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DecisionMaking Under Risk in Invasive Species Management: Risk Management Theory and Applications

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Abstract

Invasive species management is closely entwined with the assessment and management of risk that arises from the inherently random nature of the invasion process. The theory and application of risk management for invasive species with an economic perspective is reviewed in this synthesis. Invasive species management can be delineated into three general categories: exclusion, detection, and control. Key ideas and approaches in current literature and potential applications of existing theory are presented in this synthesis. Economic literature tends to emphasize either individual management strategies, such as preventing invasive species from entering an ecosystem or controlling extant populations. There is also a growing focus on the optimal allocation between multiple activities for the same species such as between prevention and control. The key biological and economic relationships included vary across frameworks and objectives.

The synthesis is organized into sections, which cover the salient aspects of invasive species management by separating the major veins of economic literature on decisionmaking. Section 1: invasive species management is discussed and a brief overview of risk management and economic theory is provided. Section 2: an overview of the key factors causing invasions is presented. Section 3: exclusion activities to prevent introductions is the focus. Section 4: control activities after the species has been successfully introduced are emphasized. Section 5: the tradeoffs between multiple management strategies are addressed. Section 6: a discussion concludes the synthesis.

Keywords: Decisionmaking, economics, invasive species, non-native, risk management.

Introduction: the Role of Risk Management in Invasive Species Management

An overview of decisionmaking under risk in invasive species management, with an emphasis on the economic literature, is provided in this synthesis, and the following topics are discussed: an overview of invasive species management; the key factors causing invasions; the exclusion activities aimed at preventing introductions; postintroduction control activities; and tradeoffs between multiple management strategies. Scientists have studied the impacts of invasive species on nonnative ecosystems for many years. Recently, the public has become more aware of the problems associated with invasive species, due largely to greater levels of media coverage and public information campaigns regarding the issue. Government agencies deal explicitly with risk in their ongoing invasive species management programs; thus, risk management plays a crucial role in these programs.

The synthesis is organized into sections, which cover the salient aspects of invasive species management by separating the major veins of economic literature on decisionmaking. In section 1, invasive species management is discussed, and a brief overview of risk management and economic theory is provided. In section 2, an overview of the key factors causing invasions is offered. The focus is on exclusion activities to prevent introductions in section 3. Control activities after the species has been successfully introduced are presented in section 4. The trade-offs between multiple management strategies are addressed in section 5. The synthesis concludes with a discussion in section 6.

Owing to the breadth of this risk management, and discrepancies among discipline-specific terms, the sections below clarify the usage of terminology in this synthesis.

Defining Risk

The word risk has three common definitions: (1) an [adverse] event (as in “non-native invasive species are a risk to ecosystems"); (2) the probability that the event will occur (as in "the goal of management is to reduce the risk of invasive species introductions to new ecosystems"); and (3) the probability that an event will occur weighted by the consequences of the event (as in "the possibility that invasive species will harm oak forests is a substantial risk"). In economics, the term is most often used to describe situations in which the results of a decision follow some sort of probability distribution. The probability distribution may be objectively determined, either through a priori reasoning (such as the probability that a fair die will show the number 6) or through repeated experiments. Probabilities may also be subjectively determined without clear experimental evidence. These are known as beliefs. The term ambiguity applies when probabilities are not known with certainty. When probabilities are involved, it is possible to define (and maximize) objective functions that are weighted by these probabilities. We adopt the economics usage of the term risk, referring to a situation in which management decisions affect outcomes and their probabilities.

There may be cases when it is not possible to assign probabilities to outcomes. One example is the case of global climate change as discussed by Woodward and Bishop (1997). Although it is possible to assemble a panel of experts to glean their beliefs about possible dangers, and it is possible to delineate the range of possible options, Woodward and Bishop argue that it is not reasonable to assign probabilities to these options based on the number of experts sharing a particular belief. Woodward and Bishop call this pure uncertainty, following the distinction as defined by Frank Knight in 1921. Others term this ignorance (Arrow 1972 and Hurwicz). In these cases, it is not possible to define a function that is weighted by probabilities.

However, the term uncertainty has a number of different definitions, including simply: uncertainty arises whenever a decision can lead to more than one possible consequence (Hammond 1998). This definition includes situations such as lotteries where probabilities are well-established. In the risk assessment literature, uncertainty arises due to the lack of precise knowledge about parameters, models, or scenarios. It can also come from differences among modelers (Linkov and Burmistrov 2003). We adopt the usage in the risk analysis literature, where uncertainty refers to this lack of precision, and use the term pure uncertainty to refer to the case where it is not possible to assign probabilities.

Risk Assessment and Risk Management

Risk analysis consists of risk assessment and risk management activities. Risk assessment is defined as "the systematic, scientific characterization of potential adverse effects of human or ecological exposures to hazardous agents or activities" (The Presidential Congressional Commission on Risk Assessment and Risk Management 1997). Risk assessment informs risk management decisions by supplying this characterization of potential outcomes and probabilities. In invasive species management, risk assessment informs two specific areas: the risk surrounding introductions of new species, including vectors, species, and potential damages; and the risk associated with existing invasives, including the potential spread and damages caused by established species (Andersen and others 2004). For example, the date of the introduction of a pest, like the Siberian moth (*Dendrolimus superans sibiricus* Tschetverikov) may not be known. However, numerous factors can be used to construct probabilities to characterize the chances of the Siberian moth being introduced at any particular date. These factors include the number of pathways that it has, the level of interaction between the United States and its native territory, and the introduction success of similar species. The frameworks for assessing invasive species risk vary substantially (Woodbury and Weinstein, this volume).

Risk management, as the Presidential Commission (1997) states, is "the process of identifying, evaluating, selecting, and implementing actions to reduce risk to human health and to ecosystems." Risk management relies heavily on underlying risk assessments to establish the potential for adverse events occurring as a consequence of a particular action. In addition, risk management must account for resource, social, ethical, political, and legal constraints. In this synthesis, with our focus on the economic literature, we pay particular attention to how resource constraints guide risk management decisions.

A (Brief) Primer in Economic Theory

Some common economic concepts and terms used throughout the review are briefly covered in this section. Welfare economics focuses on the implications of alternative resource allocation methods on social welfare, both in market and nonmarket settings. One criterion used to judge whether an outcome is efficient is Pareto optimality; a Pareto optimal allocation is one in which no one can be made better off without making someone else worse off. A competitive equilibrium will be Pareto optimal unless there are market failures. One example of a market failure is an externality, where a consumer or producer generates costs that they do not bear themselves. Invasive species represent an externality in that accidental introductions of invasives impose a cost to society and can occur as a consequence of consumption or production activities. Therefore, one role of management is to align individual incentives with social goals—to internalize external costs—so that a Pareto-optimal allocation will result. One possible tool that can be used to align incentives is a tax on the externality, calculated as the difference between private cost and social cost at the optimum. This is known as a Pigovian tax. Another tool is a system of tradable permits in which an agency sets the total allowable level of the externality, but the allocation of that level emerges out of a permit market. Both of these have been suggested as ways to handle the invasive species that are introduced as a byproduct of economic activity.

When situations are risky, it may not be possible to guarantee a particular outcome, but it may be possible to choose among alternative probability distributions by choosing the level of conditioning variables. Economists have developed theories of rational choice that are appropriate in risky situations, including the Expected Utility theory of von Neumann and Morgenstern (1944) for objective probabilities and the Subjective Expected Utility Theory of Savage (1954) for subjective probabilities. For example, it may be possible to reduce the probability of species introductions by altering trade levels. Expected utility theory is one framework that can guide these choices. The objective function consists of the expected level of utility, where utility represents an individual's satisfaction derived from their preferences for consuming or experiencing goods and services. Utility functions, or numerical representations of individual preferences, can account for costs and benefits that accrue under unknown future events. The vonNeumann-Morgenstern utility function offers one characterization of an individual's preferences over all potential outcomes. Expected utility theory essentially states that such a characterization exists if an individual's preferences conform to certain axioms. Such representations allow for identification of optimal behavior that maximizes expected utility. They also provide a basis to compare different risk preferences, or attitudes toward risky situations. For example, an individual may be risk-averse (i.e., he or she prefers a situation with little or no risk to a more risky situation even if the expected outcome in the risky situation is higher).

