprat (*Sprattus sprattus*) and cod (*Gadus morhua*) larvae in the Bornholm Basin, Baltic Sea. *Fish. Res.* **63**:97–111.
- Wasmund, N., G. Nausch, and W. Matthäus. 1998. Phytoplankton spring blooms in the southern Baltic Sea – spatio-temporal development and long-term trends. *J. Plankton Res.* **20**:1099–1117.
- Watson-Wright, W.M. 2005. Policy and science: different roles in the pursuit to common problems. In Browman, H.I. and Stergiou, K.I. (eds.), *Politics and socio-economics of eco-system-based management of marine resources*. *Mar. Ecol. Progr. Ser.* **300**:291–296.
- Weijerman, M., H. Lindeboom, and A.F. Zuur. 2005. Regime shifts in marine ecosystems of the North and Wadden Sea. *Mar. Ecol. Progr. Ser.* **298**:21–39.