FISH STOCKS AND FISHERIES IN RELATION TO CLIMATE VARIABILITY AND EXPLOITATION

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Contents

Summary

Commercial fish stocks are inherently variable due to their mode of reproduction whereby each mature female produces a very high number of eggs (typically of the order of one million) that are released into the environment. In the number reduction from a very high number of eggs to on average two adult reproducing individuals, there are stabilizing mechanisms involving density-dependent processes. These can dampen but not prevent variability, which is typically one order of magnitude in range in time series that span several decades. Spawning migrations to spawning areas and drift and spread of eggs and/or larvae to nursery areas are parts of the spatial or geographical closure of the life cycle of fish populations. This spatial closure is in relation to the ocean currents and flow fields in their habitats. Climatic variability, which affects the currents and flow fields, will directly influence the recruitment and population size of fish stocks. In addition there are strong biological interactions involving predator–prey relationships among fish populations, zooplankton, and other components of marine ecosystems. This is illustrated with examples from the Barents Sea ecosystem in the northern North Atlantic. The effects of alterations in flow fields and the continuous nature of the ocean circulation system provide a general mechanism for the observed high degree of co-variability in fluctuations in different fish populations.

The state of the world fisheries is according to the Food and Agriculture Organization (FAO) characterized by an overall high degree of exploitation. The world marine capture fisheries increased 5-fold from 17 million metric tons (tonnes) in 1950 to about

85 million tonnes in 1990, but with no further increase during the 1990s. For major fish stocks globally, about 50% are fully exploited, 16% are overexploited, and 10% are depleted. In the northeast Atlantic, 60% out of a total of 90 stocks are considered by the International Council for the Exploration of the Sea (ICES) to be outside safe biological limits, while only 20% are considered to be inside safe limits. A precautionary approach has been developed where scientific advice is given based on reference points set for both spawning stock biomass and fishing mortality. These are so-called limit reference points, which should be avoided due to possible stock collapse, but are set with a statistical safety margin. A stock is considered to be overfished if the fishing mortality exceeds the set limit, even if the spawning stock is above its limit. This is because such high fishing mortality is likely to lead to a decline in stock size. The dual principle including stock size and fishing mortality in the precautionary approach is a major step forward. However, there is still scope for improvements. One critical element is the underlying assumption of current theory of fish populations that recruitment levels off as spawning stock biomass increases. The concept of safe biological limit hinges on this assumption as it is only below this limit that recruitment is considered to be impaired. Arguments are provided to suggest that this assumption may be wrong and that we may have been underestimating the role of recruitment overfishing in contributing to declining trends and the present poor status of many fish stocks. An alternative theory is presented which assumes that the density-dependent processes that contribute to the stability properties of fish populations occur in the part of the life cycle from recruits to adults and not between eggs and recruits.

1. Introduction

Large changes and fluctuations in fisheries have been commonly experienced in many parts of the world. In the introduction to his classic work on the fluctuations in the fisheries in the North Atlantic, Hjort (1914) stated:

> From the earliest times, a characteristic feature in all branches of the fishing industry has been the fluctuation of the respective yields from year to year. At the present time, we find the United States complaining of the failure of the mackerel fishery, while in France, a “sardine crisis” has arisen, …The Norwegian fisheries, …, have for hundreds of years experienced alternating periods of rich and poor yield. These periodical fluctuations have as a rule been of some considerable duration, a series of years of profitable fishery succeeding and succeeded by several years of dearth. Thus the term: a good (or bad) *fishery period* has become an expression of common occurrence.

Many historical or recent examples of such changes in fisheries exist (Cushing, 1982, 1986; Rothschild, 1986; Wyatt and Larreneta, 1988; Kawasaki et al., 1991; Lluch-Belda et al., 1992). While the prevailing belief in earlier times was that this reflected changing migration patterns and availability of fish for the fisheries, the investigations of Hjort (1914) and others at the beginning of the twentieth century, made it clear that changing stock size as a result of variable recruitment was a major factor for the different fisheries.

