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Climate change and resilience value of mussel farming for the baltic sea

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1. Introduction

The impact of climatic change on freshwater was investigated already in late 1980s and early 1990s (e.g. Coutant, 1988; Waggoner, 1990). Similar studies on the Baltic Sea were carried out more recently (e.g. Eckersten et al. 2001; Pettersson, 2003; Arrheimer et al., 2005, Blenckner et al. 2007; Lewan and Wallin, 2007; Ulén and Weyhenmeyer, 2007; Zillén, 2008; Klavins et al. 2009; Möllman et al., 2009). In spite of this relatively early concern, the environmental economics literature on climatic change and water quality management is scarce and is mostly applied to water supply management and/or estimation of impacts on agricultural and other water dependent industries (Mendelsohn, 2003; Lacroix, 2005). However, climatic change is likely to affect a variety of ecosystem services related to water quality, such as recreational values and reproduction of fish. On the other hand, certain measures may buffer against large variability in climate and resulting pollutant pressure on a eutrophied sea. The purpose of this paper is to calculate potential values, so called resilience values, of mussel farming from combating eutrophication in the Baltic Sea under climate change conditions.

Potential resilience value of mussel farming emerges from the stochastic nature of pollutant transports in soil and water in drainage basins, which implies risk in reaching predetermined targets in pollutant loads to water recipients. Pollutant emission sources are spatially spread in drainage basins where pollutants transports to the water recipients follow one or several different paths: air, soil, subsurface- and groundwater streams. Therefore, the final impact on the recipient is predicted only under conditions of risk and uncertainty. This uncertainty is one reason for EU water directive's recommendation of expressing water quality targets in precautionary terms where the targets should be obtained with high reliability (EU, 2000). Difficulties of managing stochastic pollution of waters constitute an important cause of aggravation of several types of water quality problems in spite of societies' relatively early perception of the environmental problem. One prominent example is damages from eutrophication caused by nutrient enrichment in several part of the world, such as the Baltic Sea, Black Sea, Missisipi delta, Cheasepeake Bay, and the Mediteranien (see e.g. Turner et al., 1999; NRC, 2000; Bodungen and Turner, 2001). Damages from nutrient enrichment occur from the oxygen depletion that takes place due to biological growth of certain algal species. Huang et al. (1997), Söderqvist (1998), and Markowska and Zylicz (1999) show that people are willing to pay a significant amount of money for reducing damages from nutrient enriched bays.

Holling (1973) is among the first to point to the need of accounting for resilience in ecosystem management. Resilience is then defined as the magnitude of disturbance a system can experience before it shifts into another state with different controls and functions. Although the resilience concept was introduced in early 1970s current considerably large literature in natural science on the role of resilience is still conceptual in nature (see Folke et al. 2004 for a review). Only a few attempts have been made to estimate the value of ecosystems in promoting resilience (Mäler et al., 2007; Walker et al. 2007; Cardona et al., 2008; Sarang et al., 2008; Mäler et al. 2009; Gren 2010).

The analysis and calculations of resilience value of wetlands carried out in this paper are most similar to Gren (2010), where resilience values are calculated for wetlands as nutrient sinks under conditions of stochastic nutrient loads to the Baltic Sea by means of stochastic programming. This study then adds to the scant literature on the value of mussel farming as an abatement option (Hart, 2003; Gren et al. 2009). However, none of the two papers carry out explicit calculations of resilience values of mussel farming, which is the ultimate purpose of this paper. This study thus extends earlier literature in two respects; *i)* on development of methods quantifying resilience values and *ii*) on valuation of nutrient retention of mussel farming.

A few caveats are in order. Due to the focus on the abatement portfolio aspects, the dynamics of water pollution is not included. This neglect is particularly serious for phosphorous pollution due to the long adjustments in the sea to changes in load. As shown in Hart (2003) consideration of dynamics may have significant impact on choice of mitigation or adaptation measures for water pollution. However, the delayed effects of nutrient emission changes in the drainage basins on load to the coastal water is a strong justification for the stochastic framework applied in this paper. Given a relatively short period of time, say five years, it is difficult to determine the load effects from emission changes undertaken in the drainage basin in the beginning of the period. In principle, a long term perspective with a dynamic model would give more precision nutrient transports can be modeled, although the effect in each time period would be difficult to predict.

