7. Optimizing policies to combat aquatic invasive species

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7.1 Introduction

Invasive species are a major threat to aquatic ecosystems. They can result in biodiversity loss and adverse environmental, economic and social impacts (Leppäkoski *et al*., 2002; Occhipinti-Ambrogi and Savini, 2003; Pimentel *et al*., 2005). Arctic areas are particularly sensitive to distortions and climate change can further emphasize their sensitivity by allowing increased human activities in the area. International ship traffic from Europe to Asia via the Northeast route in combination with the warming of the oceans can increase invasions of species in the Arctic areas. Ballast water, sediments and ship fouling associated with ship traffic provide species with routes to spread quickly over long distances in a manner which is not in line with their natural pattern of spread. According to Molnar *et al*. (2008), 31% of all identified aquatic invasions have occurred via ballast water.

Thermal pollution due to increased human activity in the Nordic regions is a largely neglected issue. Establishments of new heat-producing infrastructures can increase the temperature of water at least locally and hence provide a place for aquatic invasive species to settle down in the Arctic. Thermal pollution near the warm water discharge outlets of power plants are typical gateways for aquatic invasive species to enter an area from warmer environments.

Cooperation between stakeholders and preventive abatement (Fernandez 2007), as well as behaviour of stakeholders are important for the choice of and the effectiveness of policies to control invasive species

(Levente and Phaneuf, 2009). It can be very difficult and costly, if possible at all, to eradicate aquatic species which have been established in a region. International Maritime Organization (IMO) has suggested improvements in ballast water treatments to reduce the risk of invasion. However, for a decision-maker choosing measures to combat invasive species it is important to have information about measures which are beneficial. It is also important to notice that the measures are not chosen separately. Benefits that can be obtained through more intensive monitoring or preventive measures depend on the damage that can be avoided. As adaptation and eradication are ways to reduce the losses caused by invasive species, they can also affect the optimal monitoring and prevention policies, and hence should be studied simultaneously.

Asian clam (*Corbicula fluminea*) is a small bivalve originating from Asia, from where it has been spreading rapidly in recent decades (Darrigran, 2002; McMahon, 2002; Sousa, 2008). The clam is a freshwater species which tolerates salinities up to 13 PSU (Practical Salinity Units) and which aggressively outcompetes native invertebrates (Karatayev *et al*., 2003), fouls water intake pipes (Eng, 1979), alters benthic habitats (Hakenkamp *et al*., 2001) and reduces the recreational value of beaches (Pimentel *et al*., 2005).

Invasive species in the context of power plant investments have been studied previously (e.g. Leung *et al*., 2002), but research in the context of cold water is sparse. The goal of this study was to conduct an ex-ante analysis of management (prevention, eradication, control and adaptation) of Asian clam in an area close to the harbor of Kemi in Northern Finland. Because of thermal water pollution expected from a planned nuclear power plant, the environment was potentially suitable for the Asian clam.

Our analysis is built on a previously published stochastic dynamic programming model by Hyytiäinen *et al*. (2013). Earlier results are enriched through additional analysis with respect to some of the most critical model parameters, which are jointly minimised. The model accounts for both private and social costs of Asian clam and control measures. Our analysis contributes to the previous knowledge by taking into account how new information about the state of a clam invasion and associated risks affects the optimal management policy.

7.2 Summary

Invasive species can cause substantial damages to various industries. Ballast water, sediments and ship fouling associated with ship traffic provide species with routes to spread quickly over long distance to the Nordic conditions. In this paper we examine the control of Asian clam, an invasive aquatic species. Analysis revealed a set of relevant policies. This set includes *preventive policies* aimed at preventing an invasion, and to some extent also to adapting to the invasion and eradicating the clam from the region. Also, *mitigative policies* involved efforts on the timely detection of clam population and preventing an established population from growing thereafter or from causing excessive damages. Interestingly, monitoring and chemical antifouling as preventive measures (if taken before any invasion) could be substitutes. *Adaptive policies* focused on reducing the negative consequences of the invasion for the power plant without paying too much attention to prevention and monitoring. Finally, in *eradication policies* efforts were put on both eradication and prevention of clam invasion. These policies benefit stakeholders differently as the costs are borne by different stakeholders. Policies which focus on adaptation involve the power company over other stakeholders more than other policies. This is because adaptation focuses on mitigating failures at the power plant whereas other policies put more emphasis on reducing the clam stock.

