Documentation to MARE’s fish Ecosim model

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Short version

The **fish model** was developed by Chris Harvey *et al.* (2003, corresponding author is Sture Hansson, sture.hansson@system.ecology.su.se), using the Ecopath with Ecosim software (http://www.ecopath.org). It is a food web model of the Baltic Sea proper, with 15 functional groups from phytoplankton to seals. The model was parameterized with the main focus on fish (sprat, herring and cod). The original model has been slightly modified by Olle Hjerne (olle.hjerne@system.ecology.su.se).

Reference:

Harvey, C J. Cox, S P. Essington, T E. Hansson, S. and Kitchell, J F. 2003. An ecosystem model of food web interactions and fisheries effects in the Baltic Sea. ICES Journal of Marine Science **60**:1-12

Long version

The fish model

There are substantial evidence that the nutrient status of aquatic environments influence the fish community structure, production and yields (Nixon 1982, Lee and Jones 1991), but it is also evident that the fish (and fisheries) can structure entire food webs (e.g. Carpenter *et al.* 2001, Carscadden *et al.* 2001) and even influence nutrient dynamics (Hjerne and Hansson 2002). To explore possible food web responses caused by fisheries and nutrient management in the Baltic Sea proper, we use a food web model with 15 functional groups (Tab 1 or see list in application). We use a model developed by Harvey *et al.* (2003), using the Ecopath with Ecosim software (http://www.ecopath.org, Walters *et al.* 2001), with some changes explained below. The model uses diet compositions to calculate a mass-balanced budget of production, consumption, fishing and biomass change for all functional groups in the **starting year (1974)**. The model dynamics during the **calibration period (1974-2000)** are driven by observed fishing patterns and recruitment processes including environmental forcing on cod recruitment. Predator-prey relationships are specified to maximize the fit of the modelled dynamics in the biomasses of juveniles and adults of sprat, herring and cod to ICES (International Council of Exploration of the Sea) assessments of stock sizes (ICES 2001a). This calibrated model is then used to predict the responses to predetermined and distinct fishing, nutrient and seal management scenarios and all possible combinations among them during the **simulation period (2001-2100)**.

Functional group	**Explanation**
Spring phytoplankton	Spring bloom algae, important food source for benthos
Other phytoplankton	Summer and autumn algae, main food source for mesozooplankton
Bacteria	Bacteria, except for cyanobacteria
Microzooplankton	Small pelagic invertebrates (pass a 90 μ mesh net)
Mesozooplankton	Medium sized pelagic invertebrates (retained by a 90 μ mesh net)
Mysids	Mysids (i.e. large pelagic invertebrates)
Meiofauna	Small benthic invertebrates (pass a 1 mm mesh sieve)
Macrofauna	Large benthic invertebrates (retained by a 1 mm mesh sieve)
Juvenile Sprat	Younger than 2 years
Juvenile Herring	Younger than 3 years
Juvenile Cod	Younger than 4 years
Adult Sprat	2 years and older
Adult Herring	3 years and older
Adult Cod	4 years and older
Seals	All seal species combined

Tab 1. List of the functional groups in the model.

Scenarios

Available fisheries scenarios were selected to cover a broad range of what we assumed to be realistic and/or relevant management options. In comparison, the scenarios for nutrient and seal management were selected to be distinctly different from the current situation (status quo), but yet not ecologically unrealistic. Even though some scenarios might be very hard or even impossible to reach, they can give important information about the direction of change. In general the simulation results should be viewed as mainly qualitative: Does one management action produce a result that is likely to be much stronger/weaker than another action or are the effects of the same magnitude and in the same direction?

Fisheries management

Six management scenarios for each individual fish species (sprat, herring and cod) are available, which makes the total number of fisheries management options 216 (6×6×6). In the **status quo** scenario the fishing intensity (fishing mortality) is kept at the average fishing intensity 1996-2000. This fishing intensity corresponded to an annual fishing mortality of about 25, 35 and 60% for adult sprat, herring and cod. In the **precautionary approach** we use the fishing intensity suggested by ICES (2001b) to be the highest sustainable fishing intensity. The precautionary fishing intensity is 18% higher than the status quo level for sprat, and 64 and 44% lower for herring and cod. In the **half precautionary approach** we use half the fishing intensity of the precautionary approach, which is 41%, 82% and 72% lower than the status quo level for sprat, herring and cod.

In addition, these three scenarios can each be combined with **no juvenile bycatches**, resulting in three more scenarios. No juvenile bycatches means that no fish younger than 2, 3 and 4 years, respectively, for sprat, herring and cod is caught.