2. Operational definition of resilience value

This paper applies a risk based approach for the calculations of resilience values, which is characterized by cost effectiveness analysis under stochastic environmental quality (Sarang et al. 2008; Gren 2010). Given environmental targets set by policy makers, resilience value is then estimated as the value of changes in the reliability of reaching the predetermined environmental target(s). More precisely, policy makers are assumed to minimize total costs for achieving a certain environmental quality with a minimum probability at minimum costs. In such a setting, new cleaning technologies may bring about two types of values; replacement and resilience values.

The environmental targets for the Baltic Sea are set by the intergovernmental agreement in autumn 2007 where decreases in nutrient loads to the marine basins of the Sea were determined. Gren et al. (2009) have shown that these targets can be achieved at lower costs if mussel farming is introduced as an abatement option. The estimated value ranged between SEK 0.2 and 2.3 kg^{-1} live mussel depending on assumption of nutrient sequestration by mussels, and option of selling the mussel for food.

In addition to replacement values, mussel farming may generate resilience value. Resilience value is then defined as the decrease in total cost for achieving a certain load reduction target at a minimum probability caused by the introduction of mussel farming as an abatement measure. Resilience value then arises from the existence of uncertainty in reaching the target, which includes stochastic nutrient loads in the drainage basin from the emission sources and also uncertain abatement capacity of mussel farming. It is shown in Gren (2010) that the resilience value is positive only if the introduction of mussel farming reduces overall risk, which is measured as the total variance in nutrient load and abatement by mussel farming. Total risk is reduced only if the covariance between nutrient load to a basin and the abatement capacity of the measure, which is mussel farming in this paper, is positive. Nutrient abatement of mussel farms is then high when load from the drainage basins is high. The associated resilience value is calculated in a similar way as replacement value, which is illustrated in Figure 1.

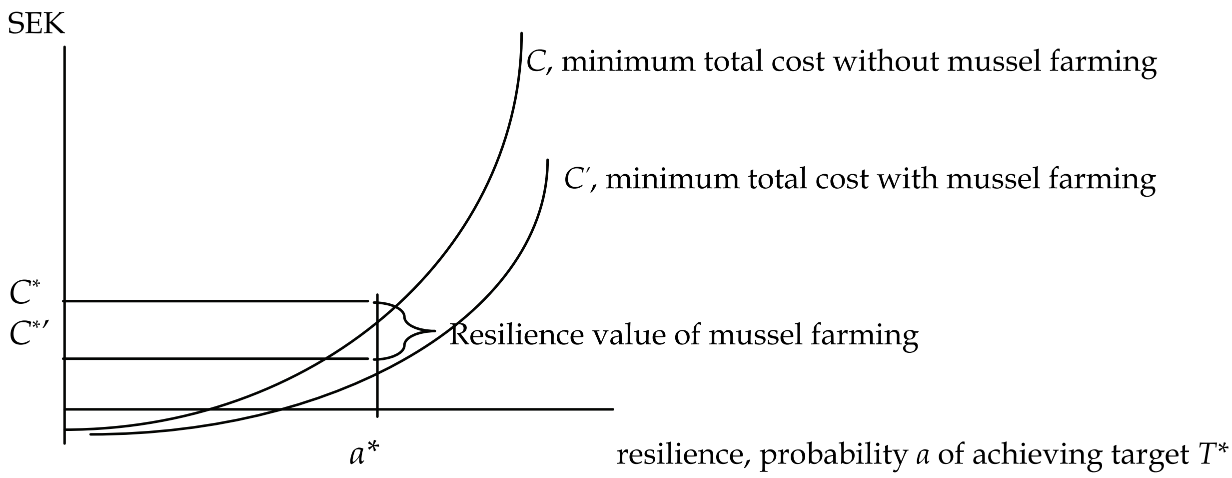

Fig. 1. Illustration of the calculation of resilience value of mussel farming as the reduction in total abatement cost for reaching a certain cleaning target T* with a minimum probability α* from introduction of mussel farming.

The two curves C and C' illustrate resilience provision cost functions which show the minimum cost for achieving the environmental target T^* at different levels of probabilities. The higher the chosen probability, or resilience level, the higher is the cost due to the need for more costly abatement (see Gren 2010 for a further description). The resilience value of mussel farming is then calculated as C-C' for a given predetermined a. As illustrated in Figure 1, the resilience value of mussel farming is C^*-$C^{*\prime}$ for $a= a^*$.

