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Analysis

An optimization framework for addressing aquatic invasive species

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ABSTRACT

This study develops a bio-economic model framework to optimize the management of aquatic invasive species. Stochastic dynamic programming is applied to investigate when and to what extent a society should engage in efforts to reduce the likelihood of an invasion, to control and eradicate a newly established population, and to adapt to damages. The framework is parameterized for a potential Asian clam (*Corbicula fluminea*) invasion in the warm water discharge area of a nuclear power plant planned on the northern shores of the Baltic Sea. The sensitivity analysis reveals three distinct strategies: an adaptive strategy, which reduces the damage that an existing invasive species population causes to the private sector; a preventive strategy, which delays the invasion and the resulting damage; and a mitigative strategy, which puts effort into timely detection, control and eradication of the newly established population. Choice of the optimal strategy is sensitive to the unit costs and effectiveness of the measures required, to the level of externalities and to the size of the clam population after the invasion has been detected. The results emphasize the need for the energy sector to identify and internalize the external costs of potential invasions when making any large-scale investment plans.

1. Introduction

The introduction of invasive species has been identified as one of the major threats to aquatic ecosystems, where the alien species cause biodiversity loss and adverse environmental, economic and social impacts (Leppäkoski et al., 2002; Occhipinti-Ambrogi and Savini, 2003; Pimentel et al., 2005). The eradication of aquatic invasive species after they become established is very difficult. Accordingly, managers and policy makers should pay attention to preventing introduction of potential invasive species. Then again, preventive measures and policies should be economically viable. This raises questions such as whether the expected benefits of preventive measures are likely to exceed their cost and how much society should invest in reducing the probability of invasion in comparison to post-invasion measures geared to controlling the population and adapting to damage.

The principal global pathway by which aquatic invasive species are introduced is ship traffic, which causes transfers by ballast water, sediments and ship fouling (Molnar et al., 2008). Ship traffic is an efficient vector that enables alien species to overcome natural dispersal barriers, such as vast oceans. Larger ship sizes and drive speeds have increased the number of successful invasions globally. According to Molnar et al. (2008), over 80% of all identified aquatic invasions have been unintentional and 31% have occurred via ballast water.

In the Baltic Sea, more than 50% of all introductions occur via shipping (Zaiko et al., 2011). Thermal pollution areas located near the warm water discharge outlets of power plants are typical gateways for aquatic invasive species entering the area from warmer environments. One such species is the Asian clam (*Corbicula fluminea*), a small bivalve that is native to Southeast Asia. It has been spreading rapidly worldwide in recent decades (Darrigran, 2002; McMahon, 2002; Sousa, 2008). It was purposely introduced on the west coast of North America in the early 1900s and has since spread to occupy ponds, lakes, streams and reservoirs virtually throughout the United States (Vaughn and Spooner, 2006 and references therein). It was first reported in Europe in the Minho estuary, Spain, in 1989 (Araujo et al., 1993) and is now a major component of the benthic fauna there in terms of density and biomass, accounting for more than 95% of the overall benthos biomass (Sousa, 2008). The clam is a freshwater species which tolerates salinities up to 13 PSU, and thus its further spread to estuaries and brackish seas is possible. It has been shown to aggressively outcompete native invertebrates (Karatayev et al., 2003), foul water intake pipes (Eng, 1979), alter benthic habitats (Hakenkamp et al., 2001) and diminish the recreational value of public beaches (Pimentel et al., 2005). Fouling at power plants has caused problems and costs and has been eradicated using either mechanical means or continuous chlorination (Goss and Cain, 1975; Satpathy et al., 2010). Mechanical cleansing requires shutting down and dewatering a power plant, resulting in

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severe economic losses, while chlorination may affect the aquatic ecosystem outside the discharge pipes.

Optimal management of the risk of invasive species is a rather new, but increasingly popular topic in the economic literature. The principal modeling approach adopted in the case of already established non-indigenous species has been a continuous-time optimal control (Olson and Roy, 2002; Eiswerth and Johnson, 2002; Buhle et al., 2005). Other optimal control models include those of Knowler and Barbier (2000), who analyzed the economic consequences of invasion in a predator–prey setting, and Ranjan et al. (2008), who extended the modeling framework to include options for both preventing an invasion and mitigating its impacts. In an example of a discrete-time application for an aquatic invasive species, Leung et al. (2002) developed an optimization framework to quantify the relative merits of different management strategies. Their model was parameterized for a representative lake with a power plant before a potential zebra mussel (*Dreissena polymorpha*) invasion. Fernandez (2007) emphasized that ships are the primary channel for aquatic species transportation and developed a game-theoretic model for aquatic trade where ports in different countries minimize their costs from the damage caused and abatement measures occasioned by invasive species. Cooperative and preventive abatements were found to be optimal vis-à-vis other policies. Levente and Phaneuf (2009) combined the demand for recreational boating with an ecological model describing the spatial and temporal spread of zebra mussels in Wisconsin and demonstrated that accounting for the behavioral responses of boaters is essential to the effectiveness of particular policies.