Variable recruitment translating into variable stock size is an intrinsic property of large commercial fish stocks, related to their mode of reproduction with a high number of small eggs produced by each female fish (Skjoldal and Melle, 1989). Climatic variability is a main driving force for the variable recruitment and size of fish populations. The climatic forcing works in concert with biological interactions to produce the dynamic patterns of fish stocks in marine ecosystems. The pattern of large variations in fish stocks and yields will continue, as in the past, to be a characteristic feature of fisheries. This poses a great challenge to scientists and managers involved in fisheries management. Firstly, the changes in fish stocks due to natural variability need to be detected and described as an additional component to the changes due to fisheries exploitation. Secondly, the exploitation needs to be attuned to the changes due to natural variability.

This paper addresses the role of natural variability and its interactions with exploitation in the dynamics and management of fish stocks as major components of marine ecosystems. It attempts to provide an overview of the current status and a critical examination of basic concepts, assumptions, and future challenges in our assessment and management of fish stocks. While the scope is general and global, the focus is on the North Atlantic and in particular the Barents Sea, which provides an example of the dynamics and interactions of fish stocks and other components in a marine ecosystem.

2. State of Fisheries

The FAO publishes every second year a world review of fisheries in its SOFIA report (*The State of World Fisheries and Aquaculture*). World marine capture fisheries production has increased 5-fold from 17 million tonnes in 1950 to 84.1 million tonnes in 1999 (Figure 1). The rate of increase has, however, slowed markedly, from about 6% per year in the 1950s and 1960s to no increase after 1994. The world total capture fisheries production, including inland fisheries, was 92.3 million tonnes in 1999. The world aquaculture production has more than doubled since 1990 to 32.9 million tonnes in 1999. The total world fisheries production, as the sum of capture fisheries and aquaculture, was 125 million tonnes in 1999 (Figure 1).

About 60% of the world marine capture fisheries production is taken from the Pacific Ocean, with the northwest Pacific as the most important fishing area with a production of about 25 million tonnes in 1999 (FAO, 2001). This area alone produces a higher yield than the Atlantic Ocean, where the capture fisheries production was about 20 million tonnes in 1999. One likely reason for the higher fisheries yield from the Pacific than from the Atlantic is the considerably higher nutrient concentrations there (Sverdrup et al., 1942; Sakshaug and Holm-Hansen, 1984; Kamykowski and Zentara, 1985). In the "conveyor belt" of the global ocean circulation, old and therefore relatively nutrient-poor water submerges through deep-water formation in the Arctic part of the North Atlantic. Through remineralization processes the nutrient content gradually increases over time, so that this water upwells centuries later as nutrient-rich water in the southern ocean (Broecker and Denton, 1990).

The degree of exploitation of the main fish stocks overall is high. Among the major fish stocks for which information is available, about 50% are fully exploited and are therefore producing catches that have reached or are very close to their maximum limit (FAO, 2001).