As noticed above, a necessary condition for a positive resilience of mussel farming is a positive co-variance between sequestration by mussels and nutrient load from drainage basins and sediments. However, this is not sufficient since abatement by mussel farming is also uncertain. Resilience value of mussel farming is then positive if the reduction in total risk due to a positive covariance between nutrient loads and abatement by mussel farming is higher then the increase in risk associated with uncertainty in nutrient abatement by mussel farming.

3. Data retrieval

The calculations of resilience values of mussel farming in the Baltic Sea under climate change conditions require data on: nutrient transports to the sea from basins, quantification of climate change, uncertainty quantification of nutrient sequestration by mussel farming, costs of mussel farming and other measures. Data on nutrient transports and costs of measures in the drainage basins, such as reductions in agricultural, household and industrial nutrient loads, are obtained from Gren et al. 2008, and data on costs and effects of mussel farming from Gren et al. 2009. Climate change impacts are quantified as changes in variability in nutrient concentrations in the marine basins of the Baltic Sea.

3.1 Nutrient loads and abatement costs

Although the nine countries with coasts along the Baltic Sea constitute decision units in negotiation processes, the choice of regional division of the Baltic Sea drainage basin is not a self-evident matter. One important reason is the difficulty of matching data on nutrient drainage basin transports with estimates of abatement costs. For that reason, the entire water catchment of approximately 1 745 000 km^2 is divided into 23 drainage basins, which are shown in Figure A1 in the appendix. For each of these regions nutrient emission originates from three types of sources: agriculture, sewage from households and industry, and air deposition. The calculations of nutrient loads to the coastal waters of the Baltic Sea from these emission sources are divided into two steps. First, all emission sources are identified and quantified. Next, these emissions are transformed into loads to the Baltic Sea by means of data on leaching from the root zone into waters stream in the drainage basins, retention of nutrient during the transport to the sea, and air transports of nitrogen oxides and ammonia (see Gren et al. 2008 for a further presentation).

Measurement and data on risk in nutrient loads are obtained from Elofsson (2000), which contains coefficients of variation in nutrient loads for the 23 drainage basins. These are, in turn, based on measurements of nutrient concentration at all river mouths along the Baltic Sea coastal lines. Table 1 presents the coefficients of variation in nutrient loads together with data on nutrient loads to the coastal waters.

Regions	*Nitrogen;*		*Phosphorus:*	
	Kton[1]	*CV*[2]	*Kton*[1]	*CV*[2]
Denmark	44	0.25	1.1	0.27
Finland	49	0.21-0.25	1.7	0.21-0.27
Germany	46	0.2	0.5	0.2
Poland	318	0.18-0.29	22	0.18-0.25
Sweden	74	0.17-0.35	1.6	0.18-0.31
Estonia	56	0.18	1.6	0.18
Latvia	44	0.20	3	0.21
Lithuania	93	0.15	3.5	0.15
Russia	83	0.17-0.39	4	0.39-0.45
Total	*824*	*0.09*	*38.9*	*0.12*

Table 1. Nutrient loads, share of non-point source load, coefficient of variation. Sources: 1. Gren et al. (2007), Table 1 page 13, estimated for year 2005 2. CV (coefficients of variation) Elofsson (2000), Table CV(I, N), page 54

Total calculated annual loads of both nitrogen and phosphorus come relatively close to similar calculations carried out by Helcom (2004). Poland is the country with the largest share of both nitrogen and phosphorus loads, followed by Lithuania and Russia. For most countries, coefficients of variations are larger for nitrogen loads than for phosphorus loads.

Cost estimates of different nutrient abatement measures used in this study are obtained from Gren et al. (2008) and measured in 2007 prices. In addition to mussel farming, the study includes measures for changes in agricultural practices, increased cleaning capacity at sewage treatment plants, and reductions in nitrogen oxide emissions from traffic and industry. More precisely, the measures included in this empirical analysis are: increased nutrient cleaning capacity at sewage treatment plants, sewage treatment at industry and households, phosphate free detergents, catalysts in cars and ships, flue gas cleaning in stationary combustion sources, and reductions in the agricultural deposition of fertilizers and manure. Included land use measures are: change in spreading time of manure from autumn to spring, cultivation of so called catch crops, energy forests, lye grass, and wetland creation. A change of spreading time from autumn to spring implies less leaching since, in spring, there is a growing crop which utilizes the nutrients. Catch crops refer to certain grass crops, which are drilled at the same time as the ordinary spring crop but the growth, and thereby the use of remaining nutrients in the soil, is concentrated to the period subsequent to the ordinary crop harvest. The nutrient abatement cost estimates for fertiliser reductions are based on econometric estimates of panel data. Abatement costs of all other measures are obtained from enterprise budgets.