When probabilities cannot be assigned to possible outcomes—situations of Knightian pure uncertainty—it is possible to use other criteria, such as maxi-min (choose the course of action that leads to the best case when the worst state of nature occurs) or mini max-regret (choose the course of action that leads to the lowest possible regret, Loomes and Sugden 1982). Ciriacy-Wantrup (1964) promoted the Safe Minimum Standard criterion, which would suggest that irreversible losses should be avoided. This is echoed in the Precautionary Principle of Perrings (1991). These criteria can be justified as rational in situations where possible future outcomes are knowable, but the probabilities of those outcomes are not.

The theme of optimization over time is prominent in the area of natural resource economics, and the balance of the productivity of natural assets with that of other assets typically characterizes an optimal solution. In the context of renewable resources, the optimal harvest rate is one that equates the returns from the stock of the resource to the returns one could achieve in an alternative investment. Extinction can be an optimal outcome, particularly if there are no nonmarket benefits associated with the resource. This theme is echoed in the literature on invasive species, where both corner solutions (eradication) and interior solutions (control at some positive population level), are possible. The probability of random catastrophic events has been shown to increase the appropriate discount rate (risk

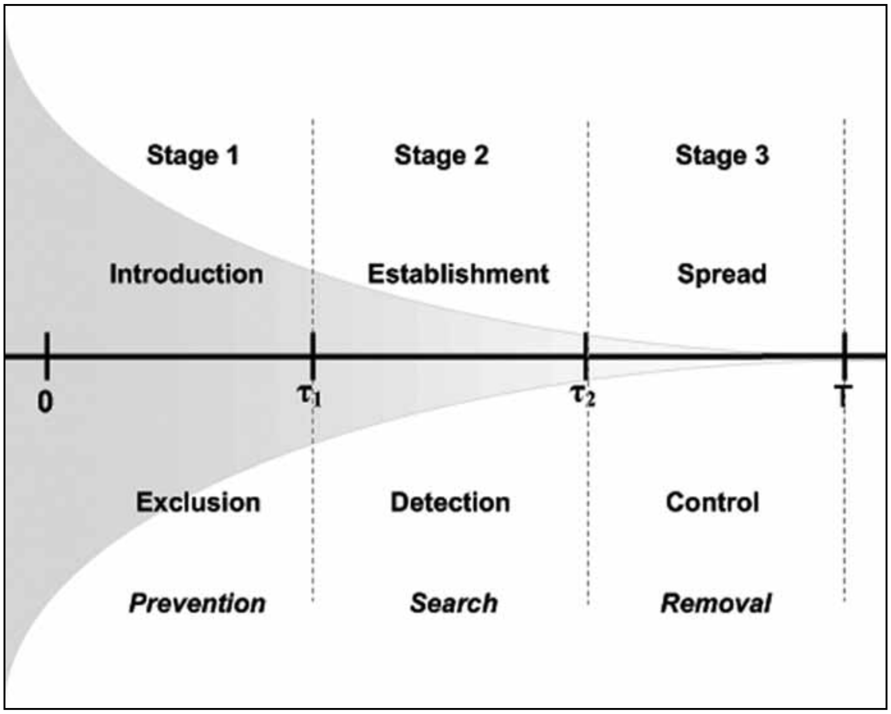

Figure 1—Management activities and corresponding invasion process stages. This diagram depicts the major management activities—exclusion (prevention), detection (search), or control (removal), which correspond to the stages of the invasion process—introduction, establishment, and spread—as used in this synthesis. Whereas many of these activities occur concurrently, the focus in the synthesis is largely on the individual management activities (sections 3 and 4) with a lesser emphasis on the relationships between multiple activities (section 5). To illustrate the simplest example, the finite-horizon timeline represents a situation where an agency is managing a single species and activities are undertaken in isolation. Thus, the manager first engages in preventing introductions and, if that fails, switches to detection (at time period τ_1) and then potentially to controlling the species if it establishes and spreads (at time period τ_2)

adjusted discounting) and accelerate harvest (Reed 1984). It is also possible to factor in the stochasticity associated with population growth (Pindyck 1984), and this can either introduce caution or intensify harvest pressure. An alternative approach is to specify some probability of extinction and then set management levers so that this probability is not exceeded; for example, one possible criterion is that the probability of extinction should never be higher than 1 percent (Haight 1995, Montgomery and others 1994). Analogous criteria can be used in invasive species management.

Invasive Species Management

Invasive species management spans a variety of activities that can be grouped into three areas: exclusion, detection, and control (Figure 1). The management activities concentrate on different parts of the invasion process, which comprises three main stages: introduction, establishment, and spread. Even though agencies engage in additional activities, these categories capture the majority of decisions facing managers. Thus, the synthesis is arranged according to the general management categories. Although the theory behind the risk management models is discussed, the emphasis is on the potential outcomes.

Various species may be in different stages of the invasion process so that management agencies engage in exclusion, detection, and control activities simultaneously. Additionally, the dynamic nature of the invasion process implies that it is optimal to make management decisions in a forward-looking manner by accounting for future stages in current actions. Existing literature often analyzes such aspects of the relationships between the management activities. Many papers in the economic literature, for example, consider the optimal allocation between exclusion and management activities for the same species.

Factors Fueling the Invasion Process

Key factors are focused on in this section that are thought to contribute to the risk of invasions, including factors that can be controlled for the purposes of risk management. One commonly held view is the disturbance hypothesis (Dalmazzone 2000), which asserts human activities and their accompanying disturbances to the environment primarily cause both species' introductions and their subsequent invasions of new ecosystems. In addition, human and commodity movement provide the major vectors for species to enter new ecosystems. Risk management requires the knowledge of which vectors pose the greatest chance for new introductions of invasives, and this translates to a reliance on comprehensive risk assessment (e.g., cargo data in "Factors Fueling the Invasion Process;" Koch and Smith, this volume). Current risk assessments typically do not use an economic framework and economic data to understand the relationship between trade and invasion risk. Costello and others (2007) provided one of the few examples of such a framework when they parameterize a model based on invasive species introductions data to find that the threat of new invasions depends on the past trade level with a region and the past exposure to invasive species. Using invasion data from the San Francisco Bay over a period of 138 years, they identify trade partners from the Atlantic/Mediterranean and West Pacific regions as posing the greatest risk of introductions to the San Francisco Bay Area. Explicitly incorporating economic aspects can potentially alter the results of a risk assessment and, in turn, change suggested approaches to risk management. In this case, risk management can potentially reduce risks through targeted trade restrictions and economic mechanisms. However, such restrictions can produce unintended negative consequences if inappropriately targeted or implemented.

Economic activities can produce other externalities such as land disturbance and the loss of biodiversity. Scientists have long argued that biodiversity loss increases an ecosystem's susceptibility to invasion. This idea stems from a theory postulated by Elton (1958) that diverse habitats can better fend off invasions. One major reason for biodiversity loss to affect invasions arises from the interactions between native and non-native species. Many experts believe that interactions between native and exotic species are generally detrimental, often stemming from competition over limited space or food (e.g., Shigesada and Kawasaki 1997; Tilman 1982, 2004). However, studies have shown that the relationship between native and non-native species is quite complex, and some species may actually benefit due to mutualism (Bruno and others 2003). Hence, a simple classification based on the number of species in a geographic area can not necessarily predict the susceptibility to new invasions; instead, the effects of the interaction often depend on the spatial scale (Fridley and others 2004, Meiners and others 2004).

