

Risk and Nonindigenous Species Management*

David Finnoff, Jason F. Shogren, Brian Leung,
and David Lodge

Some nonindigenous species threaten people by contributing to biodiversity loss and environmental damage (Elton; Kareiva). Managing such threats cost-effectively requires a consistent framework that captures the biological and economic circumstances that jointly determine the level of risk and the optimal mix of prevention and control strategies. The economic theory of endogenous risk provides such a framework (see Ehrlich and Becker; Shogren and Crocker). Endogenous risk refers to the notion that people and managers influence the risk they face through their behavior. They choose the level of risk they want to avoid through their effort and investments, while accounting explicitly for the costly tradeoffs involved in these decisions. This is in contrast to the traditional “damage function” perspective which tends to separate risk assessment from risk management (Freeman). When merged with applied population ecology, endogenous risk captures the risk–benefit tradeoffs created by ecosystem conditions, invasive species characteristics, economic circumstances, and the feedbacks between the systems (Crocker and Tschirhart). Our choices, driven in part by economic circumstances, affect the ability of a biological system to absorb these changes. Analyses that explicitly account for these economic

■ *David Finnoff is assistant professor in the Department of Economics and Finance, University of Wyoming.*

■ *Jason F. Shogren is the Stroock Distinguished Professor of Natural Resource Conservation and Management, Department of Economics and Finance, University of Wyoming.*

■ *Brian Leung is assistant professor in the Department of Biology and School of Environment, McGill University.*

■ *David Lodge is professor in the Department of Biological Sciences, Notre Dame University.*

*This paper was presented at the session, “The Economics of Invasive Species Management,” organized at the Allied Social Sciences Association annual convention in Philadelphia, January 7–9, 2005.

The articles in these sessions are not subject to the journal’s standard refereeing process.

circumstances, diverse wealth levels, costs of investments, and preferences will be more likely to generate unbiased estimates of risk.

This paper briefly reviews how we use the endogenous risk perspective for nonindigenous species management. We address two questions: is the effort to integrate and capture feedback links between biological and economic circumstance worthwhile; and how do changes in managers' preferences for bearing risk affect their choice of optimal prevention and control? We begin by framing the nonindigenous species issue using a dynamic endogenous risk model that accounts for both biological and economic circumstances of invasive species and present results found in Finnoff et al. (2004, 2005).

Endogenous Risk as an Integrating Framework

The theory of endogenous risk assumes people and firms invest scarce resources to change risk. People mitigate risk through self-protection (or prevention) efforts to reduce the likelihood of a bad state; and they adapt to risk through self-insurance (or control) efforts to reduce the severity of a bad state if it occurs. Given individual freedom to mitigate or adapt, a decision maker should account for these private reactions when evaluating policy options.

A good example of endogenous risk is the response of private firms and regional policymakers to the nonindigenous zebra mussel (*Dreissena polymorpha*) in a Midwest lake. Zebra mussels affect both ecological and economic systems (Ricciardi and Rasmussen; Lodge). They clog water pipes, reduce water flow and currently cost U.S. industries an estimated US\$100 million per year in control costs (Pimentel et al.) with little if any resources spent on prevention. Governmental agencies and private producers faced with the impacts (primarily power plants and water-treatment facilities) continue to experiment with new measures to maximize the benefits of zebra mussel control. Prevention of new infestations remains timely because zebra mussels are still expanding their range within North America (Bossenbroek et al.).

The theory of endogenous risk provides a framework to link the natural processes of an invasion with these levels of human behavior which together define the extent of the risk. Following Shogren (2000), consider a framework that casts the management of a generalized invasion of highly mobile invasive species with numerous transportation pathways, such that private citizens or firms cannot control the entry of the invader into the overall system. A benevolent manager is faced with reducing the risk posed by the invasion through some combination of collective investments in mitigation (or prevention) and adaptation (or control), while realizing private individuals may also make investments to reduce risk.