Costs of nutrient sequestration by mussel farming are obtained from Gren et al. (2009) which, together with Hart (2003), are the only studies estimating the value of mussel farming as an abatement option for a eutrophied sea. The cost of mussel farming depends on type of technology, size and location of the farm, and on the possibility of selling the mussels as human or animal food. Long-line farming is the most common method of mussel farming in Scandinavia. The larvae of the blue mussel settle in early summer on vertical suspenders attached to horizontal long-lines carried up by buoys. The long-lines are typically 200 m long and the suspenders reach close from surface down to about 6 m depth. A varying number of long-lines are collected to a unit which is anchored at both ends. The growth of mussel and, hence, the nutrient sequestration depends to a large extent on the salinity content of the water, which varies in different parts of the Baltic Sea. Mussel production per mussel farm can be twice as large in the southern Baltic Sea as in the northern parts (Gren et al. 2009). The cost of nutrient sequestration also depends on the option of selling mussels for human consumption or for animal food. The calculated constant marginal costs in Gren et al. (2009) varied between SEK 0/kg nutrient cleaning and SEK 635 kg^{-1} and SEK 9000 kg^{-1} for nitrogen and phosphorous cleaning respectively (1 Euro = 9.70 SEK, April 16, 2010). The low marginal cleaning cost occurred for the Kattegat and the Sound marine basins, whereas the largest costs were found in the Northern Baltic Proper basin. In this chapter average marginal costs for each marine basin are used.

A quantification of uncertainty in nutrient abatement by mussel farming is obtained from Gren et al. (2009). A simple estimate is made where the coefficient of variation is calculated as the range in abatement divided by the mean, which gives an estimate of 0.5 for both nitrogen and phosphorus. There is no data on the co-variation between nutrient abatement by mussels and nutrient loads to the coastal waters. Calculations are therefore made with the assumption of a coefficient of variation that equals unity. The estimated resilience values of mussel farming are then the maximum values: A lower correlation coefficient generates lower values, which are zero or negative when the correlation coefficient is zero.

3.2 Climate change effects

Recall from Section 2 that resilience value is calculated as the difference in costs of resilience provision with and without mussel farming. This means that climate change will have effect on the estimated resilience value only if climate change has impacts on variability in nutrient loads. A simplification is made by neglecting effects on costs of abatement measures which can occur through changes in, for example, land and fertilizer prices owing to fluctuations in food demand. A justification for this is the lack of data on risk attitudes, which would be required for incorporating stochastic costs of abatement measures. Another limitation of the study is the neglect of climate-change impacts on the constraints as such. For example, it may turn out that phosphorus concentration and/or water transparency as operational indicators of water quality for different uses, such as for drinking or bathing purposes, need to be changed. This is not, however, accounted for in this study.

There are today a considerable number of studies on climate change effects related to the Baltic Sea (e.g. Eckersten et al. 2001; Pettersson, 2003; Arrheimer et al., 2005, Blenckner et al. 2007; Lewan and Wallin, 2007; Ulén and Weyhenmeyer, 2007; Zillén, 2008; Klavins et al. 2009; Möllman et al., 2009). A common focus of these studies has been to estimate the changes in winter North Atlantic Oscialltions on climate and associated impacts on water temperature, ice conditions, plankton phonology, and nutrient discharges on lakes and water sheds in the Baltic Sea drainage basin and in other parts of Europe.

In spite of the large literature, climatic change impacts, as expressed in terms of changes in variability in nutrient load and water quality, are limited. Studies of small drainage basins reveal that prolonged summer periods may increase phosphorus-recycling from the sediments (Pettersson, 2003), that phosphorus losses from agricultural soils may increase (Ulén and Weyhenmeyer, 2007), and that the nitrogen leaching from arable land and its retention during transport to waters are affected (Lewan and Wallin, 2007). According to Arrheimer et al., (2005) and Eckersten et al. (2001), phosphorus leaching may decrease and nitrogen leaching increase. The estimated range in increase in nitrogen leaching from arable land with current cultivation structure owing to climatic change is 10 and 70 per cent. Wallin (2002) also records increases in leaching of one nutrient, phosphorus, but retention is increased owing to higher biological activity, which implies that the discharges to the coastal waters may decrease or be unaffected. No study has, however, quantified eventual impacts of climate change on variability in loads or water quality.

