Master Degree Project

UNIVERSITY OF SKÖVDE

Simultaneous MSY management of a predator and prey species,
the Cod (Gadus morhua) and Herring (*Clupea harengus*) in the Baltic Sea

Master Degree Project in Systems Biology
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Sammanfattning

Europeiska kommissionen förvaltar fiskbestånden genom att tillämpa fiskekvoter baserat på konceptet maximalt hållbart uttag. Hittills har de flesta maximalt hållbara fiske-fångst modeller för Östersjön fokuserat på en art i taget. De få befintliga fler-arts-modeller har antagit att en arts mognad och tillväxt är beroende av tillgången på föda. Vår två-arts-modell gör det möjligt att undersöka om det finns en konflikt mellan maximal hållbar fiske-fångst på torsk och sill i Östersjön. Denna två-arts-modell med torsk som ett rovdjur och sill som byte, tar hänsyn till miljön som drivkraft på deras rekrytering. I torskmodellen ingick reproduktiv volym tillsammans med årlig tillväxt (ett års specifika effekt på tillväxten beroende av externa variabler som tillgången till föda) och predation av gråsäl. Sill-modellen var beroende av årlig tillväxt och lekbeståndets biomassa hos torsk. Resultaten visar att den viktigaste faktorn som påverkar maximalt hållbart uttag för torsk är reproduktiv volym. Lekbeståndets biomassa vid maximalt hållbart uttag är mer känsligt för förändringar i reproduktiv volym än årlig tillväxt. När predation från säl tillsätts och höga gynnsamma miljöfaktorer råder är lekbeståndets biomassa 50 % jämfört med lekbeståndets biomassa vid höga gynnsamma miljöeffekter utan säl predation. Fyra simuleringar gav hög lekbestånds biomassa för torsk vilket var förödande för sillpopulationen som utrotades pga. högt predationstryck. Sillens maximala hållbara uttag beror på mängden lekbestånds biomassa hos torsk, d.v.s. effekten av hög eller låg reproduktiv volym. Två analyser gjordes på nuvarande miljömässiga nivåer för båda arterna. Den första analysen hade en naturlig dödlighet på 0,2 för torsk, vilket gav en fiske-mortalitet på 0,20 och maximalt hållbart uttag på 410 000 ton. Sillen hade en fiske-mortalitet på 0,03 och maximalt hållbart uttag på 11 000 ton. I den andra simuleringen ingår sälpredation på torsk vilket minskade torskens maximala hållbara uttag med 98 % vid en fiske-mortalitet på 0,02, vilket gav en fiske-mortalitet på 0,19 och maximalt hållbart uttag på 275 000 ton för sill. Detta ger en ökning av maximalt hållbart uttag för sill 25 gånger jämfört med resultatet utan predation på torsk. Torskens populationsdynamik är sårbar för miljöförändringar och för att säkra ett sunt och produktivt torskbestånd bör fiskemortaliteten hållas i fas med nuvarande reproduktiva volym.

Abstract

The European Commission manages fish stocks by applying a fishing mortality based on the maximum sustainable yield concept. So far most Baltic Sea fishing maximum sustainable yield models have focused on one species at a time. The few existing multi-species models have assumed that a species' maturity and growth is dependent on the availability of food. Our two-species models make it possible to investigate if there is a conflict between fishing maximum sustainable yield for cod and herring in the Baltic Sea. This two-species model of cod, as a predator and herring as prey, takes into account environmental drivers on cod and herring recruitment. Reproductive volume together with year-growth, (a year specific effect on growth of external variables like food availability) and predation by grey seals was included in the cod model. The herring model was dependent on cod spawning stock biomass and year-growth. The result shows that the reproductive volume is the main factor that affects the maximum sustainable yield for cod. The spawning stock biomass at maximum sustainable yield is more sensitive to reproductive volume than year-growth. When predation from seals is added in mortality and high environmental factors occurs the spawning stock biomass would be 50% compared to the spawning stock biomass at high environmental effects without seal predation. Four simulations of high cod spawning stock biomass were devastating for the herring population that was eradicated with high predation pressure. The herring maximum sustainable yield depends on the amount of cod spawning stack biomass i.e. the effect of high or low reproductive volume. Two analyses were made on a current environmental state for both species. The first analysis had a natural mortality of 0.2 for cod, which gave an fishing mortality of 0.20 and maximum sustainable yield of 410 000 tons. The herring had a fishing mortality of 0.03 and maximum sustainable yield of 11 000 tons. The second simulation included seal predation in cod mortality which decreased the cod maximum sustainable yield by 98% at a fishing mortality of 0.02, which gave a fishing mortality of 0.19 and maximum sustainable yield of 275 000 tons for herring. This gives a 25 times increase of herring maximum sustainable yield compared to the result without predation on cod. The cod population dynamics is vulnerable to environmental changes and to secure a healthy and productive cod population the target fishing mortality should be kept in phase with current reproductive volume.

Table of Contents

1. Introduction

There have been large changes in the Baltic Sea ecosystem, where the Baltic Sea has undergone a possibly irreversible ecosystem regime shift in the late 1980s/early 1990s (Möllmann et.al 2008). This regime shift has reduced the production of fish for human consumption and fodder as the service of an impaired ecosystem of the Baltic Sea gives a low return (Óskarsson and Taggart 2006). Cod, herring and sprat dominate the Baltic Sea fish community and are the most essential species for the fishing industry (Gislason 1999). These species interact ecologically with cod as a predator on the Clupeids (sprat and herring), and food competition between the Clupeids (Köster & Möllman 2000). From the mid 1980s to early 1990s there was a decline for all stocks in Baltic Sea mostly because of overfishing (Swain & Mohn 2012). During the same period the Baltic Sea Herring average weight-at-age (WAA) was halved and only partly recovered to this day (ICES 2010). This depends on the availability of food caused by the decrease of abundance of the most important prey species, the copepods *Pseudocalanus elongates and Pseudocalanus acuspes*, who is important during the main herring growth period in spring and summer (Möllmann et.al 2008). The fecundity of the *Pseudocalanus sp*. was suggested to be dependent on high deep-water salinity in the Baltic Sea. Holmgren et.al (2011) suggests that the Herring growth is affected both by the salinity-induced decline in food availability and increased competition with sprat. According to Holmgren et.al (2011) there are several studies that suggest that a bottom-up control of herring body growth have great influence on the Herring population.

Despite the reduction in fishing pressure in the latest 20 years, the recovery of most of the cod stock could not be seen until recently (Swain & Mohn 2012). Several studies have investigated effects of other species interactions with Baltic Sea cod, only to find the biological cause of the non-recovery of the cod stock without any strong correlation (Swain & Mohn 2012, Köster & Möllman 2000, Köster and Schnack1994). As a more convincing explanation Heikinheimo 2008 and Swain & Mohn 2012 suggests that the recruitment of cod is more dependent on the salinity and suggests that feature multispecies models should include this finding. The reproductive success of cod in the Baltic Sea is connected to hydrographic events in the spawning territories (Heikinheimo 2008). The Atlantic cod lives in the Baltic at the border of its saline capacity where successful reproduction only occurs in the deepest basins of the Baltic Sea where the salinity is high enough, varying between 11 and 20 psu: the Bornholm basin, the Gdansk deep and the Gotland basin (Vallin & Nissling 2000, MacKenzie et.al 2000, Köster et.al 2005 and Heikinheimo 2008). The volume of water with adequate salinity (≥ 11 psu) and oxygen content (> 2ml O_2 l^{-1}) is known as the "reproductive volume" (RV), an index for the environmental effect on the development for cod eggs, combining the two important factors, salinity and oxygen content. (Vallin & Nissling 2000, MacKenzie et.al 2000 and Heikinheimo 2008).