7.3 The dynamic programming model

7.3.1 Case-study area

Our case study area is the water discharge area of a nuclear power plant, which was planned to be built in Karsikkoniemi, on the northeastern shore of the Bothnian Bay of the Baltic Sea. The place is located next to the Ajos harbour of the town of Kemi. The harbour is served with both scheduled and irregular freight traffic from European ports which are contaminated by the Asian clam. During the course of this this study the power company decided to install the power plant in another location.

Kemi is located in the northernmost corner of the Baltic Sea, where the waters are too cold for Asian clam to survive in most winters. However, heat pollution of planned power plant would have provided the Asian clam with more favourable conditions to become established. We have estimated that there would have been 200 ha of seabed where the clams could reproduce (Ilus, 2009).

7.3.2 *Objective function*

As our analysis is based on a previously presented model, we repeat here only the generic idea of the model and information necessary to interpret the results. The details of how the utility-maximising management policy was optimized are available in Hyytiäinen *et al.* (2013). Regarding the details the reader is recommended to consult the article. Given the decision to build a nuclear power plant, the social planner adjusts the prevention, mitigation and adaptation measures such that the total discounted costs from damage to shipping, power production, and people living in the area are minimized over time.

The Bellman (1957) equation of the problem is of the form:

$$
\begin{aligned}
V_t(\mathbf{x}_t) = \max_{\alpha,\beta,\gamma,\delta}\big(R_t(\mathbf{x}_t,\alpha,\beta,\gamma,\delta) + bV_{t+1}(\mathbf{x}_{t+1})\big) \quad \text{for } t = 1,..,\mathrm{T} \\
\text{s.t. } \mathbf{x}_{t+1} = \mathbf{x}_t + g(\mathbf{x}_t,\alpha,\beta,\gamma,\delta) \\
\mathbf{x}_t \ \textit{is} \text{ given}
\end{aligned}
$$

$V_t(\mathbf{x}_t)$ represents the minimized value of the risk of clam invasions and preventive measures, t is the time index and T is the total number of time periods considered, $\mathbf{x}_t$ is the vector of state variables, which contains the information on whether an invasion has been observed and what is the size of the invasion, R_t refers to the costs incurred during the period *t, b* is the discount factor (i.e. one minus annual discount rate), α,β,γ and δ are decision variables, and the constraints represent the transition equations for the state variables. As decision variables are optimise simultaneously, the model actually solve the optimal combination of measures. The optimal set of measures over time and across state space is called the optimal policy. The evolution of state variables over time is a stochastic process such that the clam population may or may not occur in a given year, the rate of population growth can vary and also the detection time of the population can vary.

The development of the clam population in the heat pollution zone is described by a stage-structured model (e.g. Getz and Haight, 1989). Recruitment and mortality functions define the growth and the proportion of clams removed from the population each year. Each year, the number of clams is reduced due to natural mortality, catastrophic mortality due to harsh weather condition, density-dependent mortality, i.e. mortality rate increasing with the size of clam population (due to competition on food and space), and mortality due to control effort (γ).

The size of clam stock is modelled by using 36 levels of stock describing the biomass of the clam population. The first class represents the situation before invasion with zero clam individuals and the thirty sixth represents the maximum carrying capacity of the area. Discovery of a clam invasion, should it occur, is expressed using a binary state variable which depends on the stock size and the monitoring effort.