Owing to the lack of data on climate change effects on variability, minimum cost solutions are calculated for both increases and decreases in nutrient load variability. More precisely, calculations are made for proportional changes in nutrient load variability compared with the reference case presented in Table 1; a decrease in all coefficient of variations by one half and a doubling of the coefficient of variations. It is assumed that the uncertainty in nutrient abatement is subjected to the same proportional changes in variability.

4. Results

Stochastic programming is used for calculating resilience values of mussel farming, where the decision problem includes minimization of costs for pre-specified target(s) of maximum

loads under probabilistic constraints (see e.g. Birge and Louveaux, 1997). The algorithm applied for all calculations is GAMS (Brooke et al., 1998).
The target used is the intergovernmental agreement in autumn 2007 on nutrient load reductions to the Baltic Sea, the so-called Helcom Baltic Sea Action Plan (see Helcom, 2007). The targets differ for different marine basins; phosphorus decreases are largest for the Baltic Proper, and the largest nitrogen reductions are needed for Kattegat and the Danish Straits (see Table A1 in appendix for reduction needs and Figure A1 for a map). It is predicted that these reductions will reduce the extension of hypoxic sea bottoms in the Baltic Proper by approximately 1/3, and nitrogen fixation, an indicator of the intensity of cyan bacterial blooms, is expected to decrease by 2/3.
Recall from Section 2 that resilience values of mussel farming are calculated as differences in costs of resilience provision with and without mussel farming. Total abatement costs under different assumptions of climate change impacts and co-variation between nutrient load and nutrient abatement by mussels are shown in Table A2 in the appendix. Costs of resilience provision are calculated as the difference in abatement costs with reliability requirement minus abatement costs without such requirement. Such calculations of resilience provision costs without mussel farming as an abatement option are shown in Figure 2.

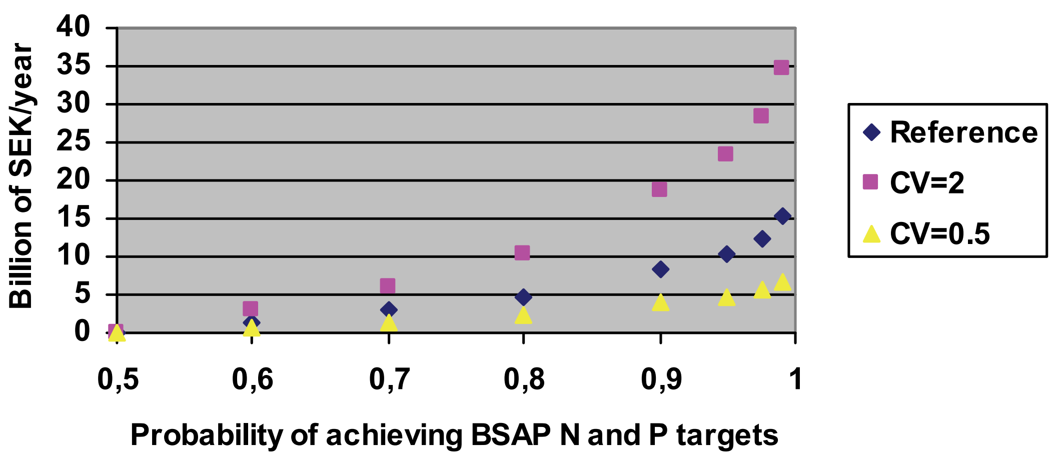

Fig. 2. Costs for resilience provision without mussel farming under alternative impacts of climate change (doubling of total variance, CV=2 and a reduction by one half, CV=0.5), (Source: calculations from data in Table A2 in appendix)

The resilience provision costs in the reference case, when there is no impact on variability in nutrient loads and abatement capacity by mussels from climate change, increase rapidly at probability levels exceeding 0.8; from approximately 5 billion of SEK to 15 billion of SEK. Total costs without reliability concern amount to approximately 25 billion of SEK. Resilience provision cost in the reference case then increases total abatement cost by 20 and 60 per cent compared with the costs without reliability concern (see Table A2 in the appendix). The results presented in Figure 2 also show that the resilience provision cost increases considerably when the total variance in nutrient load is doubled. If instead climate change causes a decline in the variability by one half, resilience provision costs are decreased by almost 2/3 at high resilience levels.

