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Enberg, K. and Heino, M.

Enberg, K. and Heino, M. (2007) Fisheries-induced Life History Changes in Herring (Clupea harengus). IIASA Interim Report. IIASA, Laxenburg, Austria, IR-07-045 Copyright © 2007 by the author(s). http://pure.iiasa.ac.at/8413/

Interim Report   **IR-07-045**

Fisheries-induced Life History Changes in Herring (*Clupea harengus*)

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December 2007

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Fishing changes not only the population abundance of the target species, but also its population dynamics and life-history traits. A number of studies have shown that life history traits related to the timing of maturation can respond quickly to fishing mortality. Because changes in such life-history traits feed back into population dynamics and, consequently, may also affect the yield and thus profitability of a fishery, we need better understand the factors that hasten or hinder such changes. In this study we analyze how fisheries have affected the maturation process of an economically important herring (*Clupea harengus*) stock, the North Sea (NSH) herring. The harvest of North Sea herring targets both mature and immature individuals. Life-history theory predicts that under this kind of mortality regime fisheries can be expected to induce an adaptive decrease in the age at maturation. This kind of studies are a critical for testing theoretical predictions, and will facilitate our understanding under which conditions large life history changes can and cannot be expected. Such understanding is needed for evolutionarily enlightened management of marine biodiversity. The results will provide guidance for evolutionarily enlightened management strategies, particularly with respect to fisheries targeting mature and immature individuals differently.

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Introduction

Field and laboratory experiments have shown that harvested populations can evolve considerably in just few generations (Reznick *et al.* 1990, Conover and Munch 2002). Fisheries scientists and managers are just now awakening to the formidable risks posed by further unmanaged fisheries-induced evolution. Fishing causes severe changes in the demographic properties of exploited stocks (Rochet 1998, Law 2000, Stokes & Law 2000). This applies, in particular, to maturation: in most stocks, fish mature earlier today than they used to only a few decades ago (Trippel 1995). It has been shown that earlier maturation may have adverse implications for the reproductive potential of fish stocks, not only because smaller females produce fewer offspring than larger ones, but also because they tend to produce offspring of poorer quality (Murawski *et al.* 2001, Berkley *et al.* 2004, Hutchings 2005). Corroborating theoretical expectations, it has recently been demonstrated experimentally that size-selective fishing can cause genetic reductions in somatic growth that result in a decline of harvestable biomass (Conover & Munch 2002, Conover *et al.* 2005). These observations can, however, be explained by three mutually non-exclusive hypotheses: (1) Harvesting usually selects for the largest and oldest individuals, and the mean age of the population decreases. As a consequence, individuals that would mature at old age are scarce in the population at the time they would mature thus lowering the observed mean age at maturation. (2) Fishing reduces stock size and releases density-dependent competition for food and space; the remaining individuals get more food, can grow faster and mature earlier (Lorenzen & Enberg 2001). (3) Fishing reduces survival probability, and early-maturing fish therefore have the highest probability of passing their genes on to future generations. These three effects, demographic, plastic, and evolutionary, can partially be disentangled with recently developed statistical methods (Heino *et al.* 2002a, b, Barot *et al.* 2004a). The results obtained from studies using these methodologies have made it increasingly clear that fisheries-induced life-history evolution likely is ubiquitous, and the magnitude of the evolutionary response depends on the type of fishing mortality (Olsen *et al.* 2004, Heino & Dieckmann 2004, Engelhard & Heino 2004b). Because evolutionary change might be slow or even impossible to reverse, it is crucial for sustainable and responsible management that we systematically explore the consequences and any potential remedies. Additional importance to considering fisheries-induced life-history changes is given by the fact that such changes do also affect the economic profitability of fisheries (Eikeset *et al.* 2006).