Apart from the externalities from economic activities, each species' unique biological traits largely affect their impacts in a new ecosystem. Thus, risk assessment emphasizes biological traits of potential invasive species as indicators of potential risk (Downing and others, this volume; Iverson and others, this volume; Pontius and others, this volume). However, given the numerous possible factors and characteristics that contribute to a species' invasiveness, the selection of appropriate characteristics poses much difficulty. For example, Rejmanek (1999) posited that all salient biological characteristics provide some information on the potential risk posed by a species. Besides the species specific biological traits, landscape characteristics of the potential habitat also provide important indicators (Page-Dumroese and others, this volume; Royo and Carson, this volume; Shore and others, this volume).

Other researchers, such as Williamson (1996), believe that very few characteristics provided suitable predictors for invasions. Williamson (1996) argued that most invasion patterns elude generalization over wide taxonomic ranges due to the specificity of success factors. Still, propagule pressure, habitat suitability, and prior invasion success serve as rough indicators of invasion success. Of these, propagule pressure, or the number of organisms in an area, is the variable that can be most directly altered through risk management. As the propagule pressure increases, the chances of survival increase, whereas the effects of predators, stochasticity, and the Allee effect ("Eradication as an Optimal Strategy") diminish. Unsurprisingly, a positive correlation exists between propagule pressure and disturbed land. Disturbed land tends to have greater economic activity, which translates to increased exposure to vectors for exotic species.

In addition to establishing general predictive factors, Williamson (1996) formulated the Tens' Rule, which postulates that of the exotic species introduced to an area, 10 percent will become established and 10 percent of those will spread (approximately 1 percent of introduced species). Although this is a very general rule-of-thumb, assigning probabilities with educated guesses for the underlying probability distributions can produce an approximation of the actual invasion process (e.g., Lockwood and others 2001). Using such approximations, a decisionmaker can perform a more structured analysis, which potentially widens the possible management options available (Perrings 2005, "Understanding Risk Mitigation Versus Adaptation"). However, whereas general rules, such as the Tens' Rule, serve as useful benchmarks to provide a sense of the magnitude of potential invasions at the aggregate level, they do not predict outcomes at a micro-level scale. The pine shoot beetle (*Tomicus piniperda*) is an example of how aggregate level predictions can fail at the regional level. Pine-shoot beetle sightings were met with strict quarantines due to its classification as a high-risk pest causing potentially high economic damages. The pine-shoot beetle actually produced relatively low damages, but the quarantine measures resulted in significant losses to the pine industry in the affected areas (Haack and Poland 2001). As the authors state, "… it is difficult for agencies like APHIS to change course once they have enacted a federal quarantine given that the concerns of the uninfested states have been heightened by the initial establishment of the quarantine." Thus, whereas risk assessment can inform risk management, it could potentially exclude key impacts such as in the economic consequences of quarantines on industry or the irreversibility of certain actions.

Risk management frameworks incorporate these relationships into the decisionmaking problem facing the agency manager along with the spatial, temporal and stochastic dimensions. However, there is no clear rule dictating which relationships must be included or how they should be included. Inclusion of specific relationships depends largely on the agency manager's objective, and the choice of relationships will impact the model's outcome.

Exclusion Strategies and Risk Management

Exclusion strategies occupy much of the limelight in risk management for invasive species because the majority of species introductions have been attributed to human activities ("Factors Fueling the Invasion Process"). Reducing the risk of species introduction involves managing the potential pathways that species use to enter a new ecosystem. Market-based mechanisms, such as tariffs or permits, can regulate trade behavior and produce socially optimal outcomes ("Policy and Market-Based Mechanisms to Manage the Risk of Introductions"). The optimal strategy necessary to prevent a species introduction may be substantially affected by whether or not you know the probability distribution of the invasion process.

Policy and Market-Based Mechanisms to Manage the Risk of Introductions

The varying policies and market-based mechanisms aimed at reducing introductions produce substantially different outcomes and can lead to unintended effects such as economic losses as illustrated by the papers in this section. Increased trade volume creates greater opportunities for species to engage in ecosystem hopping, leading some to argue for tighter trade restrictions to reduce this risk (Jenkins 1999). However, the sheer volume of trade coupled with strong political resistance and social welfare losses requires a targeted approach. The first step is identifying the high risks within trade ("Factors Fueling the Invasion Process"). The next step involves evaluating mechanisms, which reduce this risk. Market-based mechanisms can ensure socially optimal outcomes, but their implementation is often confounded by political issues and the inability to properly capture the full implications of these mechanisms. Optimal tariff policy is discussed in a majority of these papers, but the role of politics should not be overlooked. Several policies, such as phytosanitary measures (https://www.ippc.int/IPP/En/default.jsp), aim to reduce the potential damages of pests that arrive through trade. However, it can be argued that extant tariffs and trade policies often stem more from political motives than the conscious desire to mitigate environmental damages produced by trade. As Margolis and others (2005) illustrated, delineating protectionist tariffs from those designed to mitigate invasion risk requires knowledge regarding the social costs inflicted by invasive species and the value the government places on societal welfare. Without this information, it is hard to gauge the consequences of tariffs. Achieving socially optimal outcomes involves two steps: (1) identifying the mechanisms that induce behavior to produce the socially optimal outcome, as demonstrated in the papers in the following sections, and (2) implementing these mechanisms. The first step pertains to this synthesis; however, the obstacles that arise during implementation must also be kept in mind while evaluating these mechanisms.

Trade Policy—

Models that utilize taxes to manage invasive species introductions are discussed in this section. Although the economic focus on invasive species is relatively new, frameworks from the environmental economics literature can inform decisionmaking models. For example, Costello and McAusland 2003, Knowler and Barbier 2005, and McAusland and Costello 2004 draw from the pollution literature by treating invasives as a negative externality comparable to pollution. Knowler and Barbier (2005) evaluated the extent to which market-based mechanisms, such as taxes, can produce a socially optimal level of exotic plant imports. Private industry and agriculture rely heavily on exotic species for a range of purposes (McNeely 1999). To address the unintended consequences of intentional introductions, Knowler and Barbier assessed the effects of Pigovian taxes for the private nursery industry. Pigovian taxes impose a penalty on the loss associated with an agent's actions; in the pollution literature, Pigovian taxes are levied against firms based on the amount that they pollute ("A [Brief] Primer in Economic Theory"). Setting optimal levels of Pigovian taxes requires perfect information on firm practices, and, more importantly, the impacts of those actions. Assessing the contribution of individual firms on overall species' introductions is difficult. However, from a social welfare perspective, optimal Pigovian taxes provide a better alternative than total prohibition of exotic imports. As shown in the pollution literature, market-based mechanisms such as Pigovian taxes can internalize the externalities of private actions to result in a socially optimal outcome.

To assess the impacts of a Pigovian tax, Knowler and Barbier developed a model to analyze the decision facing a policymaker regulating a private industry. Specifically, they studied the commercial nursery industry, where importing, breeding and selling behaviors often occur without consideration of the potential loss to society from unintended spread following the sale of the exotic species. The social benefits of plant imports are represented by the discounted aggregate profits of the private nursery industry. The expected losses depend on the quantity of land invaded by the species once the invasion occurs. The overall net benefits are the total profits until the time when the invasion occurs minus the discounted losses following the invasion. A hazard function characterizes the probability that the species will arrive by a particular date. The hazard function in their model incorporates the salient factors driving invasions, such as the invasiveness of the species and the number of firms in the industry. Solving the dynamic optimization problem yields a time path of the optimal number of firms in the industry. The application of this model requires empirical analysis. However, the uncertainty in several relationships, such as potential damages, potential invasiveness, and the time of the invasions, necessitate assumptions based on educated guesses and a priori beliefs. To facilitate the model's implementation, Knowler and Barbier made several simplifying assumptions in their analysis of the saltcedar (*Tamarisk* spp.), an ornamental shrub, which became invasive. The hazard function is estimated from a survey of decisionmakers on their perceived risk of invasiveness. Based on USDA data for the horticultural industry, the industry's profit function is fitted at the state level using a second-order polynomial equation. The analysis of four model specifications for different treatments of the relationship between the number of firms and the hazard function, coupled with varying specifications of the hazard level (low and high hazard) and four levels of profitability illustrate two key points: (1) the optimal number of firms is always lower than the optimal long-run equilibrium without invasion risk and (2) the optimal number of firms and level of Pigovian taxes is sensitive to the hazard level. Under some conditions, the optimal number of firms is zero (i.e., it is optimal to prohibit all imports of the exotic species).

