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Editorial

The economics of invasive species control and management: The complex road ahead

As the world's economies continually grow more interconnected, an increasing number of species are being introduced into areas to which they are not native. Some of these non-native or alien species are considered invasive, with Executive Order 13112 defining an invasive species as "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health" (ISAC, 2006; NISC, 2008). The Invasive Species Advisory Committee (ISAC) suggests expanding this definition to include species that adversely affect animal or plant health, and to clarify what is meant by causing harm. Specifically, an alien species would be considered invasive if it generates ecological and economic damages that exceed any offsetting benefits, such that the net impact is negative (ISAC, 2006).

Only a small proportion of introduced non-native species – perhaps one out of every thousand, based on the 10–10–10 rule (Williamson, 1996) – are considered invasive by traditional definitions. But the associated damages can be so severe that invasive alien species (IAS) have become a real concern. IAS are believed to be the one of the most important causes of biodiversity loss worldwide (MEA, 2005; Holmes, 1998), as invaders may prey upon native species or outcompete native species for habitat and resources (ISAC, 2006). For instance, mute swans have displaced many native waterfowl in North America, feral goats in Maui have purged native Hawaiian plants that were maladapted for grazing, and lake trout are outcompeting native cutthroat trout in Yellowstone Lake (ISAC, 2006). Examples of pathogens spread from livestock to threatened wildlife include the Rinderpest virus which has spread from Zebu cattle to Serengeti wildebeest and cape buffalos (McCallum and Dobson, 1995; Plowright, 1982), the tapeworm *Cysticercus tenuicollis* which infects Andean deer in Chile, and several viruses (rabies, canine parvovirus, canine adenovirus, and canine distemper virus) which spread from domestic dogs to the endangered Ethiopian wolf (Laurenson et al., 1988).

Additionally, IAS can spread diseases to people, livestock, and cultivated plants. West nile virus and avian influenza are examples of invasive pathogens spread to humans by wildlife. Avian influenza is also spread to domestic poultry from wild birds (Shim and Galvani, 2009). Some other pathogens that are spread from wildlife to domestic livestock include bovine tuberculosis, which is spread from white-tailed deer to cattle in Michigan (Schmitt et al., 1997), and brucellosis, which is spread from elk to cattle in Wyoming (Dobson and Meagher, 1996).

IAS can also directly damage agricultural crops and nursery stocks. Soybean aphids, for example, have caused significant damage to soybean crops (Zhang et al., 2010), and emerald ash borer has destroyed millions of dollars of ash trees in nurseries, residential communities, and in the wild (Sydnor et al., 2007). Rangelands are also threatened by a variety of invasive species such as yellow starthistle (*Centaurea solstitialis*) in California (Eiswerth and van Kooten, 2002).

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Finally, IAS can damage or degrade human-made assets (e.g., power plants, boats, piers, and reservoirs) and natural assets (e.g., beach fouling), reducing both production processes and recreational opportunities. For instance, zebra mussels clog water intakes for power plants and manufacturing facilities (Connelly et al., 2007) and can also degrade beaches (Murray et al., 2001).

The overall economic damages from IAS are estimated to be substantial. Pimentel et al. (2005) estimate annual IAS damages within the U.S. to be $128 billion. Estimated damages are over $4.5 billion in Australia (Sinden et al., 2004; Bomford and Hart, 2002; McCleod, 2004), and over $2 billion in New Zealand (Barlow and Goldson, 2002; Clout, 2002). While the estimates are based on assumptions that are subject to debate (Holmes et al., 2008; Hoagland and Jin, 2006), it is generally accepted that damages due to IAS are large and that IAS problems deserve our attention. However, simply recognizing that damages are large does not properly inform managers about the appropriate course of action. A better understanding of how IAS generate damages, and of how human choices can reduce IAS risks so as to reduce or mitigate damages, can help determine how much to invest in different management actions.

To guide management efforts, the National Invasive Species Management Plan (NISC, 2008) defines four phases of investments: (i) prevention, (ii) early detection, rapid assessment and rapid response (EDRR), (iii) control and management, and (iv) restoration. Prevention involves identifying potential threats before they are introduced (e.g., Kolar and Lodge, 2002), and making investments to keep them out. Often, these problems are modeled as a form of biological pollution resulting from international trade (e.g., Horan et al., 2002; Horan and Lupi, 2005; Knowler and Barbier, 2005; Margolis et al., 2005; Simberloff, 2006; Perrings et al., 2010), with management intended to limit the risk of exposure.[1]

Prior work has shown prevention can be more cost-effective than control of established populations (Leung et al., 2002). But, as prevention will never be 100 percent effective, *in situ* management strategies are still needed. Early detection and rapid response (EDRR) involves making investments to identify and address newly introduced, localized populations of invasive species. Passive discovery of IAS (i.e., not actively searching for invaders) can result in a significant time lag between introduction and discovery (Costello and Solow, 2003), during which time the invader can gain a significant foothold and spread to multiple areas. In these cases, the costs of controlling or eradicating an invader will generally be lower if the invader is targeted before it can successfully establish and spread. However, it may be difficult and costly to actively search for and discover a newly introduced invader. Therefore, there may be tradeoffs associated with detection and response efforts.