The North Sea herring fishery expanded rapidly in the mid 1960s because of the development of the purse seine fishery (Serchuk *et al.* 1996). Between the 1940s and 1970s, the spawning stock biomass of North Sea herring declined by two orders of magnitude leading to a collapse in the beginning of the 1970s (Serchuk *et al.* 1996). As a result, herring fishing was banned and a fisheries moratorium on herring was in effect from 1977 to 1983. The recovery of this stock was not purely the cause of decline in the fishing mortality (which because of rather high by-catches on herring did not decrease as much as intended), but also due to years of good recruitment (Serchuk *et al.* 1996). The North Sea herring fishery targets both immature and mature individuals. This type of harvest mortality strongly selects for earlier maturation (Law & Grey 1989, Heino 1998, Ernande *et al.* 2004), because delaying maturation will not pay off but rather will increase the risk of dying without any offspring.

Probabilistic maturation reaction norms (PMRNs, Heino *et al.* 2002a) help in disentangling between the three possible causes of changes in the maturation schedule introduced above. A PMRN gives the probability of a given individual of certain age to mature at a certain size in a given time interval. The reaction norm is not affected by changes in growth and demography, but reflects the inherited properties of the population. Consistent trends in reaction norms suggest evolutionary change in the maturation schedule. Even though changes in the reaction norm cannot conclusively prove that fishing has caused the changes nor that the changes are genetic, there is ample support to this phenomenon among several fished species (Heino *et al.