The invader that causes damages has traversed several interrelated processes: introduction, establishment, and growth of the invader. Not all species that invade become established; and not all established invaders cause damage (see Williamson). Once a species is established, we assume the system is invaded. After establishment, the invader can increase in abundance, which directly relates to damages. Unlike standard pollution, in which remedial efforts have lasting effects, biological organisms reproduce so control may be necessary in

perpetuity. In our interpretation, private individuals or firms can only adapt and apply control effort towards the invader.

Firms and managers use a discount rate when thinking about future costs and benefits. Assume citizens and firms are relatively more myopic about the future than a benevolent manager, that is, they have a higher discount rate. This restriction reflects the notion that firms make private decisions based on market discount rates, whereas the manager employs a rate based on social preferences. In general, the market discount rate is assumed to not exceed the social rate (e.g., Weitzman). For tractability, assume the firm is completely myopic, that is, a zero discount rate. Lacking foresight, they take the current abundance of the invasive species as given, and ignore future repercussions of their behavior.

In any period, a representative individual (in our case, a firm) behaves in its self-interest, taking as given the current state as defined by invader abundances. Invader abundances cause damages to the firm such as clogging power plant water cooling systems that serve to diminish initial private wealth. In response, the firm can adapt to the invader. Adaptation or self-insurance is a strategy that accepts the direct damages and compensates in response to reduce the consequences of the damage. For example, a power plant may be able to compensate/adapt to the damage inflicted when mussels clog coolant systems by employing factors of production and operating longer hours or burning more fuel than otherwise necessary. In contrast, control reduces actual damages, and can indirectly influence the transition to future states. Examples of control include flushing the coolant system with chlorine.

The private individual's optimal choice of adaptation balances the benefits of adaptation with the extra costs. Benefits arise from reduced consequences of damages given the adaptation response, and as the individual is myopic, all benefits and costs (from the individual's viewpoint) accrue in the current period. Similarly for control, the private individual's optimal choice requires a balance of the marginal benefits of control with marginal costs such that the marginal damage reduction equals the marginal cost of private control. Again, benefits arise from reduced damages *in the current period*. From these conditions, the individual's optimal adaptation and control in any given period and state can be determined.

While private individuals or firms can only adapt and/or apply control towards the invader, the manager can partially control future invasions and growth of the invader. The resource manager uses collective *prevention* to reduce the probability of invasions. If one has occurred, they invest in collective *control* to reduce the abundance and damages in the next period. For example, if the state of nature is uninvaded, the probability of invasion during the transition to the next period is a diminishing function of prevention. If the invasion is successful, invaders become established and cause damages in the following period. If the invasion is unsuccessful, the invader does not become established and no damages occur. But in the invaded state there are damages and society faces the threat of even larger damages in subsequent periods through growth of invaders. The probability of growth is conditioned on the invader's abundance and evolves following a stochastic process. Collective control serves to reduce the reproducing invader population in subsequent periods so that the magnitude of growth in the transition to the next period depends on control.

The Analytical Model

We now proceed by sketching out a formal analytical model to integrate and organize these principles. In our model, a manager takes current period damages as given. He/she expends resources on collective prevention and control in the current period to reduce realized consequences of invasions in subsequent periods. The manager's objective is to maximize discounted social welfare over a given time horizon. Current social welfare is firm profit net of damages and collective costs of invasion. In a discrete framework, the stochastic dynamic programming equation is simply the summation of optimized discounted welfare in year t and all future years. For the reader interested in the complete technical details and full-blown version of the model see Finnoff et al. (2005).

Formally, let $W_{\theta,t}$ be the maximum discounted expected social welfare from the perspective of initial period t to the horizon T , where states are defined by current period invader abundance θ (state variable). Social net benefits w for any given state are a function of firm profits and costs of collective strategies. Firm profits in turn depend on revenues, factor costs (analogous to adaptation here), and private control costs all subject to damages from current invader abundances. In response to damages, firm adaptation, Z^P , reduces the magnitude of loss; whereas private control, X^P , also reduces actual damages and it indirectly influence the transition to future states.