1.1 Management of the Baltic Sea Herring and Cod

The International Council for the Exploration of the Sea (ICES) gives scientific advices of the management and the amount of herring and cod that should be harvested in the Baltic Sea. By the request of the European Commission the ICES shall apply a fishing mortality based on the maximum sustainable yield concept (MSY). The MSY of a population is related to the maximum rate of population increase that occurs at a midpoint of the curve of logistic growth where the growth rate is highest (Stiling 2002). The effect of this makes a surplus of individuals that can be harvested and known as the fishing mortality that produces the maximum sustainable yield (F_{MSY}) (Larkin 1977). The reference point $B_{trigger}$ can be obtained from the low percentile on observed spawning stock biomass (SSB) range in F_{MSY} analysis. ICES use the MSY $B_{trigger}$ as a biomass reference point that triggers a cautious response (ICES 2012).

Accounting for multiple ecological and physical factors operating at different scales of space and time, is required in order to promote sustainable exploitation of small pelagic fish (Lindegren et.al 2011). So far most Baltic Sea F_{MSY} models have been focusing on one species at a time and the multi-species models such as in the work of Gislason (1999) is calculated by the concept that the species' maturity and growth is dependent on the availability of food. The aim with this work is to develop a two-species F_{MSY} model and perform a mutual response analysis between cod and herring in the Baltic Sea in order to obtain a more carefully examine result of how different F_{MSY} on one species affects the other. Like previous models this one is also using the access to food as a factor of growth but takes also into account environmental factors for cod and herring recruitment. A two-species model makes it possible to investigate if there is a conflict between F_{MSY}´s for cod and herring in the Baltic Sea. A multi-species F_{MSY} model with maximization of yield regardless of species composition, could lead to predators being fished down to the lowest biomass possible in order to promote larger productive capacity of their prey (Gislason 1999).

2. Methods

2.1 The model framework

This two-species MSY model is divided into two model compartments (one herring- and one cod part) that are simulated separately. The two-species model is built by the assumptions that the cod stock is negatively affected by fishing and predation from seal. Environmental effects (RV) and predation on herring (fig 1) works as input to cod. The herring stock is negative affected by fishing and predation by cod and is positive affected by foraging on zooplankton. The herring and cod models has two variables: average weight-at-age (WAA) and numbers at-age (NAA) where each contains 8 values NAA and WAA of each age class 1 to 8+, in which 1 = 1 year olds and 8+ = a merged age class of 8 year olds and older (cod starts with age class 2). The dynamics in the models was set by four stochastic functions (i) a recruitment function, (ii) a growth function, (iii) a mortality function and (iv) a function determining the weight of the recruits.

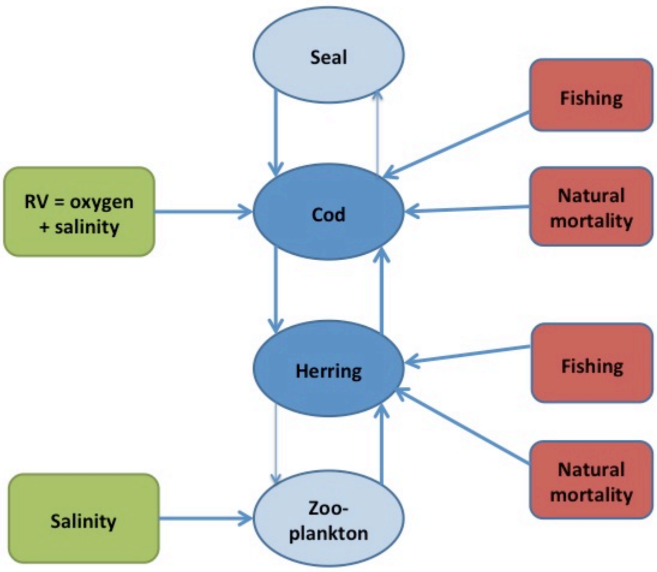


Figure 1. Model overview with the assumptions of the dynamics for cod and herring. The green boxes represent environmental effects and the red boxes represent mortality. Cod is negatively affected by natural mortality, fishing and predation by seal. The positive input to cod is represented by the amount of RV and herring as a food source. Herring is negatively affected by natural mortality, fishing and predation by cod. The positive input to herring is represented by zooplankton as a food source. Zooplankton is positively affected on the amount of salinity.

Holmgren et.al (2011) built an operative model of the herring stock of the Baltic Sea with purpose to be used for MSY analyses. Their model is used here for the F_{MSY} analyses on herring. In this work an age-structured stock model was created for cod with the model in Holmgren et.al (2011) as a starting point. When constructing the model, special attention was paid to negative feedbacks on total biomass, which is a requirement for the yield function to peak. Surplus production implies negative density dependence in recruitment or survival, and yield-per-recruit analysis captures a reduced growth rate with increasing biomass (Jennings et.al 2001). It is important to quantify negative feedback, because they have a direct effect on the estimate of the yield that can be harvested sustainably (Holmgren et.al 2011). These effects, from negative feedback were estimated when building the cod and herring parameter functions. The influence of environmental effects such as predators and salinity was also investigated for negative influences. The cod model is built with the corresponding four stochastic functions as in Holmgren et.al (2011) with differences in some model parameters and their values: recruitment (eqn 2), growth (eqn 4) and updating number of the recruits.

2.2 Data

ICES data and outputs from stock assessments (ICES 2012) were used for parameter estimations for yearly changes in the model functions. WAA herring data from 1974-2011, and weight in stock cod data from 1966-2011 was used from the Baltic Sea main basin (subdivisions 25-27, 28.2, 29 and 32; ICES, 2011). The cod weight data set contains unchanged weights between the years of 1966-1993 for 2 and 3 year olds, and from 1966 to 1982 for 4-7 year olds. Information of NAA, SSB and amount of maturity per age class came from extended survivor analyses (XSA; ICES 2012). General Linear Models using the programing language R (R Development core team 2008) and STATISTICA (StatSoft Inc.) were used to perform the statistical estimations of population parameters. The confidence intervals of the parameter estimations were derived from the sums of squares in the ANOVA tables. All RV data is derived from table A2 Bornholm basin in MacKenzie et.al (2000) where the data is Kiel estimates from 1952-1996. During 1993, 1995 and 1996 there were no August estimates so for this analysis values for July was used instead. Salinity data from 1997-2007 station BY5, Bornholm basin is retrieved from Swedish national marine archive at the Swedish metrological and hydrological institute.

2.3 Recruitment

The ICES data over cod contains 7 age classes where the recruits are represented by 2-year olds. The recruits per SSB (R/SSB) were calculated with a two-year offset in the linear regression. The Herring per SSB unit reproduction is assumed to depend on spawning stock biomass (SSB; eqn 1). This means that the number of recruits (R) is a quadratic function of SSB. Density-independent reproduction, b (number of recruits y + 1) is added to SSB times its change rate, d. As for cod an equivalent quadratic function is used with the addition of RV and its change rate, d_2. The SSB is multiplied with its change rate d_1 (eqn 2). The error term ε_y is the unexplained variation over year.

Herring $\frac{R_1^{y+1}}{SSB_y} = b + d\, SSB_y + \varepsilon_y$ (Holmgren et.al 2011) (eqn 1)

Cod $\frac{R_2^{y+2}}{SSB_y} = d_2 RV + d_1\, SSB_y + \varepsilon_y$ (eqn 2)

2.4 Growth

A Von Bertalanffy growth model was fitted to data where the fish grow asymptotically to its final weight. There was no relation of density dependence on growth in the ICES data. A year-growth parameter is included in the model to account for year specific effect on growth for example due to variation in food availability. Year-growth is obtained from multiple linear regression (GLM mixed model) of weight increments G_{ya} (the difference in WAA from age a at year y to a+1 at y+1) against age specific growth, k_a, year-specific growth, k_y, the biomass (BM) estimated by the negative parameter, *l.* The error term ε_{ya} is the unexplained variation over year and age (eqn 4).

Herring $G_{ya} = c + k_y + l * BM + \varepsilon_{ya}$ (Holmgren et.al 2011) (eqn 3)

Cod $G_{ya} = c + k_y + k_a + l * BM + \varepsilon_{ya}$ (eqn 4)

Growth in the herring population is also a Von Bertalanffy model. The parameter *c* is the constant intercept for all age classes (eqn 3).