* 2002b, Vainikka *et al.* 2006, Barot *et al.* 2004b, Olsen *et al.* 2004, 2005, O'Brien *et al. in prep.*, Grift *et al.* 2003, Barot *et al.* 2005, Mollet *et al.* 2006, Engelhard & Heino 2004b, Heino, Yin & Dieckmann *in prep.*, Haugen & Vøllestad 2007). In this study we analyze North Sea herring data from Institute of Marine Reseach acoustic surveys ranging from year 1990 to 2006. These surveys take place during the summer months, which allows determining the maturity status of the fish. Our aim is to clarify whether there are any trends in the life-history traits of this herring stock.

Material and methods

The data used in this study are collected in an acoustic survey conducted by the Institute of Marine Research (Bergen, Norway) as a part of the ICES-coordinated international survey. The survey is carried out usually in June-July, and is spatially concentrated on the area northern North Sea; we use data collected between 56°- 62° N, 2° W- 8° E (Figure 1) with pelagic and bottom trawls. Because these herring are autumn spawning, the timing of the survey allows good estimation of the maturation status of the fish. The study period spans for 17 years from 1990 to 2006, and total number of observations with maturity status observed was 36522, annually between 1100 and 5986 observations.
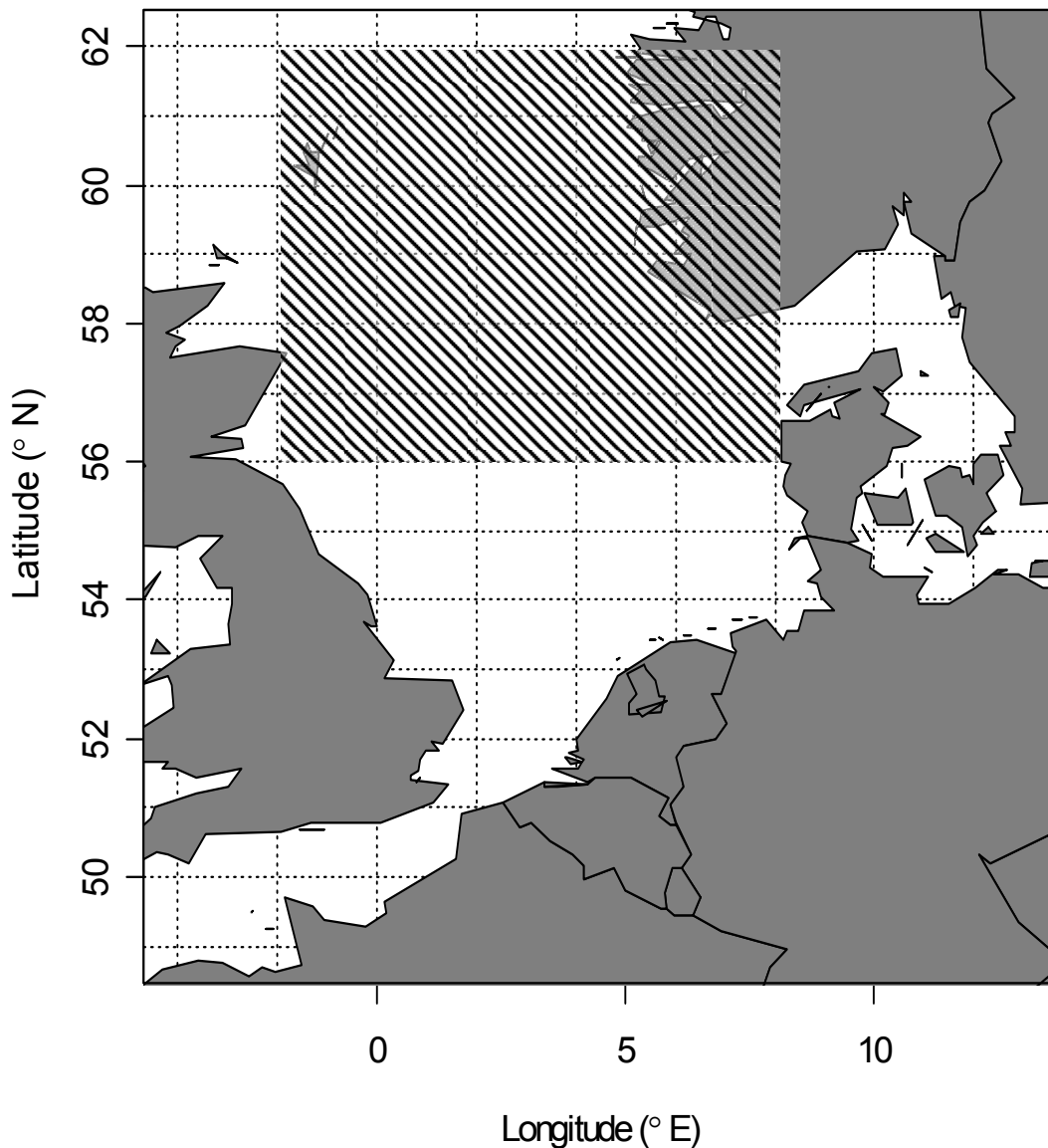
Figure 1. The North Sea, shading shows the data collection area.