Nutrient management

A strong reduction in nutrient load would, probably with some time lag, lead to reduced primary production. However, there is still a debate whether reduction of a) only phosphorus or b) phosphorus and nitrogen in combination, is the best/most efficient management option to counteract eutrophication. We ignore the management of phosphorus and nitrogen, and instead focus directly on the effect on the **primary production of spring and other phytoplankton,** independently of each other. In the **status quo** scenarios we do not deliberately change the primary production in relation to the calibration period (1974-2000), but the primary production and phytoplankton biomass might still be influenced by changes on higher trophic levels. The overall primary production in the early 1900's has been estimated to approximately 35% of its current level (Schneider & Kuss 2004, Wulff *et al.* 2005). In the **early 1900 level** scenario we therefore decrease the primary production (of spring and other phytoplankton respectively) to approximately 35% of the average primary production during the calibration period (1974-2000), but especially other phytoplankton production vary (31-44%) depending on fisheries and seal management scenario.

It is difficult to predict the effects of nutrient reductions on phytoplankton production. The spring bloom is mainly nitrogen limited, while cyanobacteria in the summer bloom are phosphorus limited (Granéli *et al.* 1990). Nitrogen leakage from these cyanobacteria may also indirectly stimulate other summer plankton. A decreased spring primary production could thus be interpreted as a result of reduced nitrogen load, while decreased production of other phytoplankton could be interpreted as a result from reduced phosphorus load.

Cod recruitment depends on the volume of water where cod eggs can survive (>2ml O_2/l, and >11 PSU, Vallin *et al.*1999). This **reproductive volume** (RV) is restricted to the deep basins and is negatively influenced by eutrophication due to increased oxygen consumption in the bottom water (Mackenzie *et al.* 1996). In the **status quo** scenario we use the average RV from the calibration period.

The average RV in the early 1900's (1900-1950, measured in 11 years) is 2.22 times larger than the average RV in the calibration period (1974-2000). Besides eutrophication and oxygen consumption, the RV also depends on occasional inflows of water with high salinity and oxygen content from the North Sea. However, since the average total volume of water with a salinity over 11 PSU (including water <2 ml O_2/l) was slightly smaller in 1900-1950 than during the calibration period, we think the difference in RV is rather caused by eutrophication and not by more and stronger inflows. In the **early 1900 level** scenario RV is therefore 2.22 times larger than in the status quo scenario. Spring phytoplankton sediment to a much higher degree than other phytoplankton (Elmgren 1978), and therefore bottom oxygen conditions and the cod reproductive volume should be more dependent on spring than on other phytoplankton. Consequently, the low primary production in the early 1900 level scenario for spring phytoplankton could preferably be used together with the more favourable cod reproduction conditions in the early 1900 level scenario for RV.

Seal management

Populations of piscivorous marine mammals were much larger (88 000-100 000 grey seals, 190 000-220 000 ringed seals, 2000 harbour seals and 10 000-15 000 harbour porpoises, Elmgren 1989, Harding and Härkönen 1999) in the early 1900's than today. Since the 1970's the grey seal population has had a positive development while the other populations are still very low, and in the model we focus on grey seals. Based on the Swedish annual counting program, the annual grey seal population increase has been estimated to 7.5% between 1990 and 2004 (Karlsson and Helander 2005) and the population size in year 2000 was approximately 16 000 individuals (Hiby *et al.* 2005). The model start with 1440 individuals in 1974 and with the annual population increase of 7.5% during the entire calibration period, we get 9440 animals in year 2000 for the Baltic proper. This is slightly more than half the population size for the entire Baltic Sea and we consider this a realistic estimate. Consequently we assume that that the number of grey seals in the Baltic proper (including the Åland Sea and the Gulf of Finland) is somewhat larger than the population in the Gulf of Bothnia. In the **status quo** scenario the population size in year 2000 is kept constant at 9440 grey seals during the simulation period. In the **early 1900 level** scenario, the annual population increase of 7.5% continues until the population reaches 100 000 individuals in year 2033, and after that it is kept constant at this high level. This is an overestimation of the Baltic proper grey seal population around 1900 (see above), but probably reflects the overall predation pressure from marine mammals, including harbour porpoises, ringed and harbour seals quite well.

Management implementation period (year 2000-2033)

Fisheries management measures are in theory possible to implement immediately, but in reality this is often difficult. Extensive reductions in primary production will most likely take much longer times to achieve, especially considering the time lag between the nutrient reduction and the response in nutrient levels and primary production in the marine environment. In the simulations, however, we have not considered differences in implementation time, but to avoid model instability the fishing mortality and primary production where changed linearly between year 2000 and 2033 (the same period in which the seal population increases in the early 1900 level scenario).

Simulation results

Warnings

It is important to note that a model, like this one, that tries to catch the dynamics of such a large and complex system as the Baltic Sea food-web, by necessity has to rely on many implicit and explicit assumptions (see the model description in Harvey *et al.* 2003). Even though we, based on our ecological experience, think the assumptions are reasonable, we still consider the simulation results as possible responses rather than the truth.

By presenting the results as 3456 scenarios, it is not possible to analyse questions like "If we reduce the primary production by 50%, what will that mean to the cod catches compared to a 65% reduction in primary production (to the level of the early 1900)?". The reason that we intentionally removed the flexibility to address this kind of detailed questions is that the answers would give the user a false impression of our understanding of the Baltic Sea ecosystem – we are simply not able to provide reliable quantitative answers on that type of question. This is particularly true as we have to simulate beyond the limits of empirical data (e.g. strong reductions in fishing intensity, primary production or substantial seal population increases).