Unlike the firm, the manager considers the dynamics of the invasion process and can partially control entry and growth of the invader. The manager influences the realized state θ subject to random invasion and stochastic population growth. The manager influences the transition process and reduces the damages associated with invasion *in future periods* through collective control, X^G , and prevention, S^G . Combining the effects and costs of private and collective behavior in reduced form, social net benefits w are a function of private optimal choices of control and adaptation \hat{X}^P , \hat{Z}^P , and the combined costs private adaptation, control, collective prevention, S^G , and collective control, X^G , so that $w_{\theta, \hat{Z}^P, \hat{X}^P, X^G, S^G}$.

The influence of risk attitudes are included in the model through a flexible risk attitude social von Neumann–Morgenstern utility function U . The SDP equation is,

$$(1) \quad \max_{X^G, S^G} W_{\theta,t} = U(w_{\theta, \hat{Z}^P, \hat{X}^P, X^G, S^G}) + \rho \sum_i \Psi_{\theta, \hat{X}^P, X^G, S^G, i} W_{i,t+1},$$

where $W_{\theta,t}$ is discounted cumulative welfare from the end time horizon T to the current time t , and the discount factor ρ is related to the discount rate r by $\rho = 1/(1+r)$. Ψ is the probability of moving from state θ to state i , given random invasion, stochastic population growth, private control \hat{X}^P , and also dependent on collective strategies S^G and X^G chosen to maximize $W_{\theta,t}$. Human and ecological circumstances influence both outcomes and transition probabilities so for each state at each time interval, the model determines both optimal strategies and future trajectories.

Applications

We use this risk framework to guide our numerical simulations exploring (1) whether feedback matters, and (2) how risk aversion affects the mix of prevention and control. First, we address whether accounting for feedback is worth the effort by focusing on two dimensions (see Finnoff et al., 2005 for complete details). We consider two feedback loops—the link between the biological system and firms, and the link between the manager and the firm. For both loops, the decision maker's beliefs about invasions are central. In the absence of the link between the biological system and firms, the firm behaves *as if* there is no change in the biological system—that is, it has incomplete beliefs about the nature of the system. The consequences depend on whether there is an invasion in the initial period such that invader abundance in the initial period $N_{t=0} = 0$ or $N_{t=0} > 0$, and whether the firm acknowledges the presence of the invader. For example, with no initial invasion (e.g., $N_{t=0} = 0$), the firm neither controls nor adapts. The consequences imply that as the biological system and states change, the firm either uses too few or too many inputs relative to our optimal baseline. In turn, output correspondingly either under- or over-shoots its targeted level; either way this results in opportunity cost losses from production shortages or surplus, determined *ex post*.

The second dimension is the feedback between the benevolent manager and firm. Removing the feedback causes the manager to act *as if* the firm does not respond to changes in state. We define this situation as when the manager holds incomplete beliefs over firm behavior. Also either there is an initial invasion or not, and the firm continues to behave as though circumstances remain constant. For example, following a successful invasion, the manager ignores the private control actions of the firm. This has direct welfare consequences as resources may not be allocated efficiently. When excluding feedbacks, the model necessarily determines the consequences of the invasion and behavior of firms, even though the firm or social planner does not take them into account. The current welfare is determined by all implemented strategies.

Table 1 summarizes key results from the simulations. The baseline includes all feedbacks and serves as a natural reference point to compare all other scenarios. The table shows the percentage change in expected mean annual magnitudes from the baseline. Removing the feedback link between the biological system and firms generates both biological and human impacts. Magnitude of impacts depend on whether the firm acts as if there was an initial invasion or not, i.e., $N_t = 0$ versus $N_t > 0$.