2.5 Natural mortality

Natural mortalities (m_a eqn 5) for all cod age classes were taken from ICES (2012) that is constant of 0.2 for all ages. To take account for seal predation on cod a combined natural mortality with seal predation was used. A Canadian study estimated a natural mortality including seal predation in year 2000 to 0.5 (Chouinard et.al 2005). In the simulation with seal predation the natural mortality was increased to 0.5 on all cod age classes. Natural mortality on Herring takes into account the impact of age-specific predation by cod (C_y). For cod the C_y is set to zero when calculating natural mortality. The constant m_a is derived from estimations by Holmgren et.al (2011) based on ICES (2009a) (appendix 1) including variation of mortality between years (ε_y) and statistically estimated by the equation:

$M_a = m_a + v_a C_y + \varepsilon_y$ (Holmgren et.al 2011) (eqn 5)

2.6 Weight of recruits

For both herring and cod the weight of recruits is positively correlated with parental weight. The average weight of the recruits ($\overline{w}_1$) is included in the model as a linear relationship with their parents average weight ($\overline{w}_{p,a}$). Equation 6 computes the recruitments average weight each year and statistically estimates the parameters *k* (the rate of change and *m* (the intercept).

$\overline{w}_1 = k\, \overline{w}_{p,a} + m$ (Holmgren et.al 2011) (eqn 6)

The average weight of all recruits depends on the relative proportion on numbers at age and the average WAA of the female parents:

$$\overline{w}_r = \frac{\Sigma w_{1,a}}{\Sigma N_{1,a}} = \frac{\Sigma w_{1,a}(k\,\overline{w}_{p,a}+m}{\Sigma N_{1,a}} \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 7)}$$

where $N_{1,a}$ is the number of herring1-year olds with parents of age *a.* As there was no ICES data over cod 1-year olds, the recruitment weight is calculated for 2-year olds i.e. all "1" is changed to "2" in equation 7. The equation of the weight of the recruits (eqn 7) is combined with the linear relationship (eqn 6):

$$\overline{w}_{y+1,a=1} = m + k\,\frac{\Sigma_{a>1}(\,N_{1,a}\overline{w}_{y,a})}{\Sigma_{a>1}N_{1,a}} + \varepsilon_y \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 8)}$$

where *m* is the intercept of the regression (eqn 6) and the ratio of sums is the average weight of the female parent (Σ_a).

2.7 Updating functions

2.7.1 Updating population numbers

The number of surviving fish (*N*) in age class a to year y+1 is calculated flowingly:

$$N_{a+1}^{y+1} = N_a^y e^{-Z_a^y} \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 9)}$$

$$Z_a^y = M_a^y + F_a^y \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 10)}$$

where the total mortality (*Z*) is the sum of M_a^y, natural mortality and F_a^y, the fishing mortality. Baranov`s catch equation is used for calculating the fishing yield (γ_a):

$$\gamma_a^y = N_a^y \frac{F_a^y}{F_a^y+M_a^y}\left(1 - e^{F_a^y+M_a^y}\right) \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 11)}$$

2.7.2 Updating weight

The average weight of fishes in age class a, $\overline{w}_a$, a= 2 to7, is updated with following equation with the growth parameter G_a^y from equation 3 and 4:

$$\overline{w}_{a+1}^{y+1} = \overline{w}_a^y + G_a^y \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 12)}$$

The recruits are updated using equation 8, with random error added. Updating the average weight of age-class 8+ (eqn 13) is different, since they contain the accumulating group of fish that is 8 years old and older. The 8+ average weight is calculated by measuring the average weight decrease from previous years 7-year olds against the average weight increase from the surviving fish that are more than 8-years old. The weight parameter $\overline{w}_7^y$ is calculated by equation 8.

$$\overline{w}_{8+}^{y+1} = \frac{(\overline{w}_{8+}^y + G_{8+}^y\,)N_{8+}^y e^{-Z_{8+}^y} + (\overline{w}_7^y + G_7^y\,)N_7^y e^{-Z_7^y}}{N_{8+}^y e^{-Z_{8+}^y} + N_7^y e^{-Z_7^y}} \quad \text{(Holmgren et.al 2011)} \quad \text{(eqn 13)}$$

2.7.3 Updating number of recruits

Recruitment is founded on the SSB (see Recruitment) where maturity increases with age appendix 1 herring and appendix 2 cod). As in mortality and growth, a random error is added in the simulations. The population updates represents the state of 1 January. The herring reproduction occurs in spring (ICES 2012) and therefore is SSB calculated by removing herring by partial (= 0.3) in natural mortality and fishing mortality before reproduction. The SSB in the first three months is not generating any recruits. WAA increases by partial linear growth (=0.3) before reproduction:

$$SSB_a^y = \left(\overline{w}_a^y + 0.3G_a^y\right)N_a^y e^{-0.3Z_a^y} \quad \text{(Holmgren et.al 2011)} \qquad \text{(eqn 14)}$$

The cod reproduction occurs in winter (December) (ICES 2012) and time before reproduction is set to zero.

2.8 Environmental effects

Two environmental effects affect the cod population model: RV (eqn 2) and the year effect on body growth, “year-growth” (k_y eqn 4). The year-growth parameter represents the food availability where the highest and lowest values from GLM year-growth analysis (2.4 and 1.76) were used (appendix 3). To analyze the cod population at different RVs the highest and lowest RV values (222 and 47) from table A2 in Mackenzie et.al (2000) were used. The stochastic variance of the environmental parameters were not estimated and hence not included in the model. The herring stock model has also two environmental variables: the cod SSB and year-growth (high 0.0095 and low -0.0004) (k_y eqn 3, appendix 1). The herring year-growth represents the combined effects of salinity and competition with sprat (Holmgren et.al 2011).

2.9 Obtaining FMSY

To analyze the productivity of the herring and cod populations Monte Carlo simulations of the populations where performed, with values of the environmental parameters given above. Fishing simulations with constant *F* over a period of 200 years for cod and 40.000 years for herring with the intention to offsetting long lasting effects of stochastic disturbances and register the average yield and its standard deviation (SD). The simulations are repeated with *F* rising from a minimum value to a maximum in steps of 0.01 for both species to evaluate what rate of F gives the MSY for the population.

2.10 Simulations

To assess the future effects of fishing on the herring and cod populations several different simulations was produced on the basis on the limiting environmental values, RV, year-growth and predation of seal for cod and year-growth and cod SSB for herring. There were seven different simulations for cod (table 1). There were four combinations of high and low RV with high and low year-growth; one scenario of current environmental values (RV=90km^3 and year-growth=2.3) and two scenarios including seal predation (a current state and a state with high RV and high year-growth).

For the herring simulations there were ten different scenarios (table 1). Eight combinations of the cod SSB result from the first four cod simulations (RV and year-growth) combined with high and low year-growth for herring. Two simulations of a current state for both herring (year-growth 0.002 in 2006 Holmgren et.al 2011) and cod (RV 90 and year-growth 0.2) where seal predation is included in one of them (natural mortality on cod 0.5). The populations’ variables WAA and NAA start with ICES estimates of the 2011 stock values.

For each simulation *F* was adjusted with changes in year-growth, RV, seal predation or cod SSB to achieve MSY.

3. Results

3.1 Estimations of recruitment, weight and growth

The environmental factor with most influence on the production of cod recruits is RV. The amount of R/SSB follows the size of RV with a few years delay (fig 2). The linear regression analysis shows a positive effect of RV on R/SSB (d_2 = 0.00802 (eqn 2); F-statistics$_{1.27}$= 13.2, p<0.001). d_2 multiplied with mean RV gives 1.04 recruits per kg SSB. In cod, we estimated the density dependence of recruitment per SSB with cod SSB (d_1= -2.04e-07 (eqn 2); F-statistics$_{11.27}$ =0.06, p= 0.68). The test was not significant but the parameter values were used anyway in the absence of other significant values. The number of recruits per SSB decreased with 6.6% at average SSB due to density dependent effects. There was no significant effect from clupeid SSB to number of cod recruits/SSB (F-statistics$_{11.20}$= 4.12, p=0.056). The cod population structure in the latest decades can be declared by the variation in RV. Cod SSB peaked in the early 1980s shortly after the peak in R/SSB dependent on high levels of RV (fig 2) in late 1970s. Clupeid SSB decreased substantially in the 1970s but made a small increase in the 1990s. The clupeid increase occurred when the cod SSB reached is lowest point i.e. there was a low predation from cod. Cod R/SSB would be low if high clupeid SSB has a negative impact on cod recruitment through predation and competition. Here the opposite is shown were high cod R/SSB occurs in the same time as high clupeid SSB (fig. 3).