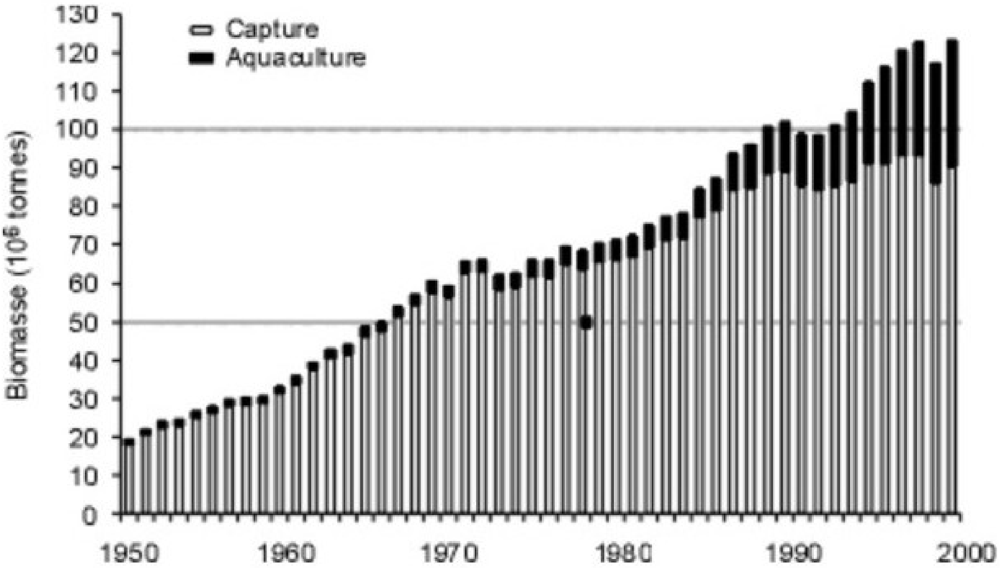

Figure 1. Development in world total annual capture fisheries and aquaculture production (marine and freshwater) in the period 1950–1999 (FAO, 2001).

About 16% of the stocks are overfished, with catches likely to decrease if remedial action is not undertaken. About 10% of the stocks have been depleted or are recovering from depletion. The areas where total catches still follow an increasing trend, and where some potential for increase still exists, are the eastern and western Indian Ocean, the western central Pacific, and the northwest Pacific. These areas tend to have more underexploited or moderately exploited stocks, although the degree of uncertainty of state of exploitation is high.

In the Atlantic the largest catch has come from the northeast area. In this area the catch reached a maximum of about 13 million tonnes in the 1970s and has since leveled off with a decrease to about 10 million tonnes in 1990 and a slight increase to about 11 million tonnes in 1998.

The state of the fish stocks in the northeast Atlantic is assessed by ICES, who also provides advice on catch quotas and other management actions. The state of each fish stock is assessed as to whether the stock is outside or inside safe biological limits based on the criteria that the size of the spawning stock should be above some set minimum level and that the fishing mortality should not exceed a set maximum value. These set values are called biological reference points (ICES, 2000a). This is described in more detail below.

The state of the commercial fish stocks in the northeast Atlantic is overall poor, with 60% out of 90 stocks being outside safe biological limits. Only 20% of the stocks are considered to be inside safe biological limits, while the status of the remaining 20% is uncertain or close to the border of being outside safe limits (Figure 2). There are fewer but often larger commercial fish stocks assessed and exploited in the northern part than in the southern part of the northeast Atlantic. There is an overall tendency to higher proportions of stocks outside safe biological limits in the southern than in the northern parts. The situation also tends to be better for some of the pelagic fish stocks than for stocks of demersal roundfish and flatfish.

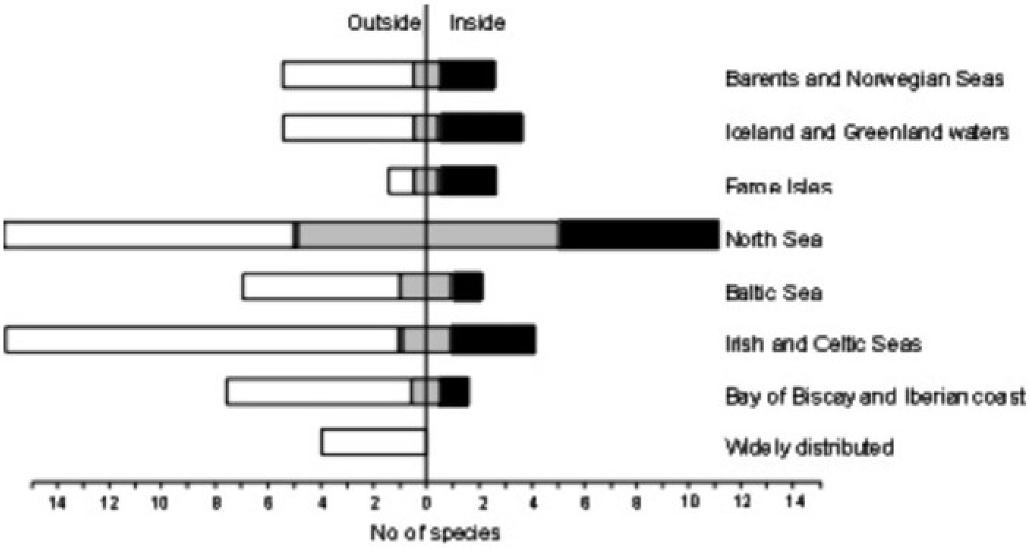

Figure 2. Number of commercial fish stocks in various parts of the northeast Atlantic assessed by ICES (2000; OSPAR, 2000) to be outside or inside safe biological limits. Stocks in the border area between inside or outside or with uncertain status due to lack of data are shown with light shading in the middle region of the figure

The overall poor state of fish stocks is a result of high rates of exploitation. Exploitation rates in the range 0.5–1.0 per year (corresponding to a removal rate of about 40–80% of the population each year) is common for many fish stocks (ICES, 2000a,b). At such high exploitation rates, only a small fraction of the recruited juveniles survives to reach reproductive age.