With initial invasions ($N_{t=0} > 0$), the firm controls at a relatively high level—but the probability of invasion and invader abundance both nearly double. This result occurs because the manager free rides on the firm's control efforts, and never chooses to use its own control or prevention efforts. Economic welfare also decreases relative to the baseline due to the firm's inefficient control. The reductions in welfare are not due to damages. The firm's control is at an artificially high level which negates damages from increased probabilities of invasion and abundances. Welfare falls due to the inefficient employment of control by the firm. Without initial invasions ($N_{t=0} = 0$), the firm never controls. The social planner now over-controls relative to the baseline, which lowers

Table 1. Percent changes from baseline

Feedback Removed	Expected Mean Annual Percentage Change from Baseline							
	<i>P</i>	<i>N</i>	<i>W</i>	<i>W-Opp.</i> <i>Costs</i>	Firm		Collective	
					<i>Z^P</i>	<i>X^P</i>	<i>X^G</i>	<i>S^G</i>
Biology Firm								
Adaptation								
$N_{t=0} = 0$	10.827	7.117	-0.006	-0.216	-0.159	-100	18.818	-2.062
$N_{t=0} > 0$	106	103	-0.081	-0.233	-0.049	4,671	-100	-100
Manager Firm								
$N_{t=0} = 0$	-0.456	-2.647	0	0	-0.001	-2.259	1.269	0.016
$N_{t=0} > 0$	648	2,070	-2.440	-2.440	1.751	2,244	-100	-100

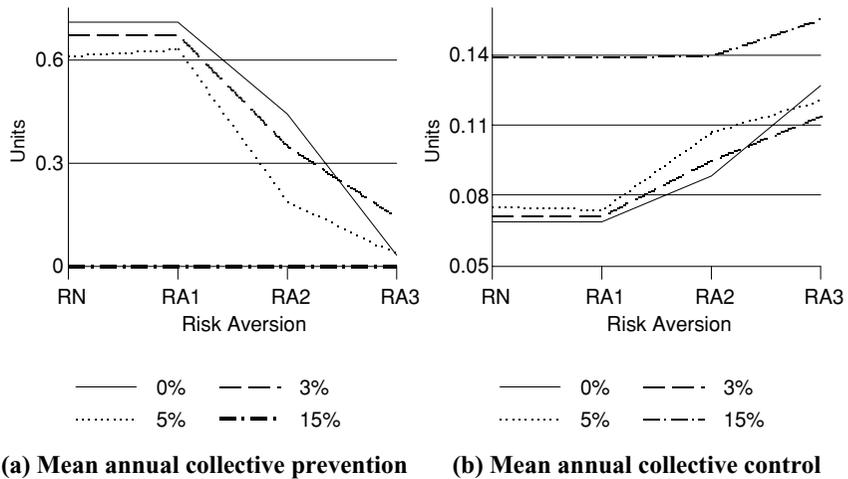
Legend: *P* = Probability of Invasion; *N* = Invader Abundance; *W* = Welfare; *W-Opp. Costs* = Welfare net of Opportunity Costs; *Z^P* = Firm Adaptation; *X^P* = Firm Control; *X^G* = Collective Control; *S^G* = Collective Prevention.

welfare. In addition, over-control causes under-prevention, which increases both the probability of invasion and populations.

If the feedback between manager and firm is decoupled, the effects again depend on the beliefs over the responses to an initial invasion or not ($N_{t=0} = 0$ versus $N_{t=0} > 0$). If the manager believes the firm behaves *as if* there was no invasion, he over-employs both prevention and control. This reduces the probability of invasion and reduces invader abundances. The firm reacts by reducing its control and adaptation to (almost) perfectly offset the manager's over-employment. No change in mean annual welfare is observed. In contrast, if the manager believes the firm behaves *as if* an initial invasion occurred, the results are reversed. The manager neglects prevention and control, which causes a rapid increase in invasion probabilities and invader abundance. Firms react by upping their control and adaptation—but not to the level the manager believes the firm is using (i.e., an initial invasion). The firm is left with persistent invader abundances, which reduces annual welfare and cumulative welfare. These results suggest that feedbacks can matter for the case of zebra mussel invasion in a Midwest lake—but not in every dimension. Both biological and economic consequences of not addressing feedbacks are sensitive to the initial conditions on the environment, behavioral perceptions about the state of the environment, and the completeness of the manager's beliefs.