7.3.3 Decision variables

Measures of prevention, eradication, control, and adaptation as proposed by Finnoff *et al*. (2010) were examined. The management of an invasion which has not yet been detected cannot be distinguished from the case where there is no invasion at all.

We consider four decision variables. Firstly, the ballast water from vessels coming from contaminated areas to Ajos harbour can be treated (α) in order to reduce the probability of invasion. Secondly, monitoring activities (β) are expected to increase the probability of detecting the invasion should it be realised. Thirdly, the clam population can be eradicated by the means of suffocation (γ), i.e. by covering the sea bed with plastic mats to kill the clam population. Fourthly, chemical antifouling system can be established at the nuclear power plant to reduce the probability of cooling water pipelines becoming clogged by the clam (δ).

7.3.4 Parameter values

We simulated a baseline scenario, which was parametrized similarly to Hyytiäinen *et al*. (2013), and thereafter altered probability and price parameters from the baseline to examine changes in the optimal management policy. The baseline cost of ballast water treatment is EUR 1,450 per ship (Seakleen® biocide, Chattopadhyay *et al*., 2004; Wright *et al*., 2007) mulitiplied by 300 ships coming from the contaminated areas. Monitoring costs due to weekly water and sediment samples are EUR 8,000 per year. The suffocation of clams by plastic mats is assumed to be EUR 18.2 per m^2 for the 5 ha closest to the shore, and EUR 25.2 for other areas. The costs of chemical antifouling are EUR 50,000 per year (Phillips *et al*., 2005). The shutdown of power plant due to clogging, if it occurs, is set at EUR 4,080,000 (Jalarvo, 2010). The value of lost recreation services due to full clam invasion for the 20,000 adults living in the area is set at EUR 50 per person per year (cf. Nunes and van den Bergh, 2004; McIntosh *et al*. 2010). Based on Gaffield *et al*.

(2003) and Dwight *et al*. (2005), the maximum human health damages are set at EUR 100,000 per year.

The probability of invasion is set at 0.05 without and 0.005 with ballast water treatment (Port of Kemi, 2012). The probability of detecting a clam invasion increases with the stock size and follows a sigmoidal (S-shaped) distribution as defined by Hyytiäinen *et al*. (2013, Appendix). Clam mortality rate due to the proportion of sea bed covered by plastic mats decreased with the stock size. The probability of additional service breaks is higher with than without chemical antifouling and decreases linearly with the size of clam. The simulations reported here were conducted for T=100 years period.

7.4 Results

7.4.1 Optimal policies under different costing scenarios

The baseline scenario represents a default situation and other scenarios are compared to it. In tables 1 to 3 the column "Cost 1" refers to the baseline scenario. The net costs of risk of Asian clam invasion in the vicinicity of the planned nuclear power plant were simulated to amount almost EUR 5 million when discounted over the 100 years time horizon. The costs are substantially higher if an invasion is realised and also the timing on invasion impact eventual costs. In the baseline scenario the model suggests to implement the monitoring programme, but not ballast water treatment in cases where an invasion either does not exist or it has not yet been observed (Table 1). When an invasion is detected, the model suggests reducing the monitoring effort (result not shown) and starting to use chemical antifouling and suffocation as methods to reduce the invasion and damage caused by it (Tables 2 and 3). This result is due to the fact that once an invasion has taken place, measures are needed to control the damages. Then the marginal benefits associated with monitoring decrease as possible new invasion would not spread uncontrolled due to measures that are already in place due to the current invasion.

The current size of invasion that has been observed also has an impact on the optimal mitigation and adaptation policy. A small invasion in Tables 2 and 3 is defined as observed clam population falling in any of clam stock size levels 1 to 10, and the percentages in Tables 2 and 3 refer to an index of average use calculated across these ten levels. In the event of a binary variable, the average use simply refers to the percentage of classes using the measure. In the event of continuous variables the extent of use in each individual class affects the result because the range of use in each individual class can range from zero (not used at all) to 100% (used at up to the maximum extent) in that class.