Resilience provision costs when mussel farming is included as an abatement option show a similar pattern as provision costs without mussel farming see Figure 3.

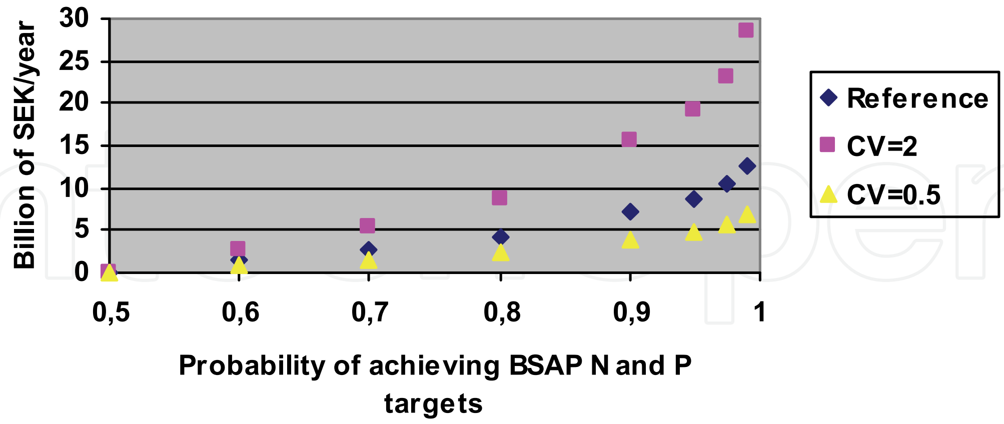

Fig. 3. Costs for resilience provision with mussel farming as an abatement option under alternative impacts of climate change (doubling of total variance, CV=2, and a reduction by one half, CV=0.5). (Source: Calculations based on data in Table A2 in appendix.)

A notable observation is that resilience provision costs with mussel farming are lower than corresponding costs without mussel farming as an abatement option for all three scenarios. Recall that the costs in Figure 3 are calculated with the assumption of a correlation coefficient between nutrient load and nutrient abatement by mussels that equals unity. Cost data in Table A1 show that mussel farming generates no resilience value when the correlation coefficient equals zero.
Calculated resilience values of mussel farming are displayed in Figure 4. These are the maximum possible values since it is assumed that the correlation coefficient between nutrient load and abatement by mussels equals unity.

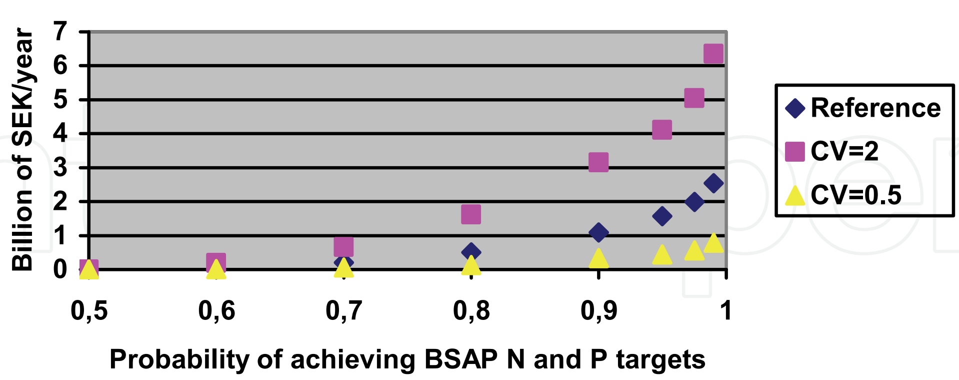

Fig. 4. Maximum resilience values of mussel farming at different resilience levels and impacts of climate change (doubling of total variance, CV=2, and a reduction by one half, CV=0.5). (Source; calculations based on Table A2 in the appendix)

The probability levels along horizontal axis are choices made by decision makers on the minimum probability for achieving the BSAP targets. For a given variability, the resilience

value then increases for higher probabilities, since certainty in reaching the targets becomes prioritized by decision makers. This resilience value is then increased by climate change effects if they cause larger total variability, or risk, in nutrient loads. On the other hand, if variability is decreased (which is less likely), the resilience value of mussel farming also decreases.
It is interesting to compare the estimated resilience value of mussel farming with the more conventional replacement values, and also with the sales price of live mussels for human consumption. The conventional replacement value of mussel farming is obtained by subtracting the total abatement cost with mussel farming, which amounts to 24381 mill SEK, from the corresponding cost without mussel farming, which are 25 185 millions of SEK (see Table A1 in the appendix). This gives a total replacement value of 804 mills SEK, or approximately 1 SEK/ kg mussel. The estimated resilience values depend on choice of resilience level and effects of climate change on variability in nutrient loads, see Table 2.