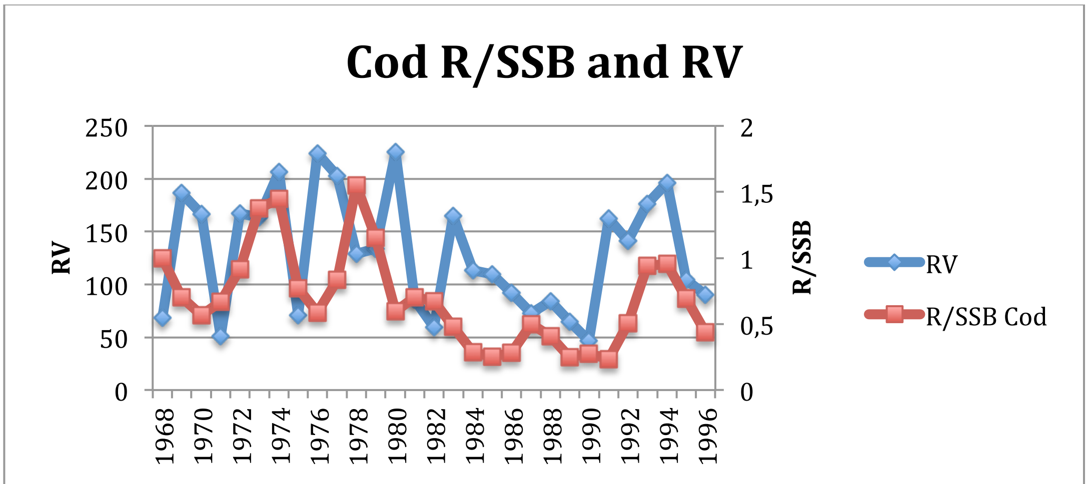


Figure 2. Plot of RV (blue diamonds) and R/SSB (red quadrats). R/SSB is given for the year SSB. The changes in R/SSB follow the changes of RV with a few years delay.

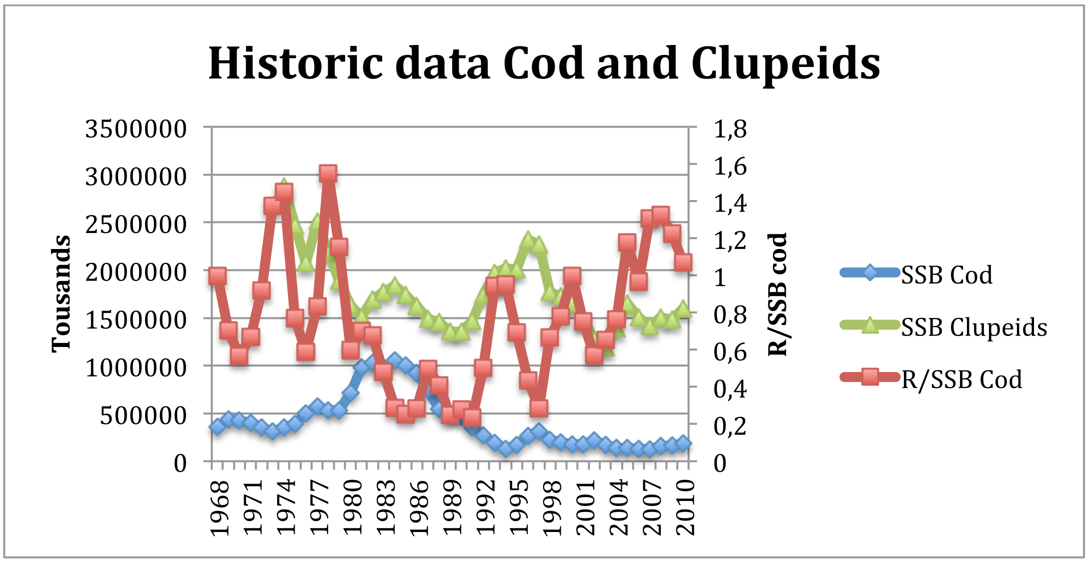


Figure 3. Plot of the relationships between Clupeids SSB (green triangles), Cod SSB (blue diamonds) and Cod R/SSB (red quadrats). R/SSB is given for the year SSB. The changes in Cod SSB and R/SSB are independent from the changes in Clupeid SSB.

For cod weight, the estimated positive relationship between weight of the cod recruits (two year olds) and the parental weight was used in the model. (F-statistics$_{11.16}$= 3.33, p= 0.087). The test was not significant but the parameter values were used anyway in the absence of other significant values.

When estimating growth there was significant effects of age (F-statistics$_{11.5}$= 19.3, p<0.001), year (F-statistics$_{11.43}$= 2.95, p<0.001) and weight (F-statistics$_{11.1}$= 8.67, p=0.003) (GLM mixed model eqn 4). The yearly body growth decreases with body weight where the amount of growth is affected differently from one age class to another. The year-growth parameter has first declined in the early 2000s that in the last years increased again (appendix 3). Clupeid SSB contributes to cod year-growth (F-statistics$_{11.35}$= 9.81, p=0.003).

3.2 MSY analyses

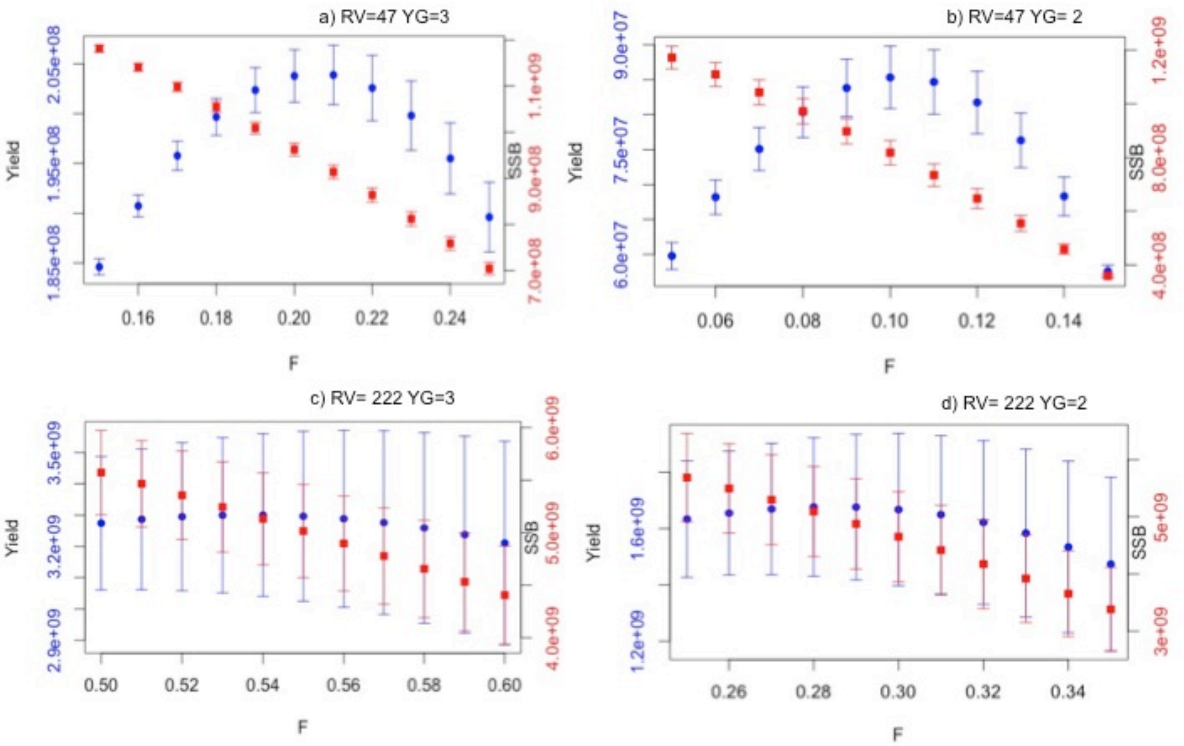
Table 1. Cod simulation output with different combinations of the variables: reproductive volume (RV km^3), year-growth (YG) and natural mortality (M). The result is shown in maximum sustainable yield (MSY tons), fishing mortality (F), B trigger and spawning stock biomass in thousands (SSB). The second half shows the herring simulation output with different combinations of the variables: cod spawning stock biomass in thousands (SSB) year-growth (YG). A total MSY for both species is presented for the combined simulations (H+C tot. MSY).