There are no corresponding studies investigating optimal management of Asian clam invasions. Rosa et al. (2011) carried out a survey to evaluate the costs of the Asian clam invasion in Portugal, which was the gateway for this species to Europe some 30 years ago. The researchers show that as of 2010 the invasion had caused only minor costs to agriculture and different industries, including drinking water treatment and thermal power, but concluded that the costs may increase markedly in the near future as the invasion reaches the stage of full colonization. Earlier experiences from other invasive clam species (e.g. McMahon and Williams, 1986) suggest that serious infestations of sites such as nuclear power plants may not occur until as many as 50 years after the first observations.

The objective of the present study is to build up a modeling framework that can be used in ex-ante analyses of how to manage aquatic invasive species. The framework allows us to simultaneously consider the quantity of resources to be allocated in reducing the probability of an invasion or in adapting to or mitigating its negative externalities. The management problem can be formulated from the point of view of either the social planner or the private sector. The problem is solved by the use of stochastic dynamic programming, which is a powerful tool for solving sequential and discrete-time management problems. Stochastic dynamic programming has been used earlier in determining how to best manage invasive species in both terrestrial (Eiswerth and van Kooten, 2002; Bogich and Shea, 2008) and aquatic ecosystems (Leung et al., 2002). As an extension to earlier studies, we consider both private and social costs and include all four general policies – prevention, eradication, control and adaptation (Finnoff et al., 2010) – as decision variables to respond to the risk of an invasive species and the associated damages.

Our approach is suited particularly well to examining both the optimal timing and the optimal magnitude of prevention, eradication, control and adaptation simultaneously—as opposed to studying these separately and in a deterministic setting. It can contribute to the literature by taking into account how new information about the state of a clam invasion and its associated risks affect the optimal magnitude and timing of different management options. We construct a case study and examine crucial factors such as causes of mortality and age class structure, which drive the population dynamics and expansion of the clam population in the case study area and are thus important when determining the optimal decision. The model is parameterized for a potential Asian clam invasion in the northern Baltic Sea, where a planned nuclear power plant is likely to cause heat pollution in its water discharge area.

This paper consists of four sections. The next section describes the overall modeling framework, depicts the case study area, defines the decision variables reflecting different mitigation and adaptation policies, and presents a cohort model describing the dynamics of the invasive species population. In addition, it details the costs and effectiveness of control measures and the costs of externalities and explains how the management problem was solved. The third section presents the numerical results and examines how the probability and consequences of the putative clam invasion are affected by the choice of decision variables. We also consider optimal strategies under different parameter assumptions. The fourth section discusses the key findings and caveats of the research.

2. Materials and Methods

2.1. Model Framework

Fig. 1 shows the overall structure of our model framework and the steps required when evaluating the optimal allocation of effort to manage the risk of invasive species. Five key steps may be specified: (1) Identifying the potential species, the economic sectors affected by – or increasing – the risk of invasion, and the geographical area under consideration; (2) estimating the probability of invasion and describing the expansion of the population after the invasion; (3) selecting relevant measures to manage the risk and to describe their effects on the probability and consequences of an invasion; (4) quantifying the costs incurred by different implementing stakeholders; and (5) using stochastic dynamic programming to solve the optimal management rules recursively.

2.2. Case Study

Our case study area is the water discharge area of a planned nuclear power plant in Karsikkoniemi, on the northeastern shore of the Bothnian Bay of the Baltic Sea. Fig. 2 shows the location of the planned plant and its heat pollution area and of the adjacent town of Kemi and its harbor, Ajos, which is located on an island connected by bridge to the mainland. Fig. 3 shows the location of the study area and the Asian clam-infested European ports with regular or at least frequent shipping to Ajos. The ballast water of vessels coming into Ajos from infested areas provides the Asian clam with a continuous means of transport to the area. To date the species' possibilities to spread to the area have been poor due to the cold winter temperatures. However, the heat pollution from the

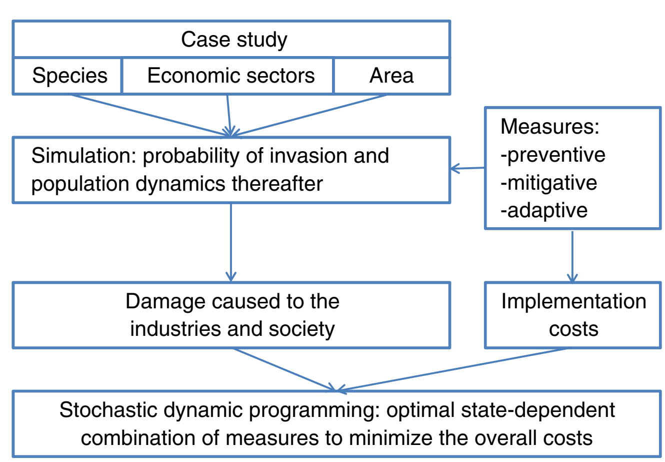

Fig. 1. Overall structure of the modeling framework.