Now consider our second question—how do managers' preferences for bearing risk affect choices of optimal prevention and control in invasive species management (see Finnoff et al., 2004 for complete details). In general, a more risk-averse manager will choose a less risky *alternative* for managing invasive species. The alternative here is defined by the portfolio of prevention and control. In theory, greater risk aversion has two effects on this portfolio. First, a direct effect exists—if one is more risk averse, holding on to a dollar is more attractive (e.g., a sure bet) than spending it on either prevention or control since they are affected by random invasion and stochastic population growth. A more risk-averse manager gets relatively greater utility out of a sure thing.

Figure 1. The impacts of risk aversion in the endogenous risk framework



Legend: For both figure 1a and 1b the horizontal axes are increasing levels of risk aversion as defined in the text. Units of collective prevention in figure 1a are the average number of prevention events that take place on an annual basis, whereas units of collective control in figure 1b are the average number of control events (e.g., molluscicide applications) on an annual basis.

Second, an indirect effect exists which serves to either attenuate or accentuate the direct effect. This indirect effect reflects the idea that prevention and control are either *technical complements* or *substitutes*. A technical complement says more prevention increases the marginal effectiveness of control (and *vice versa*); a substitute says the opposite—the use of one strategy lessens need for the other. In general, however, it is ambiguous whether the indirect effect works with or against the direct effect, which is why we now consider our numerical simulation.

Figure 1 shows our numerical results for risk neutral (RN), mildly risk-averse (RA1), moderately risk-averse (RA2), and highly risk-averse (RA3) managers (over four discount rates, $r = 0\%, 3\%, 5\%$, and 15%). The mean annual levels of prevention and control are the values in each state weighted by the probability of being in that state. Our results show more risk-averse managers selected *their* less-risky alternative, which is a portfolio with less prevention and more control. This finding seems counterintuitive at first glance. But to a more risk-averse manager a dollar spent on control is worth more than a dollar spent on prevention. The intuition is that control is relatively more attractive because its expected marginal effectiveness exceeds the expected marginal effectiveness of prevention. There is less uncertainty in the application of control—it removes existing invaders from the system; there is more uncertainty in prevention since it only reduces the chance of invasion, it does *not* eliminate it. For this reason, the direct effect on prevention dominates the indirect effect; more risk-averse managers' use less prevention. Since prevention and control act as substitutes, less prevention implies more control (here the large positive indirect effect on control dominates its negative direct effect). We see prevention is not used at all

in earlier periods and the date of its implementation is delayed. This serves to increase the probability of invasion at the end and beginning of the planning horizon, with resulting population, adaptation, and lagged control increases that ultimately lower overall welfare.

Concluding Comments

Endogenous risk can be used to frame the question on how to manage the prevention and control of nonindigenous species. The approach accounts for both biological and economic circumstances of invasions, and the feedbacks between the two systems. Within this framework, one can investigate whether the integration is worth the effort and how changes in managers' preferences for risk-bearing influence the optimal mix of public prevention and public control, and how that affects private adaptation. Our results suggest that feedback matters for the case of zebra mussel invasion in a Midwest lake—but not in every dimension. Both biological and economic consequences of not addressing feedbacks are sensitive to the initial conditions on the environment, behavioral perceptions about the state of the environment, and the completeness of the manager's beliefs. We also find more risk-averse managers tend to reduce prevention and increase control, reducing the overall welfare of the system.

Acknowledgments

The authors wish to thank the NSF (DEB 02-13698) and USDA/ERS for partial financial support.

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