			Cod				H + C
RV	**YG**	**MSY**	**F**	**B trigger**	**SSB**	**M**	**Tot. MSY**
47	2	85 000	0.10	770 000	800 000	0.2	
47	3	204 000	0.21	900 000	910 000	0.2	
222	2	1700 000	0.29	4000 000	4900 000	0.2	
222	3	3300 000	0.55	4100 000	5000 000	0.2	
222	3	1610 000	0.34	3400 000	3900 000	0.5	
90	2.3	410 000	0.20	1640 000	1800 000	0.2	
90	2.3	7 000	0.02	250 000	300 000	0.5	
			Herring				
Cod SSB	**YG**	**MSY**	**F**	**B trigger**	**SSB**		
800 000	0.0095	325 000	0.21	880 000	1100 000		410 000
800 000	-0.0004	110 000	0.10	700 000	800 000		195 000
910 000	0.0095	290 000	0.18	970 000	1200 000		494 000

910 000	-0.0004	90 000	0.09	580 000	800 000		294 000
300 000	0.0020	275 000	0.19	760 000	1100 000		282 500
1800 000	0.0020	11 000	0.03	180 000	280 000		421 000
4900 000	0.0095	0	0	0	0		
4900 000	-0.0004	0	0	0	0		
5000 000	0.0095	0	0	0	0		
5000 000	-0.0004	0	0	0	0		

3.2.1 Cod

The main factor that affects the MSY for cod is RV. The MSY at high RV is 16 times higher than in low RV at high year-growth (table 1, figure 4a and c). In low year-growth the MSY at high RV is 20 times higher than in low RV (table 1, figure 4b and d). Year-growth also affects cod population and target F. Comparing high year-growth (3) with low (2) at the same low RV (47 km^3) the MSY would be 2.4 times larger (fig 4a and b). The SSB at MSY is more sensitive to RV than year-growth. With RV at its historical highest level (222 km^3) and high year-growth (3) the SSB would be 7.17 times larger compared to its historical maximum (697 000 tons; ICES 2012) at an F of 0.55 (table 1 and figure 4c). If year-growth decreases to the low value with the same high RV the SSB would increase 7 times from its historical maximum at an F of 0.29 (table 1 and figure 3d). When predation from seals is added in mortality (m_a =0.5) and high environmental factors occurs the SSB would be 78% compared to the SSB at high environmental effects without seal predation (natural mortality, m_a =0.2) (table 1 and figure 4e). Two analyses were made on a current state (RV 90km^3 and year-growth 2.3) (table 1, figure 4f and 4g). The first one (fig. 4f) has the same natural mortality as the rest of the analyses with an F of 0.20 and SSB of 1 800 000 tons. The second simulation (fig. 4g) has seal predation included that decreases the cod SSB 6 times at an F of 0.02.



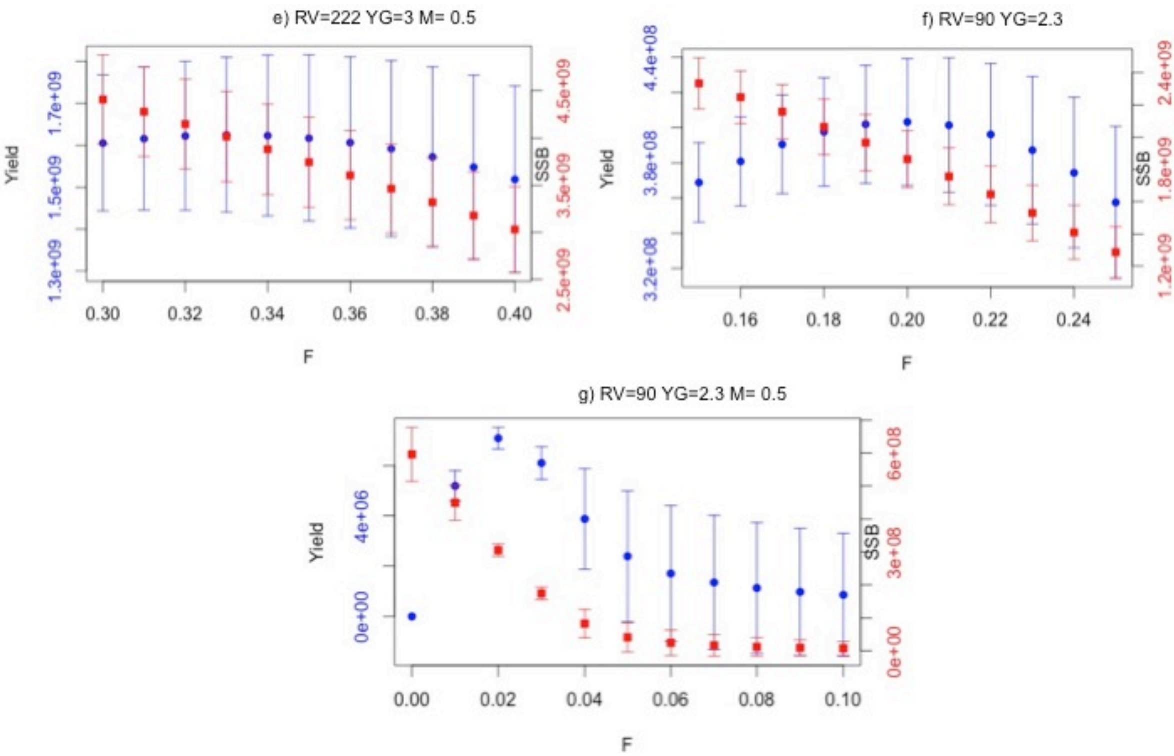


Figure 4. Simulation plot of Cod yield (blue circles) and Cod SSB (red quadrats) in relation to fishing mortality (F) with error bars representing the SD. Each figure represents a simulation: **a)** RV= 47km^3, year-growth 3 gives a F_{MSY} at 0.21. **b)** RV= 47km^3, year-growth 2 gives a F_{MSY} at 0.10. **c)** RV= 222km^3, year-growth 3 gives a F_{MSY} at 0.55. **d)** RV= 222km^3, year-growth 2 gives a F_{MSY} at 0.29. **e)** RV= 222km^3, year-growth 3 and natural mortality =0.5 (with seal predation) gives a F_{MSY} at 0.34, **f)** simulation with current values without seal predation RV= 90km^3, year-growth 2.3 gives a F_{MSY} at 0.20, **g)** simulation with current values and seal predation RV= 90km^3, year-growth 2.3 and natural mortality =0.5 gives a F_{MSY} at 0.02.