Medium-sized and large invasions refer to clam stock size levels 11 to 20 and 21 to 30, respectively. When a small invasion is detected, the model suggests implementing chemical antifouling in 80% of classes and covering a small core area of sea bed with plastic to suffocate the clams which have already been established. By contrast, if medium-sized or large invasion is observed, then the policy of suffocation is abandoned and the efforts are out on preventing power plant failure by chemical antifouling. In the event of a large outbreak, even monitoring effors are reduced to a minimum. These results are related to the view that once an invasion is large enough, it becomes very difficult and costly to eradicate it.

Next, the role of costs associated with each measure is examined. As Tables 2 and 3 show, the optimal policy was sensitive to assumptions regarding the costs. Decreasing the costs of measures can lead to more effective mitigation measures to be used and smaller costs to be expected due to the risk of Asian clam invasion. The analysis is carried out by reducing the costs of each measure by 30% (column "Cost 0.7" in Tables 1 to 3), by 60% ("Cost 0.4") or by 90% ("Cost 0.1"), while keeping the costs of other measures at the baseline level (i.e. the change in each cost *ceteris paribus*). When the costs of ballast water treatment decrease, already a 30% decrease is enough to provide incentives for the decision-maker to stop monitoring and start ballast water treatments. However, since time needed to detect an invasion is then expected to increase, chemical antifouling is to be used jointly with ballast water treatment. The result may seem surprising, but when taking into account that the costs of antifouling are only EUR 50,000 per year, it is a rational measure to reduce damages that may occur if an invasion takes place. Hence, these two measures are complements and monitoring is a substitute for them.

As monitoring was implemented already in the baseline scenario, it will be applied also at lower costs levels of monitoring activity. When the costs of suffocation by plastic decrease, it can become a measure that is used in small amounts also before observing an invasion. However, Table 1 suggests that this would require substantial reductions (-90% in Table 1) in the costs of this measure. This is quite expected result as the measure is costly and the benefits are obtainable only when an invasion has occurred. Should suffocation be used as a preventive measure, it could provide incentives to stop monitoring activities and ballast water treatment and chemical antifouling could substitute for monitoring.

Next we examine the impact of cost parameters on the use of suffocation by plastic in the event that an invasion has been observed. These results are highlighted in Table 2. In the baseline scenario, suffocation method is applied only in the event of a small invasion and even then it is used in very small amounts (<6% of the total area, on average 1% of area). When the costs of suffocation decrease dramatically (by 90% in Table 2), the measure becomes widely used as all the area will then be covered. In other cases only small areas are to be covered by plastic. While monitoring costs did not affect the use of suffocation, a decrease in the costs of ballast water treatment increased the use of suffocation method a little. Chemical antifouling is a substitute for suffocation as decreasing the cost of chemical antifouling would reduce the use of suffocation.

Table 3 represents the impact of cost parameters on the use of chemical antifouling during an invasion. The size of an outbreak has a clear impact on the use of antifouling. Table 3 suggests that chemical antifouling would be used in almost all cases where the outbreak is either medium-sized or large. In the event of a small outbreak, a decrease in the costs of antifouling measure will also increase the rate of use close to 100%. The substitution between suffocation and antifouling can be seen also here. When the costs of suffocation decrease substantially (by 90% in Table 3), the use of chemical antifouling also decreases in all outbreak size categories, although the decrease is smaller the larger the outbreak is. Finally, decreasing the costs of ballast water treatment or monitoring did also to some extent reduce the use of chemical antifouling in the event of a small invasion.