As a consequence of high exploitation rates, there has been a decrease in the mean trophic level for the global capture fisheries between 1950 and the 1990s (Pauly et al., 1998). This reflects a change in landings from long-lived, fish-eating bottom fish at a high level in the trophic pyramid, toward short-lived plankton-feeding fish and invertebrates at lower trophic level. This trend of decrease in mean trophic level is most pronounced in the North Atlantic and the North Pacific. While in theory one could expect the yield to increase as one shifts fisheries down to lower level in marine food webs, the observed pattern in the North Atlantic has been a leveling off or even decrease in catches associated with the reduction in mean trophic level. Among possible explanations for this feature are under- or mis-reporting of catches, increasing discarding of small and unwanted fish, and changes in ecosystem structure.

3. Why Fish Stocks Vary

Variable recruitment was identified as a major cause for variations in fish stocks and fisheries early in the twentieth century (Hjort, 1914). Since then the recruitment variability problem has been a major research issue. This research has been guided by several hypotheses and a wide range of factors affecting the development and early life history of fish have been investigated (Rothschild, 1986; Houde, 1987, 1997; Legget and Doblis, 1994). The hypotheses can be broadly grouped into those focusing on: (1) starvation; (2) predation; and (3) unfavorable drift, as the major cause for larval mortality. The concepts of a “critical period” in the development of fish larvae at the transition from living on yolk sac reserves to feeding on plankton prey (Hjort, 1914) and “match–mismatch” in the timing between hatching of fish larvae and occurrence of suitable prey organisms (Cushing, 1972, 1990) have been central elements in starvation hypotheses. It has become clear over recent decades that fish larvae seldom die from starvation but rather from predation from a broad range of plankton-feeding organisms, notable among them pelagic fishes (Bailey and Houde, 1989; Skjoldal and Melle, 1989).

The recruitment variability is on the very general level a trivial consequence of the reproductive mode of fish. Most fish species that form large stocks release a large number of eggs or hatched larvae into the pelagic environment. Here the eggs and larvae as ichthyoplankton drift as part of the plankton community. During this stage they are exposed to predators that roam and feed in the pelagic realm. Hence typical mortality rates of fish eggs and larvae are of the order of $0.1\ d^{-1}$ which means that about 10% of the individuals are eaten every day (McGurk, 1986). Sustained over weeks or months such mortality rates reduce the number of individuals from the order of million eggs to a low number of recruits that sustain on average two new adult individuals for each female and male that contributed to the spawning. In this number reduction game, small changes in mortality rate translate into large changes in the small fraction of individuals surviving as recruits (Skjoldal and Melle, 1989). Growth rate and mortality are related in that variation in growth rate translates into variation in the time spent to grow through a size range in the larval development and thereby the accumulated mortality experienced during that period.

In the number reduction from million eggs to two adult reproducing individuals, there are stabilizing mechanisms involving density-dependent processes. These mechanisms can dampen the fluctuations but do not remove them. Inevitably, therefore, the large recruitment variability is translated into variability in the resulting spawning stock size. This is illustrated for the northeast Arctic cod stock inhabiting the Barents Sea ecosystem (Figure 3). The pattern of recruitment shows a cyclic nature with a few years of good recruitment followed by some years of poor recruitment. This is related to climatic fluctuations with strong year classes formed during warming or warm years in the short-periodic fluctuations between cold and warm years (Sætersdal and Loeng, 1987; Ottersen et al., 1994, 2000; Ottersen and Sundby, 1995; Sundby, 2000).