For reconstruction of a PMRN, we need data on age, size, and maturity status. The methodology chosen for estimating a particular maturation reaction norm depends on the type of data at hand. There are two classes of methods, direct estimation method (Heino *et al.* 2002b), and demographic estimation method (Barot *et al.* 2004a, b). In this study we use the demographic estimation method, where it is sufficient to know only whether or not the individuals are immature or mature.

The demographic estimation method (Barot *et al.* 2004a) requires estimation of age and year specific annual growth increments and age, year and length-specific maturity ogives; we also structured our data by sex, We estimated age and year specific growth increments as the change in mean length of a cohort between the focal year and the year before; mean length was estimated with a linear model with only the main effects of age, year and sex included (all treated as factors). Maturity ogive was estimated with a logistic regression with the main effects length, age, year and sex as well as interactions age*length, age*year and length*year (no interactions involving sex could be robustly parameterized). Once these models were estimated, PMRN is obtained with the equation

$$p(a, l, s, y) = [o(a, l, s, y) - o(a-1, l-\delta l, s, y-1)] / [1 - o(a-1, l-\delta l, s, y-1)]$$

where o stands for ogive and δl for growth increments and arguments a, l, s, and y refer to age, length, sex and year, respectively.

Results

In this paper we present some preliminary results from our reaction norm analysis. The distribution of data, averaged over the total study period, is illustrated in Figure 2. The average age in the study area appears to increase from south-east to north-west (Figure 2 upper panel), and average length shows similar patter (Figure 2 lower panel).
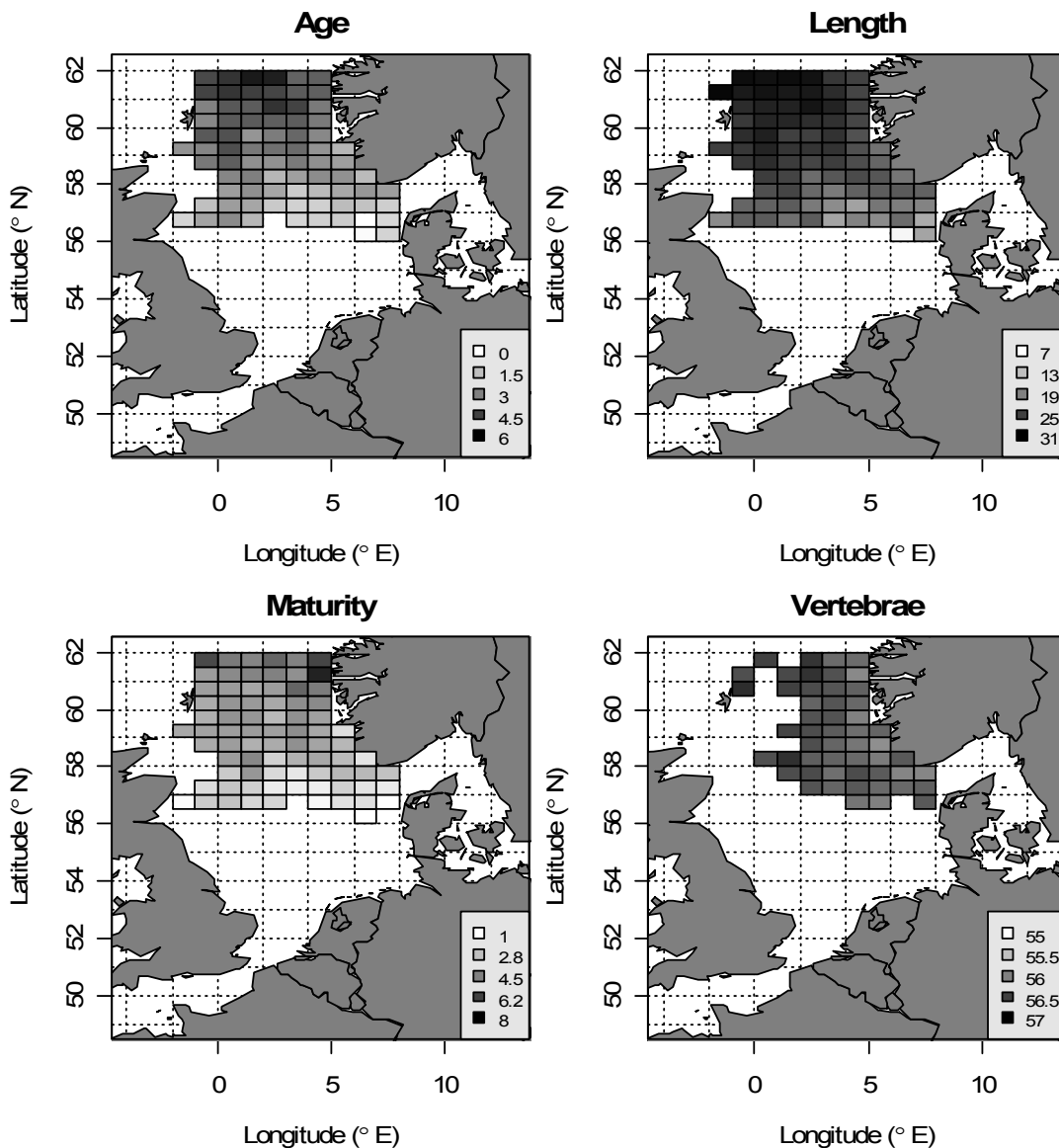

Figure 2. Spatial distribution of the North Sea herring data. Upper left panel, average age, upper right panel, length (in cm), lower left panel, maturity (standard 8-point scale), and lower right panel, number of vertebrae.

The average length at 50% maturity (L_{50}) for North Sea herring individuals has been fluctuating between 22 and 25 cm during the study period, and shows a mild trend towards smaller lengths (Figure 3 upper panel). L_{50} is slightly higher for males than for females.

The average age at 50% maturity (A_{50}) has fluctuated around two years, and males have a slightly higher average age at 50% maturity (Figure 3 lower panel).