Conventional wisdom states that tariffs, or any protectionism, will reduce invasion risk as a consequence of a reduction in trade; Costello and McAusland (2003) demonstrated that this may not be the case. Protectionist policies can achieve a reduction in overall invasive species introductions. However, the failure to account for the role of agricultural damages skews the interpretation of the true efficacy of protectionist policies, which may actually increase invasion risk. This result is an example of the aforementioned disturbance hypothesis ("Factors Fueling the Invasion Process"), and, in this case, human disturbance is often believed to increase the chance of invasion. Higher tariffs on agriculture will reduce agricultural imports, so domestic producers will increase production. This, in turn, increases land disturbance as more land is converted to agricultural production. This increase in land disturbances facilitates invasions by extant invasives as well as new ones, thus, any reductions in invasion risk from the tariffs are offset by increased risk from land disturbance. A complex theoretical framework presented in their paper incorporates the potential damages from different trade levels and commodities, the supply and demand elasticities for various commodities, and the level of protectionism on these commodities. Though their model is theoretical and difficult to parameterize, the analysis illustrates that setting policy based on conventional beliefs may lead to suboptimal results. As Costello and McAusland stated, "…the rate of introduction causing crop damages provides minimal (if not outright misleading) information about the rate of ecologically damaging invasions. This has important implications for the use of existing estimates of invasion-related damage; while existing estimates are staggering, they omit invasion-related costs to biodiversity and other non-monetized assets."

Whereas Costello and McAusland's model does not incorporate averting behavior by farmers or the role of invasive species management activities, several salient observations are provided in their paper such as the usefulness of current introduction estimates and the impact of using incorrect empirical models. Also illustrated is the value of expanding the breadth of the analysis to better inform decisionmaking by including both direct and indirect consequences of incentive mechanisms, in addition to the underlying stochastic relationships. The crucial component is acknowledging and incorporating the economic aspects, such as price distortions and demand and supply responses to import changes. An often overlooked aspect of invasive species policies is addressed—the potential behavioral responses by the import-competing industries who respond to the supply changes resulting from the tariffs impact on the importing firms. Tariffs may produce positive effects for some firms while concurrently altering production choices by other firms, which can lead to other changes such as an increase in domestic agriculture intensity. The need for analysis to encompass the full extent of changes resulting from a policy is illustrated in this paper.

In a subsequent paper, McAusland and Costello (2004) analyze the combination of tariffs and monitoring practices to achieve the socially optimal level of prevention activities. The assumption that all components are known is shown in their model. Whereas tariffs and cargo inspections reduce the introductions of invasive species, the omission of explicit stochastic elements excludes this model from frameworks that can be implemented directly for risk management. The results of the analysis, though, are worth mentioning as they can provide insight for risk management practices:

1. It is always optimal to have a positive tariff although it may be optimal not to have inspections in some situations (i.e., if the level of infection of the partner is so high that it is optimal to not inspect but instead to set a high tariff).

2. Higher infection rates necessitate higher tariffs but not necessarily greater inspections.
3. Extending the time horizon results in greater inspections but not necessarily higher tariffs.

They draw an analogy between this situation and the one involving pollution emissions, which requires monitoring to determine the pollution levels to levy the correct taxes. Here, the monitoring entails inspections that sort the uninfected goods from the infected ones. The findings from the inspections determine the amount of monitoring needed in the future and the level of taxes that should be set. At sufficiently high levels of infection, the optimal strategy is to discontinue monitoring and rely solely on taxes to repay the costs of invasives.

Permit Trading Models—
Horan and Lupi (2005) explore a tradable permit program as an alternative to current regulation of ballast water to reduce the number of invasive species entering the Great Lakes. Permits allow commercial vessels to release ballast water, which carries species. However, releases are unobservable; thus, they must be estimated as a function of vessel characteristics and management practices. The authors find that although permit trading produces the most efficient outcomes, appropriately targeted technology regulations can lead to similar results. Emission permits are considered more efficient than regulation because they provide a performance-based mechanism, which is why permits are preferred for pollution control. However, unlike pollution emissions, the existence of invasive species in ballast water is unknown beforehand, and, even after the species have been released, the species introductions are not observed due to a lack of appropriate monitoring technology. Also, a potentially lengthy lag between introductions and spread (Crooks and Soulé 1999) further obfuscates the ability to pinpoint the individual polluter. This means that a specific vessel cannot be connected to a specific species introduction, because the outcome of a vessel's actions is not directly observable. To overcome this lack of information, tradable permits can act as a proxy for the potential risk posed by each vessel via a performance measure that incorporates vessel-specific characteristics and firm actions aimed at reducing introduction risk.

Horan and Lupi's permit trading model (2005) relates to a previous one introduced in Horan and others (2002) regarding prevention strategies in risky and uncertain scenarios ("Pure Uncertainty Versus Risk in Assessing Prevention Strategies," below). In this recent model, each firm introduces a range of species, measured by their biomass, through their vessels. The potential biosecurity actions that a firm can employ to reduce the risk of transporting species are considered inputs. There are two stochastic relationships: (1) the size of the biomass, which depends upon the biosecurity inputs and the firm's characteristics, and (2) the post-introduction probability of establishment and spread, which depends on the given control strategy, the biomass, and the biosecurity inputs. Combining these two separate stochastic relationships characterizes the probability of a firm introducing an invasive species. The authors characterize the total probability of an individual species introduction as the sum of the separate probabilities of introduction over all firms. This total invasion probability drives the expected damages resulting from a species invasion. The policymaker's objective is to minimize the social costs, which are represented by the costs of biosecurity inputs for all firms plus the expected damages resulting from successful invasions. Focusing on ballast water released by vessels in the Great Lakes, Horan and Lupi illustrate the model using data and estimates for probability of introduction and successful invasion, firm characteristics, biosecurity inputs, and costs.

Optimally, the marginal cost of an action (choice of biosecurity input) for each firm equals the expected marginal benefits of that action, or the decrease in expected damages. Permit trading requires much information including vessel- and firm-specific characteristics and actions, all potential invaders and expected damages, and probabilities for introductions and successful invasions as they relate to new habitats and firm behavior. Creating permits based on the specific characteristics of each vessel and firm and for each specific species would be the first-best option. However, with this scheme, the multiple permits for each species and each vessel would result in a cumbersome system. A second-best permit trading scheme, related to the first-best option, produces a desirable outcome but with only one permit for all species, instead of several different ones targeting different species. Whereas less efficient than the first-best approach, a single permit reduces the information requirements because the policymaker does not require detailed information for each specific firm and vessel. This approach finds that the first-best scheme provides the least costly option followed by the second-best trading scheme when simulating three risk scenarios for different mechanisms: (1) the first-best trading scheme with varying permits, (2) the second-best scheme with one permit, and (3) various technology regulations. This result holds for relatively moderate permitted levels of invasive species introductions; the difference between the regulation mechanisms fades with stricter permitted levels. Interestingly, their outcomes suggest that technology regulations can inexpensively mitigate risks if suitable technology is chosen and appropriately regulated. Although direct implementation requires several assumptions, this model offers a useful tool to analyze potential regulatory policies while accounting for the major stochastic relationships. Also, it takes the Knowler and Barbier (2005) analysis ("Trade Policy") one step further by demonstrating the potential loss incurred by simplifying assumptions to address information gaps.

By characterizing the unknown elements of any situation, managers can employ explicit frameworks to evaluate the potential outcomes of various policy mechanisms as illustrated in these papers. The authors were forced to make several simplifying assumptions to deal with a lack of data or to address the stochastic elements, but they still provide valuable analysis. They also illustrate the importance of evaluating policies in an explicit economic framework to capture the full extent of the repercussions such as the social welfare loss from posing industry-wide taxes or implementing tariffs without accounting for the changes in industrial behavior.

