Combating aquatic invasive species:
An optimization framework addressing prevention, mitigation and adaptation

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Introduction

- Invasive species can severely harm aquatic ecosystems by reducing biodiversity and causing adverse environmental, economic and social impacts
- The eradication of aquatic invasive species can be difficult and costly
  - ⇒ Is it more profitable to invest in prevention than in adaptation and mitigation after invasion?
  - ⇒ How much effort should we put in preventive measures?
  - ⇒ Prevention should be continuous action because as it is not known *a priori* when species are invading!
- This presentation is based on the model represented in: Hyytiäinen, K., Lehtiniemi, M., Niemi, J.K., Tikka, K. 2013. An optimization framework for addressing aquatic invasive species. *Ecological Economics* 91: 69-79.

Ship traffic is introducing new species

- Ballast water, sediments and ship fouling
- Larger ship sizes and drive speeds have increased the number of invasions globally
- Globally 31 percent and in the Baltic Sea over 50% of identified aquatic invasions occur via ballast water.
  - IMO has suggested improvements in ballast water treatments
- Thermal pollution can help new species to enter to the Baltic sea
  - At the time of this study, a new nuclear power plant was planned new near Kemi, Finland

Objectives and method

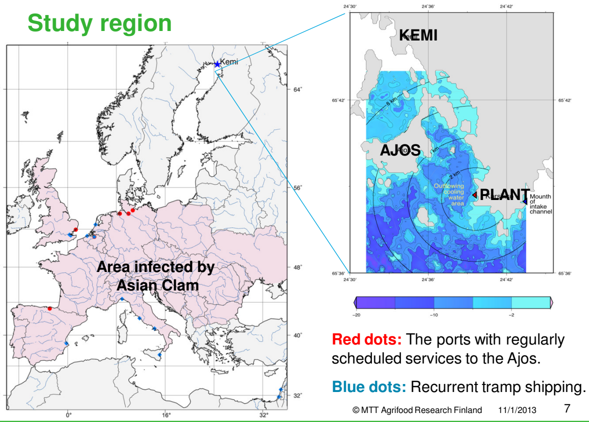
- Our goal is to examine the management of Asian clam in a thermal water pollution area of a planned nuclear power plant
- Stochastic dynamic programming is used
  - Can take into account new information when it arrives
  - The invasion is managed similarly to "no invasion" until the point where it is observed. It usually takes some years from invasion to detection and thus the clam population can grow in size.

Optimisation and simulation model

Asian clam
(*Corbicula fluminea*)

- A possible aquatic invasive species in the Baltic Sea
- Native to Southeast Asia, but has invaded lakes and rivers in Europe
- Survives in different salinities (0-13 PSU) but not cold winters
- The clam survives best at low depths (0 to 2 m)
- The heat pollution area of a nuclear power plant creates conditions suitable for the species to survive in Kemi (potential area 200 ha)
- Aggressively outcompetes native invertebrates, alters habitats and diminishes the recreational value of public beaches.
- Fouling at power plants has caused problems => Eradication by mechanical cleansing (shutdown and dewatering a power plant) or by continuous chlorination (potential damage for water ecosystem)