Control and management is required once a species has established. Often, eradication is not possible, so we take this phase to include damage mitigation efforts. This may include behavioral changes to reduce exposure to invasion-related damages (e.g., limiting exposure to an invasive toxin or pathogen). Or, as many damages are due to ecological interactions, mitigation may also involve management actions aimed at native species or habitats that are at risk from the invader. Ecological restoration efforts taking place during an invasion may also be considered a form of mitigation.

Current levels of resources devoted to prevention and *in situ* management of IAS problems are substantial. For instance, sea lamprey suppress the populations of valuable Great Lakes fisheries (Lupi et al., 2003), and international programs to control sea lamprey in the Great Lakes have been estimated to cost $10 - $15 million annually (Corn et al., 1999). Eradication costs for the emerald ash borer in southeastern Michigan alone are estimated at up to $350 million over the next decade (Herms et al., 2004). *In situ* control cost estimates can often vary widely. The cost of controlling zebra mussels in the Great Lakes has been estimated to be $100 - $400 million annually (WDNR, 2004), yet other sources (Connelly et al., 2007) provide estimates of costs that are an order of magnitude lower. While there is uncertainty associated with measuring such costs, the potential for adaptation and learning also affects the magnitude of costs. Indeed, there may be significant cost savings associated with adopting more economically efficient approaches to management. In particular, large savings may arise from designing strategies that take into account the jointly determined economic and ecological feedbacks arising from *in situ* management (Finnoff et al., 2005). Bioeconomic modeling is a useful tool for understanding and quantifying these feedbacks to develop more efficient management strategies (Barbier, 2009).

[1] Margolis et al. (2005) discuss that managers may disguise protectionism policies as invasive species policies, and that it may be difficult to distinguish legitimate invasive species measures from disguised protectionism.

The articles in this issue address all four phases of investments to manage invasion, with several articles jointly considering multiple investment phases. Two articles use bioeconomic models to address EDRR (Haight and Polasky, 2010; Kaiser and Burnett, 2010). Haight and Polasky point out that, particularly early on, managers may be uncertain about the existence or magnitude of an invasion. Invasion-related costs may be excessive if managers passively wait for clear evidence of an invasion before deciding to act. It may therefore be beneficial to invest in monitoring prior to, or possibly in conjunction with, implementing controls. Haight and Polasky model a partially observable Markov decision process to illustrate optimal monitoring and control decisions, and they also quantify the expected value of information obtained via monitoring activities.

Kaiser and Burnett (2010) point out that EDDR can also be a spatial problem, with spread and establishment processes occurring concurrently for some rapidly spreading invaders. They model the brown tree snake (*Boiga irregularis*), which may spread into new areas prior to attaining establishment-level densities in any one location. Establishment occurs if containment is not realized in a particular location. The result is increased damages and reduced efficiency of control efforts in that location, and increased spread to other locations. Kaiser and Burnett focus on the early stages of invasion and address the questions of where and when to best target controls in locations, beyond points of entry, where there is evidence of an invader. Using a spatio-temporal bioeconomic model incorporating spatial heterogeneity for ecological and economic parameters, they find significant gains from developing strategies that vary across the ecological and economic landscapes. Additionally, they investigate gains from considering the intertemporal landscape, illustrating how targeting locations where the current-period net benefits of control are small can sometimes yield large future gains.

Once a species has become established, *in situ* management involves investments to limit the size and spread of the invader population. As with EDDR, questions arise as to where and when to target control efforts, as well as how to target them. It may make sense to target native species or habitats in addition to the invader, thereby mitigating ecological stresses and associated damages. Additional complexities arise when there are restrictions on the types of controls that are used, or how they are implemented, so that management can only be second-best. Models that incorporate realistic management restrictions or mitigation efforts targeted at native ecosystems are generally much closer to reality than the highly simplistic first-best, single species models that have characterized much of the prior bioeconomic literature on invasive species.

Two of the articles in this issue focus on second-best issues in spatio-temporal models of control (Albers et al., 2010; Finnoff et al., 2010). Albers et al. incorporate spatial heterogeneity into a bioeconomic model that combines *in situ* population controls with import inspections to prevent additional introductions, and also mitigation via management of competing habitat uses (livestock stocking) and habitat restoration efforts. They analyze both first-best and second-best approaches, where second-best management is characterized by the implementation of certain controls being restricted over space. Specifically, they consider the use of uniformly applied controls when spatially explicit controls are actually optimal. They compute the welfare loss associated with the uniform approach and analyze the conditions under which uniform policies may not be too bad.