Table 1. The impact of reducing the cost of each measure by 30% (Cost 0.7), 60% (Cost 0.4) or 90% (Cost 0.1) *ceteris paribus* from the baseline (Cost 1) level on the use of each four measures when no invasion has been observed

Costs of ballast water treatment	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Ballast water treatment	Yes	Yes	Yes	No
Monitoring	No	No	No	Yes
Suffocation by plastic	No	No	No	No
Chemical antifouling	Yes	Yes	Yes	No
Costs of monitoring	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Ballast water treatment	No	No	No	No
Monitoring	Yes	Yes	Yes	Yes
Suffocation by plastic	No	No	No	No
Chemical antifouling	No	No	No	No
Costs of suffocation costs	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Ballast water treatment	Yes	No	No	No
Monitoring	No	Yes	Yes	Yes
Suffocation by plastic	Yes	No	No	No
Chemical antifouling	Yes	No	No	No
Costs of chemical antifouling	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Ballast water treatment	No	No	No	No
Monitoring	No	Yes	Yes	Yes
Suffocation by plastic	No	No	No	No
Chemical antifouling	Yes	No	No	No

Table 2. The extent of using* suffocation as an eradication measure after a small, medium-size or large invasion has been observed by the by the cost level of each measure**

Costs of ballast water treatment	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Small invasion	3%	3%	2%	1%
Medium-size invasion	3%	3%	2%	0%
Large invasion	2%	1%	0%	0%
Costs of monitoring	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Small invasion	1%	1%	1%	1%
Medium-size invasion	0%	0%	0%	0%
Large invasion	0%	0%	0%	0%
Costs of suffocation costs	Cost 0.1	Cost 0.4	Cost 0.7	Cost 1
Small invasion	**100%**	**1%**	**0%**	**1%**
Medium-size invasion	100%	0%	0%	0%
Large invasion	100%	0%	0%	0%
Costs of chemical antifouling	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Small invasion	0%	0%	0%	1%
Medium-size invasion	0%	0%	0%	0%
Large invasion	0%	0%	0%	0%

*Percentage of use refers to an index of average use calculated across the relevant invasion size classes. Zero percentage of use refers to the measure not being used at all in *any* relevant size class, and 100% refers to the measure being used to the maximum extent in *all* relevant size classes. Small invasion represents classes 1 to 10, medium-sized invasion classes 11 to 20 and large invasion classes 21 to 36 (36 is the maximum).
**The cost of each measure is reduced by 30% (Cost 0.7), 60% (Cost 0.4) or 90% (Cost 0.1) *ceteris paribus* from the baseline (Cost 1) level.

Table 3. The extent of using* chemical antifouling as an adaptation measure after a small, medium-size or large invasion has been observed by the costs of each measure**

Costs of ballast water treatment	Cost 0.1	Cost 0.4	Cost 0.7	Cost 1
Small invasion	40%	50%	60%	80%
Medium-size invasion	100%	100%	100%	100%
Large invasion	100%	100%	100%	100%
Costs of monitoring	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Small invasion	60%	70%	70%	80%
Medium-size invasion	100%	100%	100%	100%
Large invasion	100%	100%	100%	100%
Costs of suffocation costs	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Small invasion	20%	80%	80%	80%
Medium-size invasion	10%	100%	100%	100%
Large invasion	47%	100%	100%	100%
Costs of chemical antifouling	**Cost 0.1**	**Cost 0.4**	**Cost 0.7**	**Cost 1**
Small invasion	90%	90%	90%	80%
Medium-size invasion	100%	100%	100%	100%
Large invasion	100%	100%	100%	100%

*Percentage of use refers to an index of average use calculated across the relevant invasion size classes. Zero percentage of use refers to the measure not being used at all in *any* relevant size class, and 100% refers to the measure being used to the maximum extent in *all* relevant size classes. Small invasion represents classes 1 to 10, medium-sized invasion classes 11 to 20 and large invasion classes 21 to 36 (36 is the maximum).
**The cost of each measure is reduced by 30% (Cost 0.7), 60% (Cost 0.4) or 90% (Cost 0.1) *ceteris paribus* from the baseline (Cost 1) level.