As already stressed, we hope it will be natural for every user to look upon the results as qualitative rather than quantitative. Nevertheless, the results can be useful to show the potential importance of fisheries relative to nutrient and seal management respectively, and hopefully give information of which processes we lack knowledge and need further investigations about.

Regulation of fish species and potential model problems

Cod can be controlled/influenced mainly by the fishery and changes in primary production, but also by seal predation. The cod population seems relatively productive in the model, which could at least partly be explained by the low natural mortality and the very high food conversion efficiency for adult cod (>0.5, discussed in Harvey et al. 2003). Consequently cod can sustain high fishing pressure, even at relatively low food availability (sprat, herring and macrofauna). The herring population, on the other hand, is relatively unproductive in the model, and is therefore vulnerable even to moderate fishing pressure and increased seal predation, especially at low primary production. Possible explanations could be the low food conversion efficiency (<0.05), and the population decline during the entire calibration period, resulting in high natural mortality for adult herring (0.75). The sprat population could also be influenced by the fishery, the primary production level and seal predation, but is often strongly controlled by cod predation.

Comments and interpretations of specific model results

The model predicts strong effects by **fisheries management**. As an example the status quo scenarios of fisheries, nutrient and seal management, result in a low cod biomass, high sprat biomass, while the herring population collapses. On the other hand, the same nutrient and seal management combined with the precautionary fisheries management results in very high cod and herring biomasses, while sprat collapses mainly because of increased cod predation. The no juvenile bycatch option has largest effect at high fishing pressure (at least for cod) and might therefore be a useful measure if fishing pressure cannot be kept low by other measures.

Generally decreased PP to early 1900-level decrease fish production, biomass and yield strongly, and the effect is larger if production of other phytoplankton decreases compared to decreased spring phytoplankton production. This might indicate that decreased phosphorus load influence fish production more than decreased nitrogen load. **Increased seal** population size to early 1900-level has a smaller, but especially at high fishing pressure, clear effect on fish biomass and yield.

In combination **decreased PP** and **increased seal population** has an even larger effect on fish biomass. In fact, fisheries management that are sustainable (no population collapse and reasonably large catches) at status quo nutrient and seal management levels, are often unsustainable under oligotrophication and/or seal population increase. Clearly, new fisheries management reference points based on lower fishing intensities seems necessary if we succeed to reverse eutrophication and/or increase the seal population significantly in the Baltic Sea. The results commented above are only a few examples of management scenarios, and there are many more management combinations to explore. Comments on the model and model results are appreciated and can be sent to us (olle@ecology.su.se).

Despite the strong negative effects obtained on fish biomass by decreased primary production, it is possible that the negative effect of oligotrophication is underestimated. In the model simulations the detritus pool is assumed constant, but might in reality be dependent mainly on (spring) primary production. This would effect the production of detrivores (bacteria, meiofauna) negatively and that could cascade up the food-web and eventually influence fish biomass and yield negatively.

Changes to the model

A complete description of the model is found in Harvey *et al.* (2003), but some modifications were done for the scenarios presented here. These changes are described below, but can be difficult to fully understand without reading the original paper by Harvey *et al.* (2003):

1) To keep individual seal consumption more or less constant and seals non-food limited even at larger biomasses, we (a) made all seal prey strongly top-down controlled by changing the vulnerabilities from 2 to 1000 (0.3 to 1.0 in old EwE software scaling), (b) changed the maximum relative feeding time from 2 to 100, and (c) the feeding time adjust rate from 0 to 1.

2) To avoid top-down control by benthic macrofauna on the spring bloom, the macrofauna to spring phytoplankton vulnerability was changed from 2 (0.3 in old scaling) to 1.0001 (0).

3) Macrofauna production is known to depend strongly on the spring bloom (Elmgren 1978). Therefore we changed the diet composition so that detritus was replaced by spring phytoplankton, since detritus biomass in this model is constant and not influenced by primary production.

4) Harvey *et al.* (2003) used two alternative forcing functions on cod recruitment: (a) the anomaly function which was the annual multiplier on cod egg production that maximized the model fit, and (b) a multiplier based on the relative reproductive volume (RV), defined as the volume of water in the main spawning area (the Bornhom basin) with necessary abiotic conditions, in terms of salinity, oxygen and temperature, for egg survival (MacKenzie *et al.* 2000). We use the RV multiplier in all simulations.

5) We assumed the same number of seals (1440 individuals) in year 1974 as in Harvey *et al.* (2003), but since we used an average individual weight of 100 kg instead of 150 kg, the seal biomass was reduced by 1/3. We then forced the seal biomass to increase with 7.5% annually (Karlsson and Helander 2005), which gave nearly 10000 individuals in year 2000. This is around half the number of grey seals estimated for the entire Baltic Sea for year 2000 (Hiby *et al.* 2005).

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