3.2.2 Herring

The four simulations of high cod SSB was devastating for the herring population that was eradicated with high predation pressure (table 1). The herring MSY depends on the amount of cod SSB i.e. the effect of high or low RV. For the six simulations with a result a larger input value of cod SSB gave a lower F and MSY. E.g. cod SSB 800 000 tons and year-growth 0.0095 gives a herring MSY at 325 000 tons and an F of 0.21. For cod 910 000 tons and year growth 0.0095 gives a 1.12 times lower MSY and an F in 0.18 (table 1, fig 5a and fig 5c). Year-growth also affects herring population and target F. Comparing high year-growth (0.0095) with low (-0.0004) at the same low cod SSB (800 000 tons) the MSY would increase 2.95 times (table 1, fig 5a and b). Two simulations were made on a current state (year-growth 0.002) (table 1, figure 5e and 5f). The first one (fig. 5e) is based on current cod values (fig. 4f) with the result of F at 0.03 and MSY of 11 000 tons. The second simulation (fig. 5f) has seal predation included on cod that decreases the cod SSB input (fig. 4g) with the result of F at 0.19 and MSY of 275 000 tons which is an increase of herring MSY of 25 times.

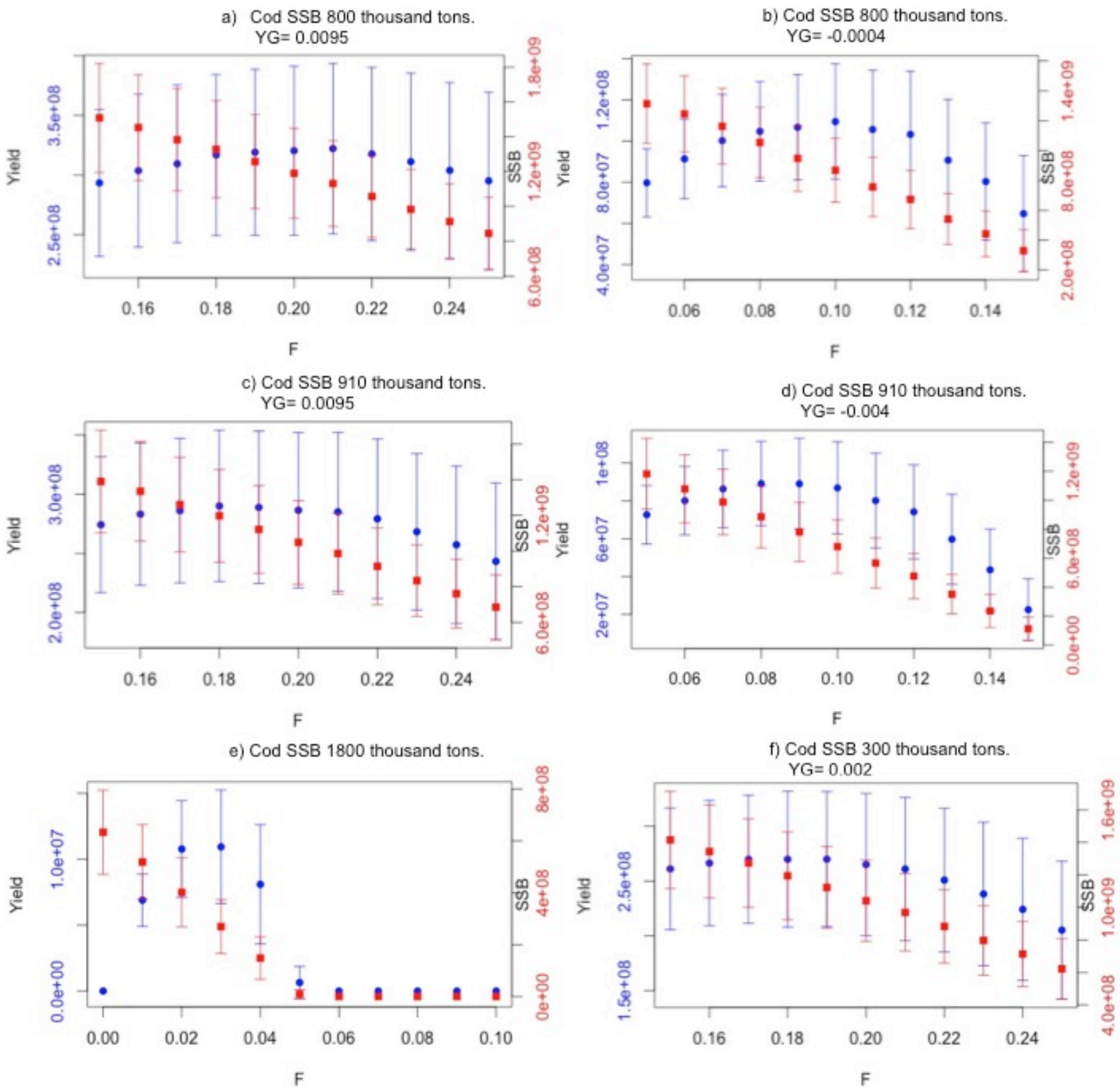


Figure 5. Simulation plot of Herring yield (blue circles) and Herring SSB (red quadrats) in relation to fishing mortality (F) with error bars representing the SD. Each figure represents a simulation: **a)** With Cod SSB of 800 thousand tons and year-growth 0.0095 gives a F_{MSY} at 0.21. **b)** With cod SSB of 800 thousand tons and year-growth -0.0004 gives a F_{MSY} at 0.10. **c)** With cod SSB of 910 thousand tons and year-growth 0.0095 gives a F_{MSY} at 0.19, **d)** with cod SSB of 910 thousand tons and year-growth -0.0004 gives a F_{MSY} at 0.09, **e)** simulation with current values cod SSB of 1800 thousand tons and year-growth 0.002 gives a F_{MSY} at 0.03, **f)** simulation with current values including seal predation on cod gives cod SSB of 300 thousand tons and year-growth 0.002 gives a F_{MSY} at 0.19.

4. Discussion

Connecting species with mutual response in a simultaneous management is important when creating MSY models. By simultaneous management we get knowledge about the consequences in MSY for one species when changing effects on another. To reach a healthy ecosystem with a sustainable fishery the predicting MSY models need to have a holistic approach. This is an important tool when developing a common management plan for the fishing industry in the Baltic Sea.

4.1 RV

Lately several authors, such as ICES (2012), Eero et.al (2011), Swain and Mohn (2012), Vallin and Nissling (2000) have reached the conclusion that the reproductive volume, RV, affects the reproduction of cod. The positive correlation is again shown in the data presented in my work (fig 1). The food availability in form of pelagic fish is of course important for cod survival and development but for the population's survival and growth a sufficiently large habitat for the cod eggs to develop in is vital. The clupeids were not included in the model as there was no statistical effect on growth. Cod diet consists of different species and changes with age (ICES 2012). The significant age effect in the growth function corroborates this statement. In the 2000´s R/SSB has increased but the SSB remains low. The most likely explanation for this continued low SSB is a combination of high fishing mortality and low weights of cod during these years (fig. 3). RV and R/SSB are positive connected (fig. 2) as the curve of R/SSB follows the curve of RV. Shortly after a change in RV, the cod population changes in the same direction, a finding also confirmed by Vallin and Nissing (2000). The RV had a considerable reduction in the Bornholm basin in the late 1970s that can explain the decline in cod SSB a few years later. In the early 1990s the RV is increasing up to the high levels seen in the late 1970s with consequence of rising R/SSB (figure 2 and 3). The variation in RV in the Baltic Sea is dependent on the fresh water inflow from the catchment area and saline water inflow through Öresund and Danish straits (Fonselius and Valderrama 2002). In the winter 1975-1976 there was a major inflow of saline- and oxygen-rich water in the Baltic Sea (Fonselius and Valderrama 2002) that improved the conditions for successful spawning of cod substantially which gave large year-classes of cod in early 1980s (Vallin and Nissing 2000). In the following years the salinity and oxygen concentrations declined because of stagnation in inflow water from Öresund that explains the decreased number of R/SSB. The highest and lowest historical RV and year-growth values were chosen for the analyses to investigate what would happened to the population in the most extreme scenarios. Combinations of these four extreme values have never occurred, however there is a very low variation in the year-growth values between the years.