7.4.2 The impact of probability of invasion, monitoring and preventive measure

Next we examine the impact of the probability of invasion and measures to reduce the probability. Table 4 represents the use of four studied measures conditional on four different scenarios where the probability of introducing the clam in the study area is as in the baseline scenario, or alternatively -60%, -30% or +30% compared to the baseline scenario. Preventive measures behave quite robustly within the studied range of probabilities. Monitoring is used in most situations. However, when the probability of introduction is decreased by 60%, then monitoring is stopped and ballast water treatment and chemical antifouling are used instead. The result is related to the assumption that the probability of introduction is affecting also the size of invasion. When the probability of invasion is low enough, the benefits from timely detection of Asian clam are reduced and preventive measures are used instead.

The probability of invasion also has a small impact on adaptation and eradication as a smaller probability decrease the use of chemical antifouling and increase the use of suffocation by plastic in some cases where a small invasion has been observed (Table 4).

If policies are able to decrease the probability of invasion, they will benefit also the society (Figure 1). By contrast, the society can suffer losses when the probability of invasion increases. However, when the probability is large enough, more effective measures might be used to control the risks and thus the damages could be limited up to a level.

More effective measures to control the risk of invasive species have been suggested. In the baseline scenario ballast water treatment and monitoring were voluntarily taken up. If monitoring would be a mandatory measure at all possible states of nature and at all times, the costs of Asian clam risk would increase only a little. In addition, monitoring was chosen frequently in the baseline scenario. This shows that implementing monitoring activities would not cause much extra burden to the society. By contrast, if ballast water treatment would be mandatory at all possible states of nature and at all times, the costs of Asian clam risk were 53% higher than in the baseline scenario (Figure 2). Mandatory ballast water treatment resulted in significant reduction in monitoring activities, chemical antifouling to be used both before and during an invasion, and suffocation of clams by plastic to be applied more frequently as an eradication measure. These results suggest that when preventive measures are more efficient, they can change the marginal benefits from eradication and hence provide incentives to put more effort on eradication of Asian clam. Regulations enforcing ballast water treatments could therefore have both negative (extra costs) and positive (more effort on eradication) spillovers to the stakeholders.

Finally, if both monitoring and ballast water treatment were mandatory, the costs of Asian clam risk were approximately 2.5-fold compared to the baseline scenario. Enforcing both measures could therefore cause extra economic losses to the society. As a consequence of enforcing both measures, suffocation by plastic would be used more frequently and chemical antifouling less frequently in the event of a small invasion.

Table 4. The use of mitigative, preventive, adaptive and eradicative measures (yes or no) before an invasion has been observed, and the use of eradication and adaptation measures after a small, medium-sized or large invasion has been observed by the probability of invasion*

Probability of invasion	-60%	-30%	Baseline	+30%
Before observing the invasion				
Ballast water	Yes	No	No	No
Monitoring	No	Yes	Yes	Yes
Suffocation	No	No	No	No
Chemical use	Yes	No	No	No
When a small invasion has been observed				
Suffocation	2%	2%	1%	0%
Chemical antifouling	60%	60%	80%	90%
When a medium-sized invasion has been observed				
Suffocation	1%	0%	0%	0%
Chemical antifouling	100%	100%	100%	100%
When a large invasion has been observed				
Suffocation	0%	0%	0%	0%
Chemical antifouling	100%	100%	100%	100%

*Baseline probability, +30%, -30% or -60% from the baseline.
Percentages of use in the lower part of the table refer to an index of use calculated across the relevant invasion size classes. Zero percentage of use refers to the measure not being used at all in *any* relevant size class, and 100% refers to the measure being used to the maximum extent in *all* relevant size classes. Small invasion represents classes 1 to 10, medium-sized invasion classes 11 to 20 and large invasion classes 21 to 36 (36 is the maximum).