The maturation probability at length 20 cm (the average length of age one North Sea herring) of the youngest age class shows a slight increasing trend during the study period (Figure 4 upper panel). At the same time, length at 50% maturation probability of the same age class shows a weak decreasing trend during the last decades (Figure 4 lower panel).
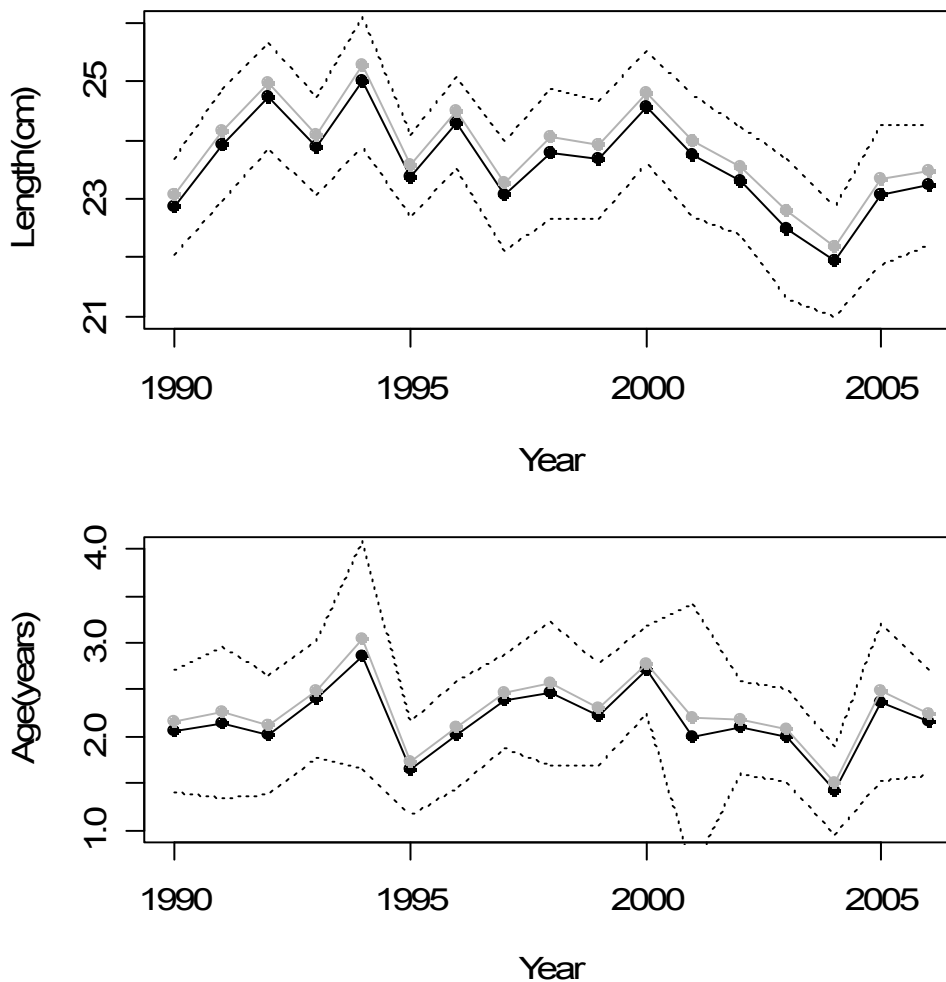