Pure Uncertainty Versus Risk in Assessing Prevention Strategies

Whereas it is assumed in most papers that decisionmakers have some information that can help characterize risk in invasive species management, there may be cases (Knightian pure uncertainty) where it is misleading to assign probabilities, and information is lost when the true lack of knowledge is overlooked. Horan and others (2002) tackle this issue using an aggregate model to capture preinvasion decisions by firms whose actions can introduce invasive species. Horan and others argue that invasions cannot be analyzed using standard economic theory, which assigns probabilities to all situations regardless of the level of uncertainty. Traditional risk-management models function similarly by characterizing all risk, irrespective of the level of uncertainty, with probability distributions. The authors argue that standard expected utility theory (or traditional risk-management) does not apply to low probability events, especially when the events are catastrophic, as they could be in the case of invasive species. Non-native species invasions can be considered catastrophic since irreversibility of invasions poses potentially very high costs and irrevocable damage to native ecosystems. To illustrate the effects of incorporating differing levels of uncertainty into the decisionmaking framework, the authors identify optimal prevention strategies by firms under the traditional risk-management framework (with assumed probabilities) versus an ignorance model (full uncertainty, which is not characterized by probabilities), which appropriately reflects the circumstances before the invasion occurs.

In the traditional risk management model, the probability of introducing a species depends on the firm's characteristics and the control strategies chosen by each individual firm. A species' successful invasion depends on the biomass of the introduced species, the characteristics of the environment, and the firm's characteristics. From the perspective of a policymaker regulating firms in an industry, the concept presented in the paper by Horan and others (2002) creates a framework where the stochastic elements are the species introductions and the success of the invasion. The framework is fairly theoretical and the information necessary to implement this model directly may not be available. General aggregate-level decisions are focused on in their paper. The probability of an invasion follows a Bernoulli distribution that depends on the actions of all firms in the industry. As the number of firms increases, the probability of an invasion approaches one. The present value of damages facing society depends on expected damages, expected costs, and the possible set of all species that may be introduced. The risk management problem is static meaning the state-of-the-world remains the same for the single planning period. The firm minimizes expected damages caused by the species plus the control, or abatement, costs that lessen the probability of a species introduction. The major distinction between the traditional framework and the ignorance model is the potential set of invading species; in the traditional framework, all species that can invade are known, whereas under the ignorance model, the set of potential species contains a subset of species that is completely unknown. This approach gives rise to the idea that events are associated with different levels of potential surprise.

According to the traditional risk-management framework (i.e., the expected value approach), the policymaker has two potential optimal strategies: (1) all firms should be unregulated or (2) all firms should undertake expensive measures so that the probability of an invasion is driven down to zero. Also, with a large number of firms, abatement is not optimal because the chances of invasion are high regardless of the control strategies pursued by individual firms. In both frameworks, the optimal strategy is to set marginal costs equal to expected marginal benefits, or the negative of damages. Under ignorance, though, firms will evaluate the marginal impacts of the events and subsequent potential outcomes quite differently. The difference in valuations of the marginal costs and damages leads to different outcomes for the two approaches. In the expected value scenario, low abatement is an optimum strategy for all firms, whereas that is not the case for full uncertainty because the firms' values are significantly different. Subsequently, policies using the uncertainty framework establish uniform performance limits for all firms as opposed to the risk management framework where limits vary for each firm. Straightforward application of this framework is unlikely; however, the theoretical model, which illustrates the importance of considering alternative decision frameworks when elements of the model are unknown is the greater contribution of this paper. Due to the importance of uncertainty in the invasion process, continued reliance on the traditional approach for characterizing risk could lead to a severely restricted view of the true situation facing us. This does not mean that the expected value approach is not valuable, but it is crucial to be aware of other characterizations and unspoken caveats of these models.

Control Strategies

After the species successfully establishes, the decision-maker may employ several control strategies: eradicate the population, slow the spread of the population through spatial control strategies, or take no action. As in the other stages of the invasion process, a species' spreading success relates to its biological characteristics and the interaction with its surrounding habitat and species. Unlike previous stages, there may be more available information on the species' characteristics at this stage, which can inform decisionmaking. From an ecological perspective, eradication may yield the most desirable outcome. However, it may be costly to achieve under conditions such as larger spatial scales or substantial population sizes. Consequently, eradication attempts often fail to reach their objectives. Section 4.1 focuses on the spatial aspects of control. "Eradication as an Optimal Strategy" highlights the efficacy of eradication as a control strategy.

Spatial Control Strategies

Invasive species management is inherently about the management of land, or space. Ecological literature provides the theoretical framework to capture the spatial aspects (e.g., Shigesada and Kawasaki 1997); however, the majority of the economic literature fails to explicitly incorporate the spatial aspect. Discussion of the spatial effects on management is only found in the literature pertaining to control strategies following successful establishment. This literature is quite limited and does not include any stochastic aspects.

Barrier zones reduce the spread of species either through eradication of small populations or quarantining a population. Using a dynamic framework, Sharov and Liebhold (1998a) assess the management of barrier zones for gypsy moths in the United States. To assess the efficacy of barrier zones, the authors construct a model of pest dispersal, which factors in the monetary damages and benefits of control. Model application requires information about the specific population: the length of the population front, the shape of the population, the spread rate, the cost of the barrier zone, the damages caused by the species, and the discount rate. The conceptual framework (based on the spatial, economic, and biological components) is evaluated for three different spatial population spread scenarios: a strip with a constant width, a rectangular area, and a circular area. Parameterizing this framework with gypsy moth data and information from the Slow-the-Spread program (http://www.gmsts.org/operations/), the authors demonstrate the benefits produced by containment and eradication strategies over disparate geographic areas.

The authors indicate that eradication is viable for a species with a limited range, whereas slowing the species spread can be optimal in several scenarios. Using gypsy moth data as a case study, the model analysis shows eradication is optimal for certain small or isolated populations or both, whereas slowing the spread is better for larger, more established populations. Slowing the spread, as a control strategy, can yield substantial reductions in population spread (Sharov and Liebhold 1998b). The merger of economic and ecological relationships into a spatial model is demonstrated for one of the first times in this paper. Hof (1998) constructed a spatial model to illustrate how the effectiveness of barrier zones is reduced by the dynamics of the managed population. As the population grows, it can extend the size of the barrier zone or splinter, thus reducing the viability of barrier zones as an optimal management tool. However, an important caveat is pointed out in these two papers that, as with most papers reviewed in this synthesis, implementing such a framework has certain limitations. The choice of functional forms, model structure, and the data greatly influence the outcomes. Altering assumptions on these functional forms or other relationships included in the model can lead to varying outcomes. However, Sharov and Liebhold's model provides a spatial framework with explicit economic aspects that can be expanded to incorporate several scenarios and could potentially be extended to analyze decisions before the species begins spreading.

Building upon the framework set forth by Sharov and Liebhold (1998a), Cacho and others (2004) analyzed the critical points that govern the optimal control strategy: eradication, containment, or doing nothing. Their model focuses on plants and includes several parameters such as maximum rate of spread, seed longevity, and costs of control. The authors represented the unknown length of seed longevity in differing environments by using a range of values in the biological parameters. They determined the switching points at which eradication and control are no longer optimal strategies by employing Scotch broom (*Cytisus scoparius*, L.) data and estimates. Based on this analysis, the salient characteristics are seed longevity and the spread rate. As the spread rate increases, the two switching points move closer together indicating that management should emphasize eradication.

Useful frameworks for incorporating the spatial dimensions into risk management strategies are proposed in these papers. Sharov and Liebhold (1998a) provided a caution in their paper, which is applicable to all models: "Control of natural resources may depend considerably on social factors; thus the model…cannot automatically generate decisions." Further work to understand and incorporate societal and other factors will increase the viability of these frameworks. Overall, very little literature explicitly analyzes the spatial aspects, and future work should definitely focus on the spatial dimension as it is one of the most crucial components in the invasive species management problem. Perhaps researchers can learn from areas with substantial existing spatial research such as wildfire prevention or land conservation.