Figure 1: The impact of adjusting probability of invasion on the costs incurred by the invasion and monitoring, prevention, mitigation, and adaptation when simulated over a hundred-years time horizon

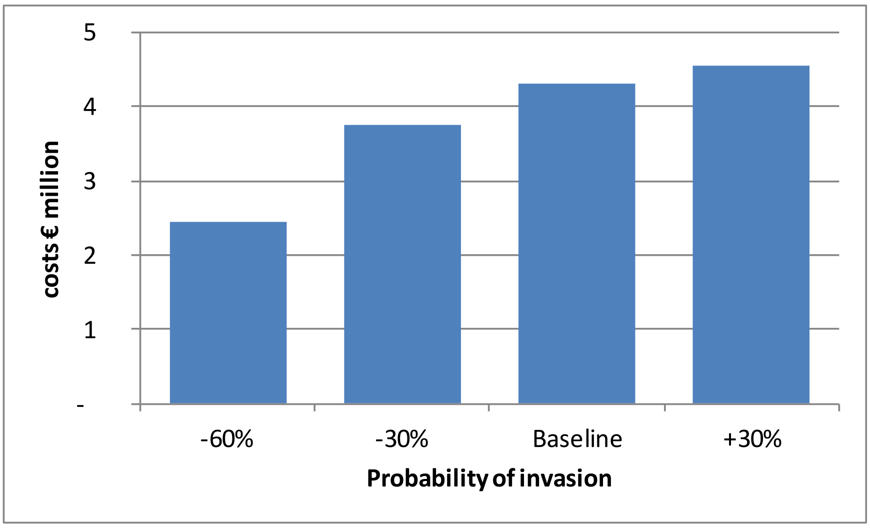
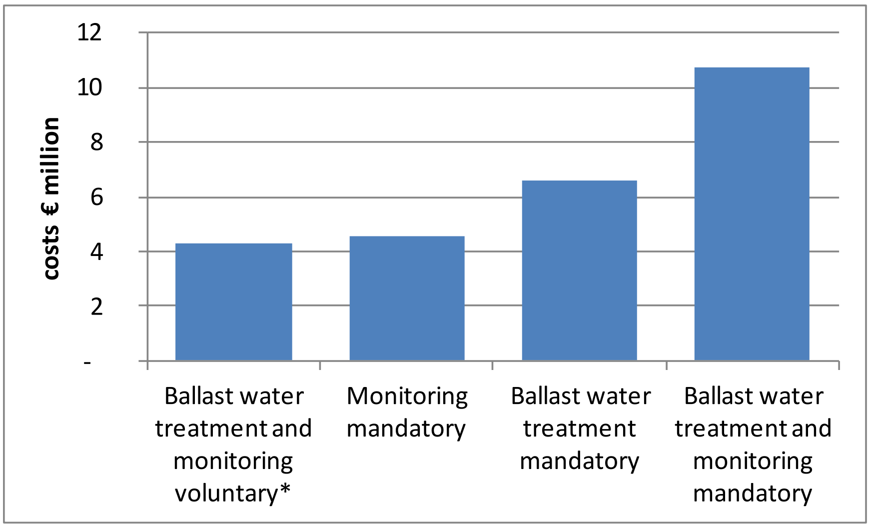


Figure 2:The impact of baseline policy and policies where monitoring, ballast water treatment or both are mandatory on the costs (the negative of the value function) over a hundred-years time horizon*



7.5 Discussion

In this study we have simulated the choice of prevention, monitoring, eradication, and adaptation measures regarding the management of Asian clam invasion. The management measures can help to narrow down the distribution of damages as they can reduce the likelihood of the most severe damages. Each management measure is justified if it can provide net savings in social costs. Although each measure can be chosen at any time and at any state of nature, monitoring and ballast water treatment for instance make the most sense before an invasion has been detected as they speed up the detection process and reduce the probability on introducing species into the region.