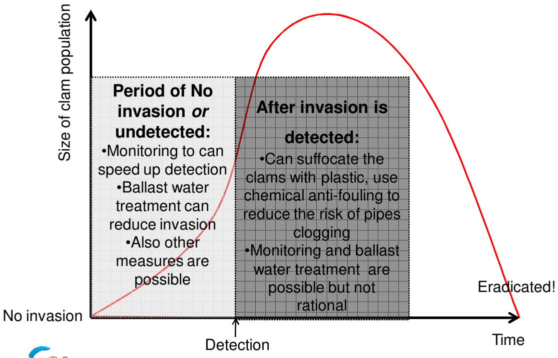
Study region



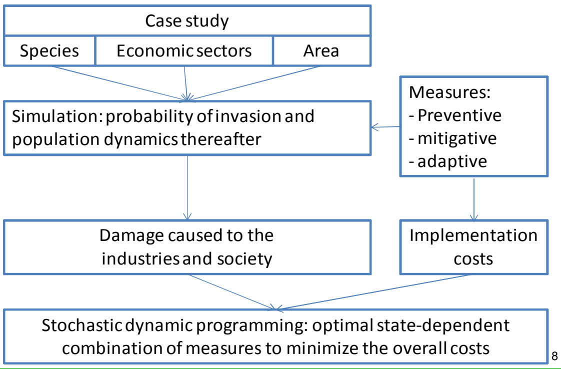
Red dots: The ports with regularly scheduled services to the Ajos.

Blue dots: Recurrent tramp shipping.

An example of possible invasion



Modelling framework



State variables

- Clam stock size S_t: 35 classes and a zero-class for no invasion in the current year
- Discovery of a clam invasion in the area depends on the stock size and the monitoring effort and it is expressed using a binary state variable [Detected, Not detected]

$$n_t = f(S_t, \beta_t),$$

Decision variables

1. *Prevention* by ballast water treatment of vessels coming from contaminated areas to Ajos harbour
2. *Monitoring* effort (water and sediment sample testing) that makes it possible to observe the invasion earlier
3. *Control & eradication* by covering sea bed with plastic mats
4. *Adaptation* by installing chemical anti-fouling system to the power plant to reduce the probability of extra service breaks

Population dynamics

- An age class (*i*=1,..,5) model

$$p_{i,t} = p_{i-1,t-1}\,(1-m1_{i-1,t})(1-m2_t)(1-m3_{i,t})(1-m4_t)$$

- Natural (*m1*), density-dependent (*m2*), catastrophic (*m3*) and measure-related mortality (*m4*)
- Number of individual new clams depends on the introduction ($v_{t-1}\eta_{t-1}$) and regeneration (*g*) parameters:

$$p_{1,t} = v_{t-1}\eta_{t-1} + g_t$$

Annual costs depend on possible invasion and the management measures

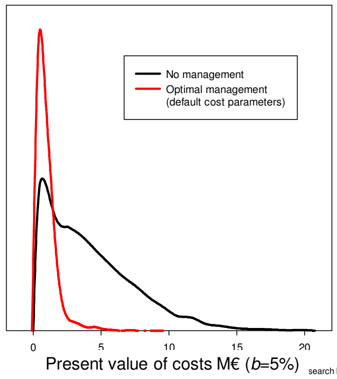
$$C_t = c1_t(\alpha_t) + c2_t(\beta_t) + c3_t(\gamma_t, n_t, S_t) + c4_t(\delta_t, n_t, S_t)$$

$$c5_t(\delta_t, n_t, S_t) + c6_t(n_t, S_t) + c7_t(\delta_t, n_t, S_t$$

Cost item		Annual cost
c1	Ballast water treatment	435,000 €
c2	Monitoring	8,000 €
c3	Suffocation with plastic	0 - 50,050,000 €
c4	Chemical use	50,000 €
c5	Additional nuclear power plant service break	4,000,000 €
c6	Damage to recreation	0 - 1,000,000 €
c7	Healt damage from chemical use	0 - 100,000 €

The cost of suffocation is the area applied (max 200 ha) times labor and material costs (18.2 €/m² for the first 5 ha and 25.2 €/m² thereafter)

Probability distribution for the discounted costs with and without management (*b*=5%)



The Bellman equation

$$\min_{\{\alpha,\beta,\gamma,\delta\}} V_t(n_t, S_t) = -C_t(\alpha_t, \beta_t, \gamma_t, \delta_t, n_t, S_t) + bE(V_{t+1}(n_{t+1}, S_{t+1})) \quad \text{for } t = 1, \ldots, T$$

$$\text{s.t.} \quad S_{t+1} = f_s(n_t, S_t, \alpha_t, \beta_t, \gamma_t, \delta_t)$$

$$n_{t+1} = f_n(n_t, S_t, \alpha_t, \beta_t, \gamma_t, \delta_t).$$

and n_t and S_t are given.