Eradication as an Optimal Strategy

Eradication as a control strategy yields the most desirable outcome—total elimination of the invasive species from the habitat—but this strategy often fails due to numerous obstacles that impede complete removal, leading many to question the circumstances when eradication is feasible and optimal. Myers and others (2000) cited several successful eradication cases noting that success relies upon certain key conditions. Simberloff (2001) argues that eradication in itself is not impossible, but is idiosyncratic and contingent upon several criteria:

1. Sufficient resources to successfully complete the project.

2. Clear and identifiable authority to oversee the project.
3. Fairly good information regarding the biological characteristics of the species; i.e., the same basic criteria needed for successfully implementing any activity involved in invasive species management.

He mentions resource constraints but without explicitly employing economic frameworks to assess the management options in the control stage. Several authors have addressed this gap by identifying the economic conditions under which eradication is optimal (e.g., Eiswerth and van Kooten 2002, Olson and Roy 2002, Regan and others 2006, Taylor and Hastings 2004).

Olson and Roy (2002) focused on the costs of control and damages of species currently under management (i.e., they captured the decision of a manager who must choose future strategies for an existing population). The policymaker minimizes the expected discounted control costs plus the damages caused by the remaining population conditional upon the species' growth function. The growth function incorporates environmental disturbances as a random process. As these disturbances increase, so do the chances of the population growing. Using this framework, they develop a rough guide of conditions favoring eradication. For small populations with marginal damages greater than marginal control costs, eradication is always optimal. When marginal damages are less than marginal costs, eradication is still optimal if the growth rate is sufficiently high. Irrespective of population size, eradication is optimal if the damages significantly outweigh the control costs in the worst possible scenario of environmental disturbances. Whereas this stylized framework is fairly general and cannot be directly implemented, it provides an approximate rule-of-thumb to ascertain the optimality of eradication as a management strategy. The one drawback is the information requirements; the marginal costs relative to the marginal damages must be known fairly well to determine the optimal management strategy.

Eradication not only depends on the relative costs and damages of controlling the population, but also upon the tenuous relationships between the population and its habitat. Environmental and demographic stochasticity and the Allee effect can drive low-density populations towards extinction (Liebhold and Bascompte 2003). The Allee effect works similarly to the critical depensation point or a threshold under which a population cannot survive. The Allee effect has been observed for low-density populations, but could apply to other populations as well. This effect contributes to an extinction threshold; if a species' population is low enough, extinction will automatically occur. All species exhibit this effect, except asexual organisms like some plants. In general, management methods should be aimed at increasing the probability of extinction. Extinction is highly likely if an adequate number of the population is removed, although achieving 100-percent eradication is difficult. Taylor and Hastings (2004) utilized *Spartina alterniflora* (a non-native grass in Washington that exhibits a weak Allee effect) to test this theory while accounting for economic aspects. Their analysis of the *Spartina alterniflora* data indicates that, in the absence of an Allee effect, the optimal strategy involves the removal of isolated, high-growth, low-density species. The model analysis establishes a relationship between budget and optimal strategy: lower budgets necessitated the removal of low-density plants, and the optimal strategy with larger budgets is to focus on eradicating high-density areas. For this particular species, the Allee effect does not lead to cheaper eradication. Hence, the Allee effect plays a role in determining eradication strategies, but it must be considered on a species-specific basis and in conjunction with budget constraints.

Regan and others (2006) constructed a theory to analyze the optimal time needed to survey an area before declaring that an eradication attempt has been successful. Evaluating the efficacy of eradication strategies depends on the reliability of survey strategies, which, in turn, depends on the amount of time and resources devoted to detection. These authors postulated that managers facing budget constraints may prematurely cease surveying, which could result in a new eruption of the pest if the species was not fully eradicated. The authors develop a simple rule of thumb for the optimal number of consecutive zero surveys by minimizing the sum of survey costs and expected damages. They compare this rule of thumb with the results of a fully optimal forward-looking solution derived using stochastic dynamic programming. The key difference between the two approaches is that stochastic dynamic programming incorporates all the possibilities that can occur in the future, including the possibility that the plant will re-emerge, and a new attempt at eradication will have to be undertaken and then finds the best decision. The authors parameterize these two seemingly different approaches—the rule-of-thumb and the stochastic dynamic problem—using bitterweed (*Helenium amarum*) data. The authors state that this rule-of-thumb can reduce variability in decision strategies while increasing evaluating the sensitivity of their decisions to various parameters in the eradication programs.

Eiswerth and van Kooten (2002) argued that the categorization of risk in subjective terms necessitates the use of fuzzy membership functions, which differ from the traditional expected value approaches (similar to Horan and others in "Pure Uncertainty Versus Risk in Assessing Prevention Strategies"). Subjective risk assessments can produce widely varying outcomes depending on the scientists or experts administering the assessment (e.g., Woodward and Bishop 1997). A stochastic dynamic model maximizing the agricultural producers' discounted present value of net returns is presented in the paper. The objective function consists of the agricultural production, which depends on the size of the invasion and the choice of control technology. The objective function is conditional upon the species growth function, which includes a stochastic term. As part of this research, the authors surveyed land managers to gauge their management choices under risk. The authors parameterize this model using results of this survey and extant data for the yellow starthistle (*Centaurea solstitialis*). The analysis illustrates that land managers tend to aggressively control a species even when the economic criteria do not warrant such a stringent control regime. The optimal control strategy involves managing the spread of yellow starthistle instead of full eradication, even though this weed has significantly impacted agriculture.

Allocating Resources Among Multiple Strategies

Management activities in one stage have direct consequences on other stages although specific stages of the invasion process are the focus of several papers. For example, scarce resources necessitate allocation between several activities. Decisionmakers determine these allocations concurrently, thus the framework should incorporate the relationships between these stages. Economic literature often focuses on the introduction and postestablishment stages of the invasion process to identify the optimal strategies between exclusion and control activities. The allocation between control and other activities, such as postintroduction detection, is the focus of some papers. The interaction between mitigation and adaptation activities is discussed in "Understanding Risk Mitigation Versus Adaptation." Optimal resource allocation strategies amongst differing activities are addressed in the other sections.

Understanding Risk Mitigation Versus Adaptation

Risk analysis often treats mitigation and adaptation separately, but invasive species risk analysis needs to account for both of these actions for effective management practices. Shogren (2000) discussed the distinction between mitigation—actions where people actively reduce the probability of a bad state, and adaptation—actions which reduce the magnitude of a bad state if it happens (as with insurance). He proposed the need to account for both of these actions simultaneously owing to the fact that an action to reduce risk affects the consequences if the species does invade. His model is based on endogenous risk theory to analyze risk-benefit tradeoffs for explosive invaders, and it depicts the problem facing a representative policymaker allocating scarce resources. These ideas stem from economic theory on decisionmaking under risk and uncertainty as addressed in "Defining Risk" and "A (Brief) Primer in Economic Theory" (de Finetti 1974, Drèze 1987, Savage 1954, Von Neumann and Morgenstern 1944).

Perrings (2005) built upon Shogren's framework and extended it to examine decisionmaking practices aimed at allocating resources between these two strategies. He classified management strategies addressing risk into the same categories: mitigation and adaptation. Mitigation refers to actions that alter the chances of an event occurring. In invasive species literature, mitigation activities reduce the likelihood of invasions. Adaptation refers to actions that alter the value of the outcome. These activities would reduce the impact cost of invasions without changing the probability of the invasions themselves. Decisions regarding mitigation and adaptation activities often occur simultaneously. The chosen strategy relates to where the species is in the invasion process (i.e., whether the species has just been introduced or whether it has already established). The manager must also assess whether the situation is observable or controllable. Perrings pointed out that there are two schools of thought regarding the predictability of invasions ("Factors Fueling the Invasion Process"). The first school, including Williamson (1996), argues that invasions can rarely be predicted beyond a few indicators such as propagule pressure and the past invasion history of the species. Others, such as Rejmánek (1999), believe that the invasiveness of a species and the susceptibility of the land can be predicted by analyzing a wider range of salient characteristics.