With the baseline parameter values it was optimal for the society to invest in continuous monitoring of the area before any invasion and thus speed up the detection process, and in addition to invest in ensuring that operational failures at the power plant are minimal after an invasion. In this case, the society would not invest in preventive measures, aim at reducing the spread of population during an invasion, or engage in other activities. However, a reduction in the unit cost of ballast water treatment can change the optimal policy: treatment, which reduces the probability of clams being introduced into the area reduces the expected damage. The treatment is taken into consideration jointly with preventing damages with chemical antifouling, but the monitoring policy is abandoned. Ballast water treatment also becomes economically attractive if ballast water treatment reduces the probability of invasion enough.

Analysis with regards to the costs of control measures revealed a set of policies to address the risk of invasive species. *Preventive policies* are aimed at preventing an invasion, and to some extent also to adapting to the invasion and eradicating the clam from the region. In *mitigative policies* efforts were put on the timely detection of clam population and preventing an established population from growing thereafter or from it causing excessive damages. Interestingly, monitoring and chemical antifouling as preventive measures (if taken before any invasion) can be substitutes. *Adaptive policies* focused on reducing the negative consequences of the invasion for the power plant without paying too much attention to prevention and monitoring. Finally, in *eradication policies* efforts were put on both eradication and prevention of clam invasion. These policies benefit stakeholders differently as the costs are borne by different stakeholders. Policies which focus on adaptation prefer the power company over other stakeholders more than other policies. This is because adaptation focuses on mitigating failures at the power plant whereas other policies put more emphasis on reducing the clams.

Monitoring is a convenient standard policy. Eradication of the clam is quite problematic as it is challenging and costly. Hence, it is fair to ask whether the harm done by invasion is permanent and whether the costs should be appraised accordingly. It was assumed that the invading clam population remains within the boundaries of the heat pollution zone. However, if the clam establishes to the warm water area and is able to adapt to the abiotic conditions of the surrrounding ecosystem, it may gradually spread outside of the warm water area and survive there as well. This has been observed in Finland with Conrad's false mussel (*Mytilopsis leucophaeata*), which survived many years only in the warm water area outside a nuclear power plant in the eastern Gulf of Finland, but has now adapted to the system and spread to natural parts of the Gulf of Finland ecosystem. In addition, warming climate may make it easier for the clam to adapt to the Nordic conditions in the future. If the clam is able to spread to larger area, suffocation by plastic mats may become impracticable. If the goal of a policy is to remain free of Asian clam, then eradication could be supported by enforcing also mitigative measures as that way the benefits from eradication would increase. However, such a policy could increase the costs to the society. A public policy also involves transaction costs, which we have not examined. The role of trasaction cost could be a topic for further research. Another aspect is that the Asian clam survives well in fresh water (cf. Sousa, 2008), and the species might be able to spread gradually to one of the 188,000 lakes in Finland. This aspect may also need to be assessed if the lakes have environments that are suitable to the Asian clam to settle down.

Ship traffic is a major risk factor for such invasion both in the Baltic Sea (Zaiko *et al*., 2011) and the Arctic. The effect of climate change on introduction of invasive species can be boosted by thermal pollution. This requires that any plans involving thermal pollution should also evaluate the risks associated with invasive species (cf. European Commission, 2003). Investing in preventive, mitigative or adaptive measures when facing the risk of invasions by invasive species is an important decision for a society.

There are various approaches to model invasive species (e.g. Perry and Enright, 2007; Bogich and Shea, 2008; Kaiser and Burnett, 2010; Leung *et al*., 2002) which can have benefits in other types of decision situations. Our framework considers simultaneously the optimal allocation of effort between pre- and post-invasion measures. This is an important methodological issue because prevention and treatment choices do not always, if ever, separate. Our approach is convenient also because it accounts for uncertainty about future and for the option to adjust invasive species control policy according to the current situation, and it accounts for state-specific marginal costs and benefits. The framework as such is applicable to other ecosystems in the Arctic although the parameterizations must be adjusted case-by-case.

7.6 References

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