	No resilience[1]	*Reference case*	*CV=2*	*CV=0.5*
Replacement value	1			
Resilience value		0.07 – 3.17	0.24-7.94	0.01-0.94

Table 2. Replacement and resilience values of mussel farming in the Baltic Sea, SEK/kg live mussel under different climatic change impacts 1) Uncertainty in nutrient loads is not of concern

The estimated resilience value ranges between 0.01 and 7.94 SEK kg^{-1} live mussel. It can thus be considerably higher than the replacement value of mussel farming, i.e. the decrease in total abatement costs for achieving the targets caused by the introduction of mussel farming when uncertainty is of no concern for policy makers. It is also interesting to note that the resilience value is twice as large as the market price of live mussel in Sweden 2009, which was approximately 3.50 SEK/kg (Gren et al. 2009).

5. Conclusions

The purpose of this paper has been to estimate the impacts of climate change on resilience values of mussel farming in the Baltic Sea. Resilience value was related to the impact of mussel farming on the exposure to risk in nutrient loadings. Its value is determined by reliability concern; decrease in total risk, and on the cost of mussel farming relative to other abatement measures. Since resilience values in this setting are positive only under conditions of uncertainty, climate change effects were measured in terms of impacts on variability in nutrient loads. Unfortunately, there exist no studies with a systematic assessment of such climate change effects on nutrient loads from all drainage basins. Simplifying assumptions were therefore made; variability is either doubled or reduced by one half due to climate change effects. The results showed that the estimated resilience value ranges between 0.01 and 7.94 SEK kg^{-1} live mussel. This result can be compared with the market retail price of mussel in Sweden in 2009, which amounted to 3.5 SEK kg^{-1}. Thus, when resilience is of concern for policy makers, the value of mussel farming can be considerable.
However, the results must be interpreted with much caution since they rest on several different types of assumptions mainly with respect to quantification of climate change

effects, sequestration effects of mussel farming, and uncertainty in nutrient loads. Nevertheless, the results point to the need of considering the role of mussel farming for buffering against high variability in nutrient loads to eutrophied waters under climate change conditions.

6. References

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Appendix: Tables and Figure

	P	N
Baltic Proper	66	29
Gulf of Finland	29	5
Gulf of Riga	34	
Danish Straits		32
Kattegat		31
Total	*64*	*25*

Table A1. Helcom BSAP basin reduction targets, in %
Source: Helcom (2007) page 2

Proba bility	Inclusion of mussel farming:						Exclusion of mussel farming:		
	Reference		CV=2		CV=0.5		Refer.	CV=2	CV=0.5
	ρ= 0	ρ = 1	ρ = 0	ρ=1	ρ = 0	ρ = 1			
0.6	27409	25753	27353	27053	25139	25086	26613	28049	25899
0.7	29309	27102	30609	29797	25909	25779	28106	31255	26640
0.8	32309	28697	35002	33225	26814	26586	29951	35646	27519
0.9	32788	31535	43370	39995	28376	27917	33435	43952	29052
0.95	34788	33058	47991	43609	29219	28620	35427	48529	29863
0.975	36895	34796	53068	47619	30107	29380	37589	53465	30742
0.99	39827	37113	59501	52765	31291	30339	40454	59916	31930
Determi-nistic cost[1]	24381						25185		

Table A2. Total costs for achieving BSAP targets under different resilience levels (probability of achieving targets), climate change effects on variance (CV), and correlation coefficients between nutrient load and mussel abatement (ρ), in millions of SEK.
1) Abatement cost without any resilience provision.