For cod SSB at MSY, RV is a more important factor than year-growth. No matter if the year-growth is high or low as long as RV is high the SSB ends up at 3.9-5.0 milliards compared to low RV, which gives SSB values of millions after 200 years. These high SSB values is reasonable even if the latest 50 years historical cod SSBs never been at these levels as they occur at a constant high RV with constant low F for at least 100 years. This makes the population slowly grow to return F_{MSY} and the SSB levels resemble more like before the human fishing industry. With an increased cod population the predation pressure from seals would be higher as the seal population would grow. This effect would keep down the cod population (fig. 4e and 4g).

The cod population dynamics is vulnerable to environmental changes. Among with human-induced trophic changes, climate changes are a factor that affects the cod population negative (Eero et.al 2011). To secure a healthy and productive cod population the target F should be kept in phase with current RV. The future cod F_{MSY} models should include RV.

4.2 F_{MSY}

The current management plan for cod recommends fishing at an F of 0.30 with landings of 65 900 tons in 2013. This target F is expected to lead to an SSB of 313 000 tons in 2014. The F_{MSY} recommendation for herring is 0.16 with catches of about 99 000 tons in 2013. This target F is expected to lead to an SSB of 666 000 tons in 2014 (ICES 2012). In a prestudy based on a stochastic multispecies (SMS) model with cod, herring and sprat shows a result that the highest yields of the individual species could be achieved with fishing mortalities considerably higher than the single species Fs (0.60–0.65 for and 0.26 for herring (ICES 2012). The main interaction in the SMS model is cod predation on herring, sprat and juvenile cod and it is unclear if they have included environmental effects on population growth. The SMS model result is in contrast with this work where a cod F of 0.60 or more would not be achieved as a F_{MSY} even under the very best environmental conditions. They also shows that the yield of cod is not significantly higher than in the single species management plan, despite higher F. There is also a risk of SSB falling below their predicted limit from the single species analysis. If RV were included in their model the result would probably be different and it would be interesting to compare the result presented here.

Seal predation was taken into account in the simulation of high environmental effects on cod and in the current state. The purpose was to investigate if seal could hold down a large cod population in favor for herring. The grey seal in the Baltic Sea is a predator on both herring and cod but here there was only included in these tests on cod as it only has a small effect on herring SSB estimations (Gårdmark et. al 2012). The seal predation data came from a study in Canada by Chouinard et.al (2005) where they measured a combined natural mortality with seal predation. Even better had been to use estimates of seal predation on cod and herring from the Baltic Sea but until then the Canadian data was good enough. If the cod population increases the seal population would have more food. The main negative effect is the decreased F that has to be lower than a scenario without seals (table 1). Comparing seal predation on current state the F is much lower and MSY. In the other hand, seal predation has a positive effect for herring MSY in the cases of high cod SSB. In the current state with mortality= 0.2 the F_{MSY} is also 0.2 which gives a total mortality of 0.4. Including seal predation in natural mortality= 0.5 the F_{MSY} is 0.02 which gives a total mortality of 0.52. The former gives very high cod yields and very small herring yields, whereas the latter gives the opposite. This analysis shows that the total mortality should be between 0.4 and 0.52 where a higher total mortality of cod may be desirable to reduce the cod stock size and increase the herring fishery yields. A part of this increase can be due to predation by seals and balance the ecosystem in the Baltic Sea and still return MSY on herring and cod. The mortality on cod by seals should be investigated more. The predation pressure would probably shift by the size of its prey population, such prey-shifts has not been taken into account here. These simulations have used the same predation mortality regardless of various environmental factors.

The reason for cod SSB to raise very high thus low RV is because of lower F than previous and current years. If the current environmental conditions in Baltic Sea remain the cod SSB would raise 8.5 times compared to todays SSB (211 344 000; ICES 2012) at a target F of 0.20 (table 1). This condition would affect the Herring SSB and F negative. With an increased cod population there will be more available food for the seal population that would hold down the cod population for advantage for herring but also bring down the target F. There is also a fourth species, sprat that has cod as a predator and competes with herring that should be included in a feature model for a more realistic analyze.

The target F for cod 2013 should be set according to the simulation with current environmental values (F=0.20). The results here suggest reducing F even for herring because of high predatory pressure. As long as the amount of seal predation is uncertain the present F of 0.03 should remain.

5. References

Botsford, L.W., Castilla, J.C., and Peterson, C.H. (1997) *The management of fisheries and marine ecosystems*. Science 277: 509-515. DOI: 10.1126/science.22.5325.509

Chouinard G.A., Swain D.P., Hammill M.O., and Poirier G.A. (2005). *Covariation between grey seal (Halichoerusgrypus) abundance and natural mortality of cod (Gadus morhua) in the southern Gulf of St. Lawrence.* Can. J. Fish. Aquat. Sci. 62: 1991–2000 (2005)

Eero Margit, R. MacKenzie Brian, W. Köster Friedrich and Gislason Henrik (2011) *Multi-decadal responses of a cod (Gadus morhua) population to human-induced trophic changes, fishing, and climate.* Ecological Applications, 21(1), 2011, pp. 214–226.

Fonselius Stig and Valderrama Jorge (2002). *One hundred years of hydrographic measurements in the Baltic Sea.* Journal of Sea Research 49 (2003) 229– 241

Gislason, H. (1999). *Single and multispecies reference points for Baltic fish stocks*. ICES Journal of Marine Science, 56: 571–583.

Gårdmark Anna, Östman Örjan, Nielsen Anders, Lundström Karl, Karlsson Olle, Pönni Jukka, and Aho Teija (2012). *Does predation by grey seals (Halichoerus grypus) affect Bothnian Sea herring stock estimates?* ICES Journal of Marine Science (2012), 69(8), 1448–1456. doi:10.1093/icesjms/fss099

Heikinheimo Outi (2008). *Average salinity as an index for environmental forcing on cod recruitment in the Baltic Sea*. Boreal Env. Res. 13: 457-464.

Herdson, D. & Priede, I. (2009) *Clupea harengus.* From: IUCN 2010. IUCN Red List of Threatened Species. Version 2010.4. <www.iucnredlist.org Downloaded 2011-11-01

Holmgren, Norrström, Aps and Kuikka (2011) *MSY oriented management of Baltic Sea herring (Clupea harengus) during different ecosystem regimes.* ICES CM 2011/O:06

ICES (2009a). *Report of the Baltic Fisheries Assessment Working Group* (WGBFAS), 22 - 28 April 2009, ICES Headquarters, Copenhagen. ICES CM 2009\ACOM:07. 626 pp.

ICES (2012). Report of the Baltic Fisheries Assessment Working Group 2012 (WGBFAS), 12 - 19 April 2012, ICES Headquarters, Copenhagen. ICES CM 2012/ACOM:10. 859 pp.

Jennings S., Kaiser M. J., and Reynolds J. D. (2001). *Marine Fisheries Ecology*. Blackwell Science Ltd, Oxford.

Köster, F.W., Möllmann, C., Hinrichsen, H-H., Wieland, K., Tomkiewicz, J., Kraus, G., Voss, R., Makarchouk, A., MacKenzie, B. R., St. John, M. A., Schnack, D., Rohlf, N., Linkowski, T., and Beyer, J. E. (2005). *Baltic cod recruitment –the impact of climate variability on key processes.* –ICES Journal of Marine Science, 62: 1408-1425.

Köster Friedrich W. and Möllman Christian (2000). *Trophodynamic control by clupeid* *predators on recruitment success in Baltic cod?* ICES Journal of Marine Science, 57:310-323.

Köster Friedrich W. and Schnack Dietrich (1994). *The role of predation on early life stages of cod in the Baltic.* Dana, vol. 10, pp. 179-201, 1994

Larkin PA (1977) *An epitaph for the concept of maximum sustained yield.* Transactions of the American Fisheries Society, 106: 1–11

Lindegren Martin, Östman Örjan and Gårdmark Anna (2011). *Interacting trophic forcing and the population dynamics of herring.* Ecology, 92(7), 2011, pp. 1407–1413

MacKenzie B. R, Hinrichsen H.-H, Plikshs M, Wieland K, Zezera A. S. (2000). *Quantifying environmental heterogeneity: habitat size necessary for successful development of cod Gadus morhua eggs in the Baltic Sea.* Marine ecology progress series. Vol. 193: 143-156.