The recruitment of the northeast Arctic cod is calculated at the age of 3-year-old individuals. At this stage the amplitude of variation between poor and strong year classes is about one order of magnitude (Figure 3A). The peaks in recruitment can be followed as peaks in the size of the immature stock the same year or 1–2 years later (Figure 3B) and in peaks in the spawning stock about 5 years later (Figure 3C). This corresponds approximately to the life cycle of this cod stock where the individuals reach maturity at an age of about 7–8 years (Jørgensen, 1990, 1992; Beverton et al., 1994; Nakken, 1994; Godø, 2000b).

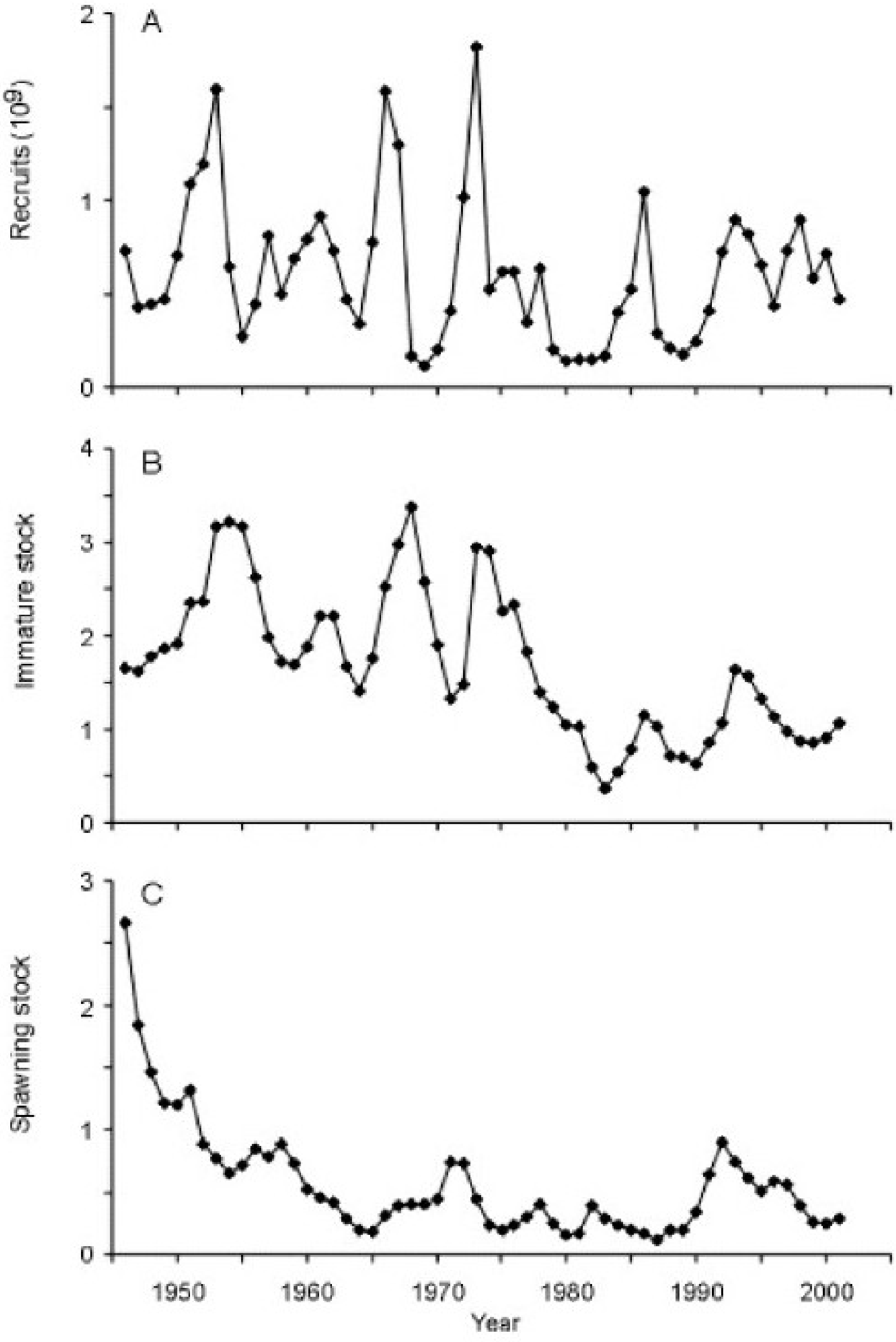

Figure 3. Time series of the northeast Arctic cod stock in the Barents Sea in the period 1946–1999. A, Number of recruits as 3-year-old individuals. B, Biomass of the immature part of thestock 3 years and older. C, Spawning stock biomass. Based on data from ICES (2000a)