Figure 3. Length and age at which the probablity of being mature is 50% (L_{50} and A_{50}) for North Sea herring. Black lines are for females and grey ones for males; for females, also length and age at 25% and 75% maturity are shown.
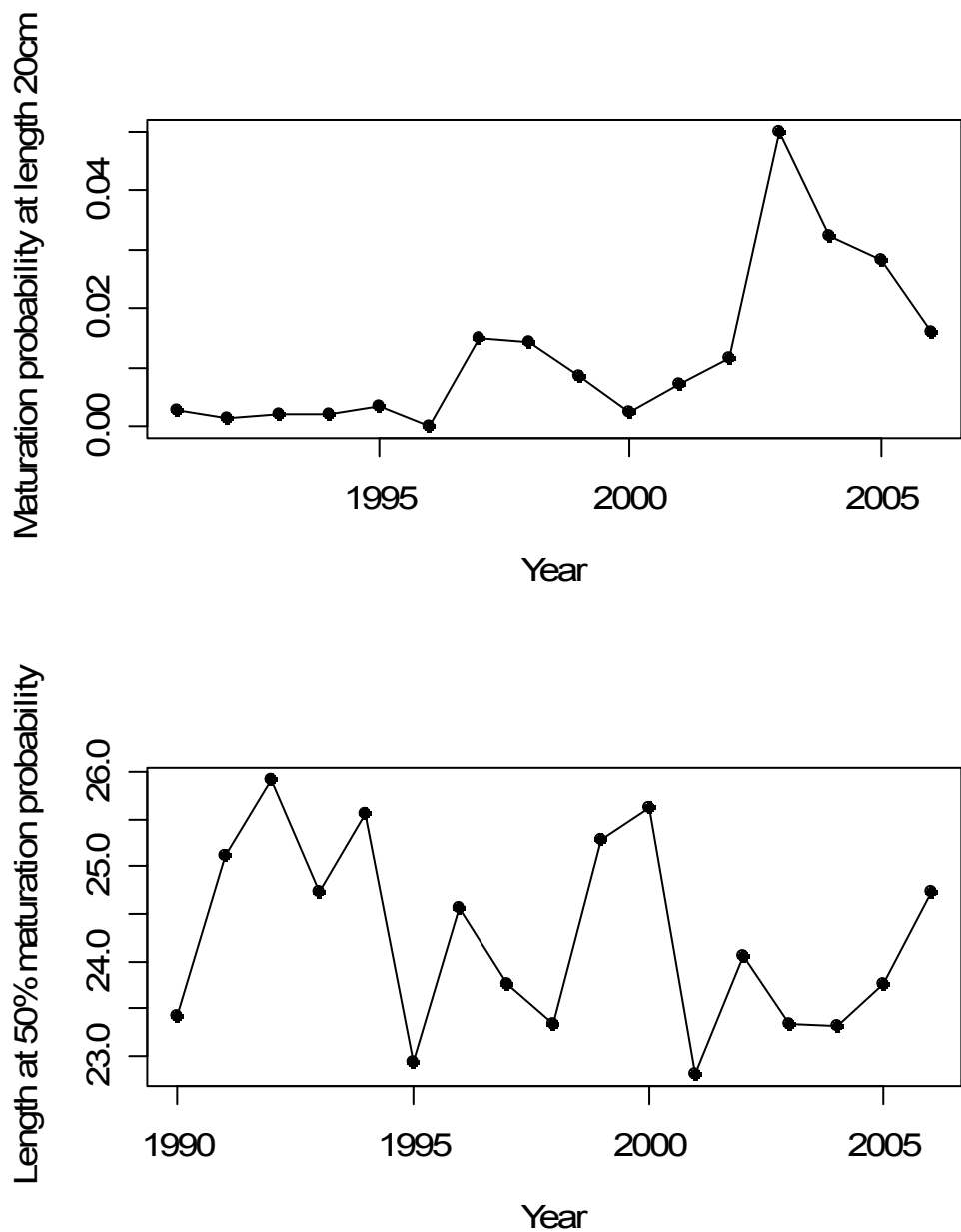
Figure 4. The probability of maturing (upper panel) for an average sized age 1 female North Sea herring (i.e., length 20 cm) and the length at 50% maturation probability (lower panel) for age 1 female North Sea herring.

Discussion

These preliminary results show some trends towards fisheries-induced changes in the maturation schedule of North Sea herring. Because the harvest of North Sea herring targets both mature and immature individuals, these kinds of changes can be expected in this stock (Law & Grey 1989, Heino 1998, Ernande *et al.* 2004). However, it is also possible that the changes could be due to changes in distribution maturity status varies in space (Fig. 2, see also Figure 2.3.1.4 in ICES 2007). A more extensive dataset, which we hopefully will be able to analyze in the near future, will give us a clearer picture about these possible changes.

Acknowledgements

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