Using probability transition matrices that follow a Markov Chain, Perrings evaluated four possible outcomes once a species has been introduced:

1. It may not establish.
2. It may establish irrespective of management activities.
3. It may establish, and its population will depend on the state of nature (including management activities).
4. It may establish and have an unstable population in the long run.

The probabilities in the transition matrices represent the overall resilience of the land against invasion. If these probabilities are known, a model of the system's dynamics and the value function (both dependent on the probability transition matrix) can guide the optimal choice of strategies. In addition to the probabilities, the model requires knowledge of the expected net benefits and costs of different control regimes, and a feedback matrix that links control choices to the probability transition matrix. If this information is known, the outcomes of control measures (e.g., those that only reduce population size, can be assessed for their long-run effectiveness).

Mitigation is an appropriate option if the expected outcomes of management activities can be assigned some probabilities. In situations where probabilities for the connections between actions and outcomes are unknown, mitigation cannot occur, and managers are left with adaptation as the only possible strategy. Perrings' main objective was to draw attention to the need to quantify unknown aspects as he stated at the end of his paper, "In an environment in which decisionmaking is increasingly dominated by non-probabilistic 'scenarios' which drive decisionmakers to focus on adaptation, it is important to remind ourselves that this may be both inefficient and inequitable." This argument arises from the idea that any structured analysis based on some quantitative information is better than the alternative because conventional wisdom does not necessarily lead to optimal strategies, such as the case of tariffs to reduce invasion risk ("Policy and Market-Based Mechanisms to Manage the Risk of Introductions").

Maximizing Welfare Through Invasive Species Management Activities

Unlike the previous papers in this synthesis, the focus in this section is on the tradeoffs between management strategies and their social benefits and costs. Welfare functions allow the analyst to capture the overall benefits and losses of a management decision. The use of welfare functions is employed in several papers in their objective functions to assess optimal resource allocation strategies (e.g., Finnoff and Tschirhart 2005, Finnoff and others 2005, Leung and others 2002).

Leung and others (2002) showed that prevention is more cost effective than control. Stochastic dynamic programming captures the situation facing a policymaker allocating resources between prevention and control activities on an aggregate level. Welfare consists of the profit function minus the costs of invasive species management activities. The invasive species grows according to a logistic function plus some stochastic term representing uncertainty in species growth patterns in the new environment. The planner's maximization problem optimizes welfare over a probability transition matrix that reflects the probability of moving across States (i.e., different invasion outcomes) given various allocations between exclusion and control strategies.

Implementing the Leung and others (2002) model requires the following: data on a species' growth function, the costs of controlling that particular invasive species, the efficacy of control, the total inputs and costs for the industry, the total outputs and prices for the industry, the monetary loss caused by the invasive species, and the probability of invasion. Data on zebra mussels and powerplants, coupled with estimates of certain biological characteristics and the probability of invasion, are used to simulate three possible scenarios for lakes: uninvaded over a 25-year time horizon, invaded over 25 years and uninvaded for 5 years. The simulations determine the optimal allocation for prevention strategies given two control options (do nothing or do something) for 10 years. The optimal expenditures for prevention activities yield the greatest welfare. However, the difference in cumulative welfare resulting from optimal expenditures, suboptimal expenditures, and taking no action is relatively small. Engaging in optimal prevention activities is ideal over the longer time horizon (25 years), whereas the optimal strategy with the shorter time horizon (5 years) is to not take any action. As in several other papers, Leung and others (2002) employ data from a highly invasive species with high growth rates and high damages (in this case, the zebra mussel). Using such a species illustrates the worst case scenario. Applying this model to less insidious invasive species may produce different outcomes. The advantage of this model is the explicit linkage between private industry and management activities. Whereas actual data may not exist for all components of the model, estimates can be used to analyze the potential scenarios facing the policymaker for diverse industries and invasive species.

Leung and others (2005) follow up their previous work with an attempt to bridge the gap between theory and application by proffering a framework to identify general rules-of-thumb for resource allocation over various invasive species management activities. Extending the concepts in their earlier paper, the authors establish the relationships underlying optimal choice of exclusion and control strategies. The policymaker endeavors to maximize cumulative social welfare conditional on several factors: (1) the welfare in an invaded state, (2) the welfare in an uninvaded state, and (3) the probability of invasion dependent on the prevention strategy, invasion parameters, and the efficacy of prevention. Based on the model analysis, optimal control expenditure increases with the system's value and decreases with uncontrollable damages (amongst other rules). The optimal prevention expenditure is closely tied to the preventability of invasions. Several rules characterize the optimal expenditure including one stating expenditures decrease as the probability of unpreventable invasions increase. The authors provide a detailed list of data required to implement the model as well as a thorough comparative statics analysis of the interaction between the various parameters and variables. This model's strength lies in its application using available data. However, the simplified framework comes at a cost—several strong assumptions (e.g., the specific functional forms, the relationships included or excluded in the framework, the availability of data necessary to implement the framework, etc.) underlie the model. The loss of specificity translates to a gain in the ease of implementation and a decrease in the time needed to reach general management rules.

Building upon the underlying tradeoff between prevention and control, Finnoff and others (2007) evaluated the effect of manager's risk preferences on the optimal investment in management activities. Risk preferences dictate the valuation and incorporation of risk into decisionmaking frameworks. The authors postulated that, based on their endogenous risk model (an extension of Shogren 2000, "Understanding Risk Mitigation Versus Adaptation"), risk-averse models tend to over-invest in control while under-investing in prevention. As a manager's risk aversion increases, so does the propensity to implement control activities. This behavior results in increased invasions as indicated in their paper. This paper was based upon an earlier one (Finnoff and others 2005) where a similar endogenous risk framework analyzed the role of feedback between decisionmakers (i.e., the firms or the manager) and biological and economic aspects associated with invasions.

Here, feedback refers to the ability of the decisionmakers to update beliefs based on changes in the situation. If decisionmakers neglect to respond to these changes, the results could range from minor efficiency loss to severe biological and economic consequences as a result of invasions.

Determining Optimal Allocations Based on Inter-Species Relationships

Like humans, plants can be thought of as welfare maximizing organisms whose survival success depends on certain biological traits, which can predict outcomes from interaction with other plants, humans, and their environment (Finnoff and Tschirhart 2005). Contrary to previous papers on species management, the focus in this paper is on the species (i.e., the plant) as an optimizing agent, which aims to maximize its biomass conditional on specified parameters and the presence of competitors in the habitat. Finnoff and Tschirhart explain the uniqueness of this model compared to previous ones: “In the plant community model herein, the theory starts prior to population updates by first assuming the individual plant behaves as if it is choosing its optimum biomass. Optimization is done given the plant’s parameters and the presence of other competing plants in its own and other species.” Using this model, the authors evaluate individual plant behavior and species interactions as they result from plant-specific traits, environmental factors such as temperature, and human interaction. Each scenario analysis offers a rough guideline for plant behavior given certain conditions.

The authors classify invasive species as redundant or successful. Redundant species fail to invade successfully but remain in the habitat as biological insurance until environmental conditions become favorable for them. Successful species effectively invade the new habitat from the start. These two categories are mutually exclusive, but species can switch groups over time as the environmental circumstances change. The plant’s efficient energy usage dictates its growth function, which updates the model. An individual plant’s optimization problem—maximizing net energy—includes the leaf size, the flow of solar radiation, the biomass, and the energy expended for the plant’s functioning. Additionally, as a member of a plant community, the population size and growth vis-à-vis the available land capacity combine to enter as a space constraint that also influences the individual plant’s optimization. The model of plant behavior is then incorporated to a policymaker’s welfare maximization problem because there is feedback between human decisions such as agricultural management and species success. Through this framework, the authors capture the interconnection between ecological and economic relationships in a situation with multiple species. The policymaker chooses prevention and control efforts to manage an invasive species. The probability of invasion depends solely on prevention efforts. Accounting for human effects on species population, the plant’s growth function has altered to now include population reductions through harvest and control measures.