The fact that recruitment is related to spawning stock size with a time delay is a general experience that is taken for granted as basic knowledge in fish stock assessments and predictions. Strong year classes may play a dominant role in the fisheries of many commercial fish stocks, and the outlook for good or poor recruitment forms an important part of judging the likely development of stocks (ICES, 2000a,b). Nevertheless, it has been the reverse relationship, the dependence of recruitment on spawning stock size, that has received most attention. This relationship is typically characterized by a large scatter of data points as illustrated for northeast Arctic cod and North Sea cod in Figure 4. Generally only a small fraction of the variance in recruitment is explained by spawning stock size (Rothschild, 1986; Myers and Barrowman, 1996), the remaining large fraction of unexplained variance being due to other factors such as the environment.

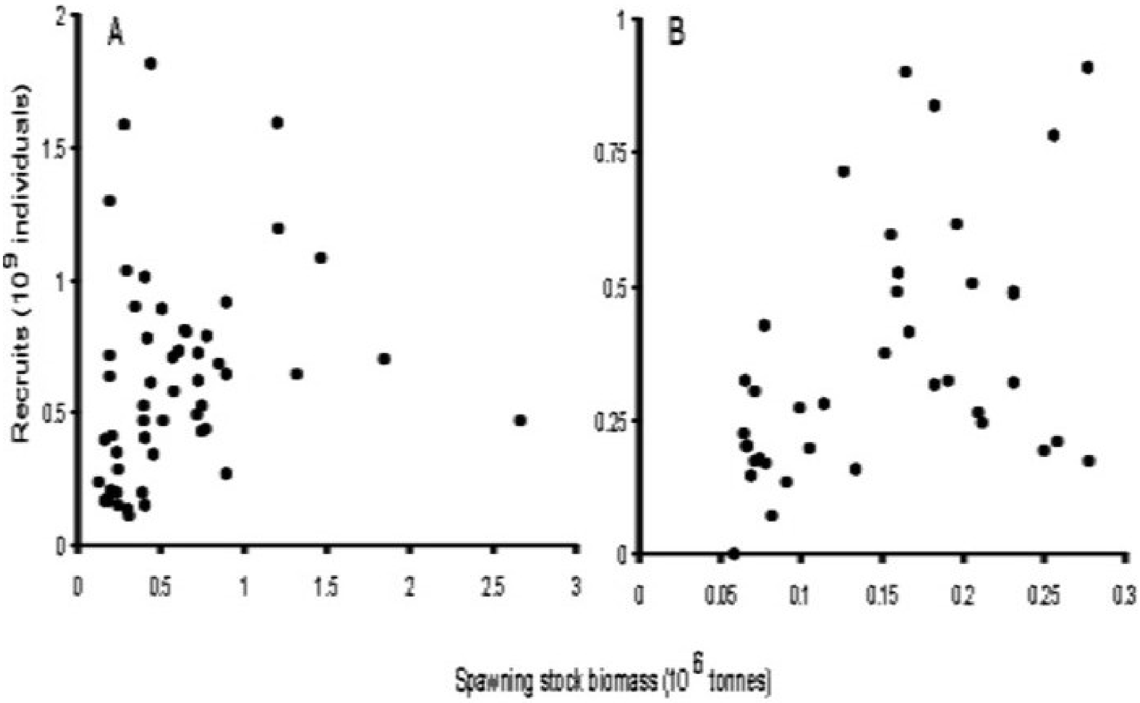

Figure 4. Plots of recruitment versus spawning stock biomass for: A, the northeast Arctic cod stock in the Barents Sea, and B, the North Sea cod stock. Data from ICES (2000a)

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