Minimised costs as a function of state

This period costs

Minimised costs from the next period

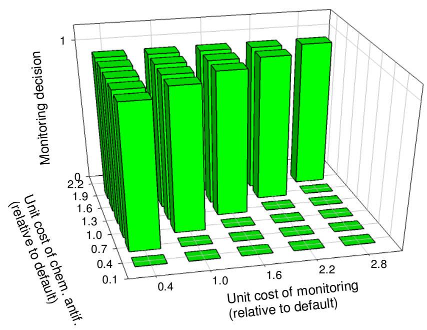
Decision variables

Transition equations (i.e. dynamics)

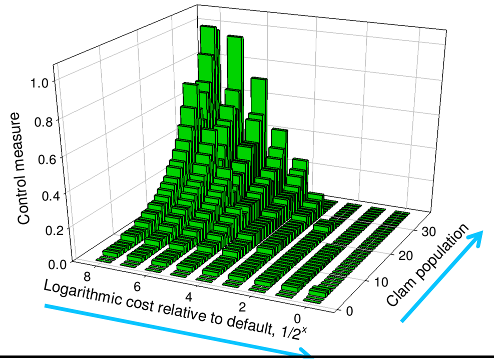
Cost alternatives	control variable	cost level	Clam population none	small (10)	medium (20)	high (30)
Default	α ballast water	100 %	no	no	no	no
	β (monitoring)	100 %	yes	no	no	ADAPTIVE POLICY
	γ (suffocation)	100 %	0.0%	0.0%	0.0	
	δ (chemical ant	100 %	no	yes	yes	yes
Alternative 1	α ballast water	10 %	yes	no	no	no
	β (monitoring)	100 %	no	no	no	PREVENTIVE POLICY
	γ (suffocation)	100 %	0.0%	0.0%	0.0	
	δ (chemical ant	100 %	yes	yes	yes	yes
Alternative 2	α ballast water	100 %	no	no	no	no
	β (monitoring)	10 %	yes	yes	no	ADAPTIVE POLICY
	γ (suffocation)	100 %	0.0%	0.0%	0.0	
	δ (chemical ant	100 %	no	yes	yes	yes
Alternative 3	α ballast water	100 %	no	no	no	no
	β (monitoring)	100 %	yes	no	no	MITIGATIVE POLICY
	γ (suffocation)	10 %	0.0%	2.6%	5.1%	
	δ (chemical ant	100 %	no	yes	yes	yes
Alternative 4	α ballast water	100 %	no	no	no	no
	β (monitoring)	100 %	no	no	no	ADAPTIVE POLICY
	γ (suffocation)	100 %	0.0%	0.0%	0.0%	
	δ (chemical ant	10 %	yes	yes	yes	yes

Results

Monitoring and antifouling are substitutes



Control and eradication depend on the clam population size and the costs of measures



Aknowledgement: This study was carried out as part of the project *Protection of the Baltic Sea: Benefits, Costs and Policy Instruments* financed by the Finnish Advisory Board of Sectoral Research

Other aspects

- An invasion becomes more likely over a longer time span as a constant threat of invasion exists
- The uptake of ballast water treatment depends on discount rate and probability of invasion
- The range of realizations across with preventive policy (less costly ballast water treatment)
- The switch between monitoring and antifouling depends on the cost parameters

 20

Conclusions

- The optimal policy depends on the costs of measures, externalities, and the size of population after detection.
  - Expected consequences of different policies also vary.
- The externalities of invasion risk should be taken into account in large-scale investments in the energy sector!
  - Do private sectors have incentives to preventive measures?
  - Reduced competitiveness of nuclear power ⇔ other energy sources
- IMO has recommended ballast water treatment
  - This measure is taken if it is efficient or inexpensive
  - If mandatory, chemical antifouling would be favored over monitoring and eradication would be quicker

 11/1/2013 21