Based on the relationships and factors in just the plant relationships, the analysis determines that the optimum plant biomass in the steady state depends largely on plant-specific traits, namely those related to respiration activity. Expanding this result to multiple species provides criteria to predict species success in steady-state scenarios. Factors beyond the plant-specific parameters, such as temperature, also drive the optimization behavior. After augmenting the aforementioned plant relationships by temperature, the authors analyze the optimization behavior to find that any number of species can co-exist regardless of the resource constraints in this model. This outcome deviates from previous papers in that the number of resources dictates the maximum number of coexisting species populations. The authors construct a conceptual framework encompassing the major economic and ecological factors that impact plant success. Although the authors do not apply empirical data to the model, this can be done using data for current species and estimates for potential species. The majority of the model is deterministic except for the probability of invasions, thus the information necessary to implement the model should be available. By explicitly incorporating complex species interactions, a creative, albeit unorthodox, approach for evaluating the ecological consequences of human actions is proffered in this paper.

Focusing on the Cost Versus Damage Tradeoff to Identify Optimal Strategies

Optimal strategies for multiple activities can be found by focusing on the tradeoffs between the management costs and the species' damages deterred by engaging in the particular management activity. The optimal resource allocation between prevention and control activities with a stochastic initial population size depends on the marginal damage function of the invading species (Olson and Roy 2005). Whereas this model cannot be directly implemented due to the theoretical nature of the framework, their analysis produces general rule-of-thumb principles for optimal resource allocation between prevention and control activities. The framework represents a situation where an invasive species has been controlled, and the decisionmaker must allocate resources for potential management strategies for the same species. As an example, the gypsy moth (*Lymantria dispar*) presents such circumstances; it has been controlled in certain areas and requires continuous management. The management options can differ from exclusionary activities for preventing new introductions of the gypsy moth, to control strategies for managing remaining gypsy moth populations.

The policymaker chooses the level of prevention and control activities. The costs of control and prevention are assumed to be known, but the damages from the resulting invasion are driven by a stochastic relationship representing the risk of an unknown invasion. The policymaker selects the prevention and control strategies simultaneously prior to the invasion, which reflects the decisionmaking process in risk management. However, the established population size is known indicating that the invasion had already occurred and these management decisions focus on potential invasions going forward from either the same species or other species.

The role of risk on optimal resource allocations is highlighted in this paper. An increase in risk is represented by an increase in the variability associated with the chance of an invasion. The optimal choice between prevention and control following such an increase in risk depends mainly on the shape of the marginal damage function. Thus, the species' damage function must be known to apply this framework. Data on past damages from the species can be used to estimate the damage function, which can then determine the optimal management strategy for the species in an uninvaded area or a reoccurrence of the species in the same area.

Whereas the focus is on the introduction and spread stages in many papers, there are few where the detection stage between the introduction of the species and the subsequent establishment and spread are explicitly addressed. The unclear relationship between species that are intercepted or discovered during the introduction stage and the established species being found in ecosystems is due to the fact that successful introductions do not often translate to successful invasions (Williamson 1996). Even those species that successfully establish often begin to spread after long lag periods (Crooks and Soulé 1999). Lags occur for many reasons such as natural lags in population dynamics or changes in the environment and the genetic composition of extant species. Additionally, past experiences with species do not provide good indicators of their future invasiveness due to an ever-changing environment and the response to and by other species. Also, species introduced many years ago may now have populations that are sizeable enough to detect (Costello and Solow 2003). These factors contribute to the uncertainty surrounding the establishment stage of the invasion process.

If populations are detected early in the invasion process, either before they fully establish or as they are establishing, control strategies can commence sooner and, possibly, at a lower cost. Some species, such as the black-striped mussel (*Mytilopsis* sp.) in Australia, have been eradicated due to detection activities, which included constant surveying followed by quick mobilization upon detection (Myers and others 2000). Mehta and others (2007) captured the stochastic and dynamic aspects of this tradeoff between detection and control activities. The model focuses on a decisionmaker minimizing costs and expected damages for a single invasive species by choosing a constant optimal search level at the detection stage. The time of detection is stochastic and depends on the effort devoted to search activities and how easy it is to detect the species.

Based on simulations representing four types of species, the model analysis indicates that it is often optimal to devote significant resources to detection efforts for species causing high damages, even if the species is difficult to detect. The optimal strategy for species that do not have a high-damage potential involves undertaking no action if the population is sufficiently small, if the detection is quite difficult, or if post-detection control activities are costly. Even if a species causes a high level of damage, it may not be optimal to invest in detection when the post-detection control strategy is relatively costly (i.e., the control costs are near or greater than the damages produced by the species). The simulations show that the biological parameters are more influential than the economic parameters. This may be an artifact of the specific model, but it is a point worthy of further exploration. It is demonstrated in the paper that the optimal detection strategy relies greatly on the detectability of the species, similar to findings from Cacho and others (2006) who applied search theory to a spatial model aimed at analyzing detection and control strategies. Whereas the Cacho and others model does not include any economic aspects, it does incorporate the risk underlying these activities and the role of detection on subsequent eradication strategies to illustrate the importance of detectability in the optimal detection strategies for weeds.

Some characterizations of the tradeoff between the costs of managing invasive species and the damages inflicted by them are provided in these papers. The variety of potential methods of addressing resource allocation amongst several activities is also touched upon. General guidelines for resource allocation are established as well. However, direct application of these models is fairly difficult. Specific models, or examples, of these strategies in practice would be quite instructive and useful for pragmatic application.

Discussion

An overview of some of the existing frameworks for evaluating risk management from an economic perspective is provided in this synthesis, as the field of invasive species management literature continues to evolve and expand. New collaborations and new knowledge have spawned, and will continue to create, a wide range of methodologies aimed at identifying optimal strategies and mechanisms for diverse management cases and objectives. The individual sections illustrate that several creative and insightful decisionmaking frameworks have already been explored. Nonetheless, there are numerous potential research areas that need to be investigated.

Space and invasive species are closely intertwined. Models, which explicitly incorporate the spatial and economic aspects are crucial to the invasive species management problem, yet very few currently exist. Also, current economic models focus on only three major management activities. Other management activities, such as restoration and public outreach, offer high returns for invasive species management and ought to be considered in the risk management framework as they occupy a place in the decisionmaking framework for agency managers. The set of activities included in risk management framework should be expanded, as well as the number of activities included in resource allocation frameworks. Realistically, management activities are undertaken concurrently and the theoretical frameworks should reflect this.

Only a few models incorporate multiple species, so this should be expanded to understand the interaction between species as well as optimal resource allocations across species. Approaches that transcend the traditional risk management, or expected values and framework are employed in some papers; they highlight crucial issues involving the levels of risk facing managers. Increasing an awareness of different methodologies for incorporating stochastic elements will help agency managers and expand the number of tools available for characterizing management risk. Overall, these models tend to be general. Whereas that is important for establishing overall frameworks and guidelines, future work should focus on specific species to emphasize the link between theory and application. Also, the focus tends to be solely on insidious species in some papers, whereas agencies face a wide gamut of invasive species. These frameworks should be applied to a variety of different types of species, and the first step towards this has been taken through the range of simulations used in these papers.

The interdisciplinary body of literature in this field is constantly growing. As such, certain key papers have been focused on in this synthesis while acknowledging that other recent or related papers may have been omitted. The purpose of the synthesis is to provide a basic overview of the existing state of invasive species risk management literature from an economic perspective. Hopefully, this review will encourage readers to continue to push the boundaries of this research by engaging across the disciplines to discover novel and exciting approaches for decisionmaking tools for invasive species.

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