Finnoff et al. analyze a situation in which the implementation of controls is restricted over time, due to the computational difficulties of deriving an intertemporally optimal solution. They compute the welfare loss associated with an "equilibrium-based" approach, in which the control strategy maximizes long-run equilibrium net benefits as opposed to the present value of net benefits, and analyze the conditions under which the efficiency loss is not too great. The work of Albers et al. and Finnoff et al. also complements the work of Kaiser and Burnett, who compare efficient EDRR strategies with myopic and spatially non-targeted strategies.

Zhang et al. (2010) focus on spatial management in an agricultural context, where management in their model can target an invasive insect directly via pesticides, or indirectly by managing the habitat of the insect's natural enemies. In the case of habitat management, they investigate the optimal spatial configuration of habitat investments over the landscape, taking into account spillover effects on neighboring fields. They find habitat management may not always be beneficial, highlighting the important role played by the opportunity cost of not using the land for agriculture which is often overlooked by non-economic analyses. When habitat management is beneficial, they find that a "random" archipelago configuration yields the largest net returns. This result is in contrast to the conventional notion that there are added benefits from setting aside large, connected habitat areas for wildlife (e.g., Parkhurst and Shogren, 2007). In Zhang et al.'s analysis, the natural enemies are also insects and these do not require large habitat areas. However, dispersing the habitat areas across crop fields provides more points of attack for the natural enemy. The added benefits outweigh the added planting and harvest costs associated with a more disjointed field.

Fenichel and Horan (2010) also consider management of a biocontrol, though in a second-best fashion. The invader is managed only via a biocontrol – a sportfish. Yet, the only control available to managers is the level of stocking of the sportfish, as anglers remain unregulated. Hence, the control imperfectly targets both the biocontrol and the invader. The analysis also highlights how *in situ* resource management endogenously determines damages. Damages are endogenously affected by management in all the analyses described so far, but a distinguishing feature of Fenichel and Horan's analysis is that the invader in this case simultaneously generates costs (beach fouling) and benefits (as a prey food source to a valuable sport fishery). Like Zivin et al. (2000), who analyze the management of feral pigs in California, Fenichel and Horan find that the management regime determines whether the invader is a source of net benefits or net damages. But in contrast to feral pigs, which were valuable due to hunting benefits, alewife are valuable due to the ecosystem service (i.e., serving as a food source) they provide to the valuable biocontrol species. Accordingly, net benefits associated with alewife depend on the *in situ* management of multiple, interacting species.

Finally, Haab et al. (2010) also specifically address the determination of damages, though they focus on different stages of the externality process. Haab et al. (2010) analyze how human behavior associated with resource consumption affects exposure to, and hence economic damages from, invaders that generate adverse health impacts. They use revealed and stated preference approaches to calculate the economic impacts of risk information and countervailing information about seafood that may have been exposed to the invasive dinoflagellate *Pfeisteria piscidia*, putting consumers at risk of exposure to a harmful toxin. While risk communication can, in principle, be used to mitigate damages by altering risk perceptions and behavior, Haab et al. find such approaches may be challenging because risk information may have different effects across different gender and race groups.

A common theme of the studies in this special issue is complexity. Invasion problems are complex, either due to the many stages of an invasion, uncertainty, limitations on management tools, heterogeneous human responses to risk, and complex intertemporal, spatial, and ecological interactions. This complexity complicates the derivation of management strategies that promote efficiency, even if the efficient strategy turns out to be not all that complex or difficult to implement. The articles in this issue provide insights into dealing with many forms of complexity. They also provide guidance for a number of invasion problems, though we stress that complexity limits the ability to generalize results across different invasion problems. The degree to which the management insights derived here are generalizable can only be ascertained by analyzing many more case studies that do not shy away from complexity.

The articles in this special issue represent a mix of theoretical and empirical analyses that serve to provide IAS management insights. Looking ahead, further integration of theory with sound empirical analyses is an important gap that needs to be filled by economists working in concert with other sciences. There are many reviews of invasive species that bemoan the dearth of sound empirical studies documenting economic costs and benefits for IAS control and prevention (Colautti et al., 2006; Andreu et al., 2009). Interestingly, where economic costs are available for some species, the analysis has often been conducted without the participation of economists (Zavaleta, 2000; Sydnor et al., 2007) or without the integration with economic theory or models (Pimentel et al., 2005). As many economists (e.g., Hoagland and Jin, 2006) have emphasized, such empirical estimates can go astray. Analyses such as those by Kaiser and Burnett, Zhang et al., and Haab et al. help bridge this gap, but more integration is needed.

A final challenge is communicating the importance of economics to natural resource managers. The articles in this special issue are the result of a workshop at Michigan State University that engaged researchers and managers on how to deal with the growing threats of invaders. It is clear that managers understand economic and ecological tradeoffs exist, but they are often skeptical of bioeconomically derived recommendations and often lack the ability to assess the quality of competing empirical estimates. Models that are simple to present and to solve may come across as overly simplistic and therefore not very useful, while analyses based on highly complex models and methods may be too intimidating to promote much confidence. These challenges can likely be overcome with more case studies, more engagement, and perhaps some natural experiments whereby bioeconomic strategies are implemented on a small scale and tested against conventional strategies.

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