Möllmann C., Müller-Karulis B., Kornilovs G., and St John M. A. (2008). *Effects of climate and overfishing on zooplankton dynamics and ecosystem structure: regime shifts, trophic cascade, and feedback loops in a simple ecosystem*. ICES Journal of Marine Science, 65: 302-310.

Óskarsson G. J., and Taggart C. T. (2006). *Fecundity variation in Icelandic summer-spawning herring and implications for reproductive potential.* ICES Journal of Marine Science, 63: 493-503.

R Development core team (2008). *R: A language and environment for statistical computing.* R foundation for statistical computing, Vienna, Austria. ISBN 3-900051-07-0, URLhttp://www.R-project.org

Stiling, Peter (2002). *Ecology -theories and applications.* Fourth edition ISBN: 013091102-X

Swain Douglas P. and Mohn Robert K. (2012). *Forage fish and the factors governing recovery of Atlantic cod (Gadus morhua) on eastern Scotian Shelf.* Can. J. Fish. Aquat. Sci. 69: 997-1001.

Vallin Lars and Nissling Anders (2000). *Maternal effects on egg size and egg buoyancy of Baltic cod, Gadus morhua. Implications for stock structure effects on recruitment.* Fisheries Reserch 49 (2000) 21-37.

Appendices

Appendix 1. Parameters of the operational population model of the Central Baltic Sea herring (Holmgren et.al 2011).

Herring			
Parameter	**Value**	**Eqn**	**Comment**
m1	0.22985	5	Natural mortality 1-yr-olds
m2	0.22773	5	Natural mortality 2-yr-olds
m3	0.22915	5	Natural mortality 3-yr-olds
m4	0.22735	5	Natural mortality 4-yr-olds
m5	0.22362	5	Natural mortality 5-yr-olds
m6	0.22261	5	Natural mortality 6-yr-olds
m7	0.22258	5	Natural mortality 7-yr-olds
m8	0.22123	5	Natural mortality 8-yr-olds
v1	0.00035	5	Cod predation on 1-yr-olds
v2	0.00018	5	Cod predation on 2-yr-olds
v3	0.00012	5	Cod predation on 3-yr-olds
v4	0.00010	5	Cod predation on 4-yr-olds
v5	0.00009	5	Cod predation on 5-yr-olds
v6	0.00008	5	Cod predation on 6-yr-olds
v7	0.00006	5	Cod predation on 7-yr-olds
v8	0.00005	5	Cod predation on 8-yr-olds
Ɛ _	0.00030	5	Mean square error of GLM fit of eqn 5
Maturity1	0	14	Maturity proportion 1-yr-olds
Maturity2	0.7	14	Maturity proportion 2-yr-olds
Maturity3	0.9	14	Maturity proportion 3-yr-olds
Maturity4	1	14	Maturity proportion 4-yr-olds
Maturity5	1	14	Maturity proportion 5-yr-olds
Maturity6	1	14	Maturity proportion 6-yr-olds
Maturity7	1	14	Maturity proportion 7-yr-olds
Maturity8	1	14	Maturity proportion 8-yr-olds
k_y	-0.0004	4	Low year-growth
k_y	0.0095	4	High year-growth
k_y	0.002	4	Current year-growth
b	3.09864	1	Density-independent reproduction; no. of recruits yr+1
d	-1.05E-06	1	Density-dependent reproduction; no. of recruits yr+1
Ɛ _	0.55602	1	Mean square error of GLM fit of eqn 1
c	0.00834	3	Independent body growth
ky		3	Year-specific growth on all ages
l	-0.13703	3	Weight-dependent-growth parameter
Ɛ _	0.00007	3	Mean square error of GLM fit of eqn 3
m	0	8	Weight of recruits, intercept
k	0.36917	8	Parental-weight effect on recruit weight
Ɛ _	0.00002	8	Mean square error of GLM fit of eqn 8

Appendix 2. Parameters of the operational population model of the Central Baltic Sea cod.

Cod			
Parameter	**Value**	**Eqn**	**Comment**
m	0.2	5	Natural mortality on all age classes
m	0.5	5	Natural mortality including seal predation.
Ɛ _	0	5	Mean square error of GLM fit of eqn 5
d_1	2.04E-07	2	Density-dependent reproduction; no. of recruits yr+1

d_2	0.00802	2	Reproduction parameter for RV
Ɛ _	0.38	2	Mean square error of GLM fit of eqn 2
c		4	Independent body growth
ky		3	Year-specific growth on all ages, see appendix 3
k_1	0	3	Age-specific growth
k_2	-2.12239	3	Age-specific growth
k_3	-2.10264	3	Age-specific growth
k_4	-1.85584	3	Age-specific growth
k_5	-1.4902	3	Age-specific growth
k_6	-0.96428	3	Age-specific growth
k_7	0	3	Age-specific growth
k_8	0	3	Age-specific growth
l	-0.25679	3	Weight-dependent-growth parameter
Ɛ _	0.1027	3	Mean square error of GLM fit of eqn 3
m	0.1095	8	Weight of recruits, intercept
k	0.12174	8	Parental-weight effect on recruit weight
Ɛ _	0.00002248	8	Mean square error of GLM fit of eqn 8
Maturity1	0	14	Maturity proportion 1-yr-olds
Maturity2	0.12	14	Maturity proportion 2-yr-olds
Maturity3	0.45	14	Maturity proportion 3-yr-olds
Maturity4	0.81	14	Maturity proportion 4-yr-olds
Maturity5	0.93	14	Maturity proportion 5-yr-olds
Maturity6	0.96	14	Maturity proportion 6-yr-olds
Maturity7	0.98	14	Maturity proportion 7-yr-olds
Maturity8	0.99	14	Maturity proportion 8-yr-olds

Appendix 3. Result from GLM model. Growth parameter is the basis for year-growth in cod.

			Effect	Comment	Growth param
Year	1966	1	Random		2.70594
Year	1967	2	Random		2.74478
Year	1968	3	Random		2.70194
Year	1969	4	Random		2.69711
Year	1970	5	Random		2.69728
Year	1971	6	Random		2.76278
Year	1972	7	Random		2.72978
Year	1973	8	Random		2.71928
Year	1974	9	Random		2.76878
Year	1975	10	Random		2.76428
Year	1976	11	Random		2.71911
Year	1977	12	Random		2.73494
Year	1978	13	Random		2.73544
Year	1979	14	Random		2.70261
Year	1980	15	Random		2.76328
Year	1981	16	Random		2.72161
Year	1982	17	Random		2.27511
Year	1983	18	Random		2.48691

Year	1984	19	Random		2.53291
Year	1985	20	Random		2.36497
Year	1986	21	Random		2.67493
Year	1987	22	Random		2.59652
Year	1988	23	Random		2.29612
Year	1989	24	Random		2.70225
Year	1990	25	Random		2.69601
Year	1991	26	Random		2.65143
Year	1992	27	Random		2.60176
Year	1993	28	Random		2.75926
Year	1994	29	Random		2.98964
Year	1995	30	Random		2.40663
Year	1996	31	Random		3.04141
Year	1997	32	Random		2.87904
Year	1998	33	Random		2.03541
Year	1999	34	Random		2.89913
Year	2000	35	Random		2.14333
Year	2001	36	Random		2.28208
Year	2002	37	Random		2.1766
Year	2003	38	Random		2.53952
Year	2004	39	Random		2.33565
Year	2005	40	Random		2.44441
Year	2006	41	Random		2.45934
Year	2007	42	Random		2.29238
Year	2008	43	Random		2.43283
Year	2009	44	Random		2.38971
Age	2	45	Fixed	Biased	-2.12239
Age	3	46	Fixed	Biased	-2.10264
Age	4	47	Fixed	Biased	-1.85584
Age	5	48	Fixed	Biased	-1.4902
Age	6	49	Fixed	Biased	-0.96428
Age	7	50	Fixed	Zeroed*	0
Weight		51	Fixed		-0.25679