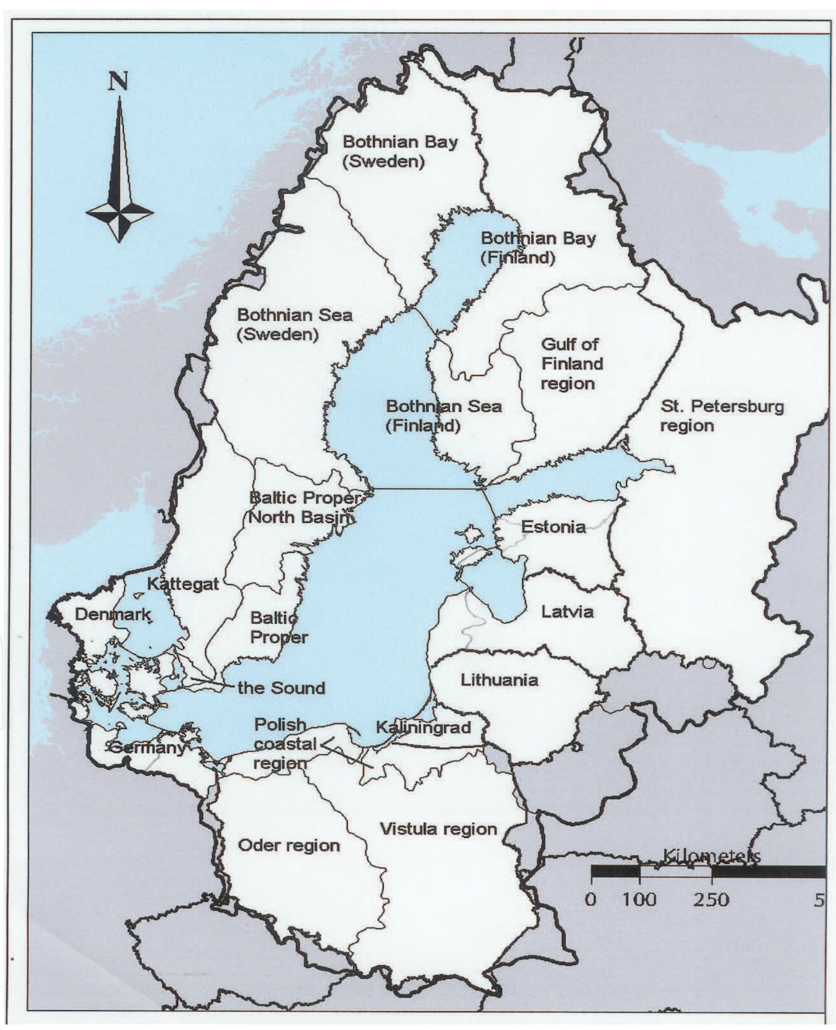
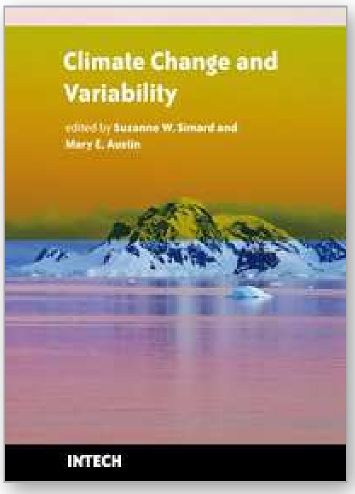


Fig. A1. Drainage basins of the Baltic Sea (originally from Elofsson, 2003). (Drainage basins in Denmark (2), Germany (2), Latvia (2), and Estonia (3) are not provided with names, but are delineated only by fine lines)



Climate Change and Variability

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Climate change is emerging as one of the most important issues of our time, with the potential to cause profound cascading effects on ecosystems and society. However, these effects are poorly understood and our projections for climate change trends and effects have thus far proven to be inaccurate. In this collection of 24 chapters, we present a cross-section of some of the most challenging issues related to oceans, lakes, forests, and agricultural systems under a changing climate. The authors present evidence for changes and variability in climatic and atmospheric conditions, investigate some the impacts that climate change is having on the Earth's ecological and social systems, and provide novel ideas, advances and applications for mitigation and adaptation of our socio-ecological systems to climate change. Difficult questions are asked. What have been some of the impacts of climate change on our natural and managed ecosystems? How do we manage for resilient socio-ecological systems? How do we predict the future? What are relevant climatic change and management scenarios? How can we shape management regimes to increase our adaptive capacity to climate change? These themes are visited across broad spatial and temporal scales, touch on important and relevant ecological patterns and processes, and represent broad geographic regions, from the tropics, to temperate and boreal regions, to the Arctic.

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