

# ECONOMIC ANALYSIS OF BIOLOGICAL INVASIONS IN FORESTS

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## **Abstract**

Biological invasions of native forests by nonnative pests result from complex stochastic processes that are difficult to predict. Although economic optimization models describe efficient controls across the stages of an invasion, the ability to calibrate such models is constrained by lack of information on pest population dynamics and consequent economic damages. Here we describe economic approaches for analyzing pre-invasion and post-invasion management of biological invasions under conditions of risk and uncertainty and emphasize the need for new microeconomic and aggregate studies of economic damages across gradients of forest types and ownerships.

## **Keywords**

Risk, uncertainty, optimization, timber, nonmarket values, biosecurity

## **Introduction**

Biological invasions by forest insects, pathogens and plants are a type of externality (or biological pollution: Horan, Perrings, Lupi and Bulte, 2002) from trade that has altered the productivity, structure and species composition of many forest ecosystems around the world. Economists have argued that an efficient solution to reducing the threat of biological invasions would be to require parties benefiting from trade in products that pose risks to terrestrial or aquatic ecosystems to pay the costs associated with environmental degradation (Perrings, Dehnen-Schmutz, Touza and Williamson, 2005). However, until policies such as tariffs and taxes or improved trading standards are implemented, current practices will persist and nonnative pests

will continue to threaten the integrity of native forests (Holmes, Aukema, Von Holle, Liebhold and Sills, 2009).

Biological invasions are complex stochastic processes that are difficult to predict. History has shown that many accidental introductions of nonnative species fail to become established in new habitats and, of those that become established, few species ultimately cause widespread economic damage (Williamson, 1996). In the United States, more than 450 nonnative insect species and 16 pathogens have colonized US forest and urban trees since European settlement. Of this number, roughly 60 insect species, and all pathogens, have caused notable damage to trees via increased mortality or reductions in reproduction and growth, and only a few species have caused major ecological disruptions (Aukema et al., 2010).

In this chapter, we provide an overview of a suite of economic approaches that can be used to analyze pre-invasion and post-invasion management of biological invasions in forests. Because forest managers and policymakers are typically confronted by a pervasive lack of knowledge about the factors that ultimately shape the establishment and spread of nonnative organisms in native ecosystems, we begin with a review of decision-making frameworks under conditions of risk and uncertainty. This is followed by a review of theoretical developments in the natural resource economics literature describing optimal prevention and control activities across the stages of a biological invasion. Next, we discuss empirical approaches for quantifying market and nonmarket impacts of nonnative forest pests. Although most empirical economic studies have focused on post-invasion analysis of individual pest species, we next present an innovative method for aggregating economic damages across multiple species of forest pests that can be used to forecast future damages from new invasions. Finally, we present our conclusions and suggestions for future research.

### **Managing risk and uncertainty in biological invasions**

When faced with threats to the integrity of native forest ecosystems, public and private forest owners generally take actions to mitigate ecological and economic impacts. Forest protection is a public good (nonrival and nonexcludable), and if forest owners fail to account for the costs and benefits generated by their individual protection efforts on other forest owners, the socially optimal level of forest protection will not be provided (Alavalapati, Jose, Stainback, Matta and Carter, 2007; Holmes et al., 2009). Therefore, governmental programs and cooperation among landowners play an essential role in the provision of forest protection.

Economic analysis supporting decisions about forest protection can be targeted at pre-invasion or post-invasion controls. Pre-invasion control focuses attention on preventing the introduction of new forest pests in native ecosystems, and economic analysis is needed to help balance the costs of improved biosecurity with the benefits of avoiding damage to forest ecosystems. Economic analysis of pre-invasion control is challenged by a lack of knowledge about factors contributing to successful invasions:

1. To the degree that each biological invasion in forests is a novel event, the past may provide limited scope for predicting future outcomes, and probabilistic damage functions based on historical invasions may be misleading (Williamson, 1996).
2. Characteristics that make newly arrived organisms invasive are poorly understood for most taxonomic groups (Kolar and Lodge, 2001).
3. As nonindigenous forest species accumulate, interactions among introduced species may facilitate the establishment of new species or magnify impacts on native species (Von Holle, 2011), causing super-additive damages.

4. Significant lags typically occur between the time at which an organism arrives in a new environment and when it becomes widely established and causes economic damage (Essl et al., 2011).
5. Forest protection from biological invasions is only as good as the weakest link in the chain of defensive actions (Perrings et al., 2002).

Economic analysis of post-invasion strategies, which focus attention on the costs and benefits (reduced damages) of controlling individual pest species, faces many of the sources of uncertainty listed previously for pre-invasion control, as well as the following:

1. Efficacy of management interventions used to eradicate or control pest outbreaks are difficult to predict and linkages between control costs and specific levels of damage reduction are highly uncertain.
2. Changes in global climate are causing some native forest pests to invade forest ecosystems beyond their historical range, and may alter future forest conditions in ways that increase forest vulnerability from nonnative forest species (Weed, Ayres and Hicke, 2013).

Most economic analyses recognize biological invasions as stochastic processes, due to either environmental (e.g. Olson and Roy, 2002) or demographic (e.g. Jaquette, 1970) stochasticity. The decision maker is characterized as either facing conditions of risk (relying upon probability distributions) or uncertainty (lack of knowledge regarding probability distributions). If a decision maker believes that biological invasions are replicable – factors causing varying degrees of invasion severity (e.g. infested area) could be known by designed or natural experiments – then the control problem can be viewed from the perspective of risk management. In this case, objective or subjective assessments of the probability of various degrees of invasion severity, at some future time, would yield a latent severity probability density function (PDF) such as shown in Quadrant I (Figure 24.1).<sup>1</sup> Such a PDF might be based on historical observations, simulation models or expert opinion. As more is learned about a pest, the PDF could be modified using methods such as Bayesian updating (Kelsey and Quiggan, 1992; Prato, 2005).

Many biological invasions cause little or no economic damage, so the threshold of economic damage is depicted to the right of the origin (the dashed vertical line). Quadrant II traces out the relationship between latent invasion severity and the level of market and/or nonmarket economic damages, which is the sum of costs and economic losses. This function could be estimated using new economic analysis or prior studies (via benefit–transfer analysis). Quadrant III translates economic damages on the vertical axis to the horizontal axis. Quadrant IV plots economic damage as a function of the associated latent invasion severity PDF. Integration of the area beneath an economic damage PDF yields the expected value of economic damages.

Risk management interventions (controls) are conducted with the intention of shifting the latent severity PDF (the state variable) toward smaller values (leftward pointing arrow in Figure 24.1).<sup>2</sup> Alternative controls incur different management costs (Quadrant II) and the cost associated with any feasible control should be less than the expected loss with no control. Given information on the relationship between the cost of a feasible control and the anticipated shift in the latent invasion severity PDF the associated shift in the economic damage function can be computed (rightward pointing arrow in Figure 24.1). Under the expected value framework, the preferred alternative is selected from a set of feasible controls as the alternative that minimizes expected economic damages. If the decision space is continuous over alternative controls, the optimal solution is found where marginal cost equals expected marginal benefits (expected reduction in economic loss) (Herrick, 1981; Horan et al., 2002). In a dynamic model, marginal benefits include the reduction of

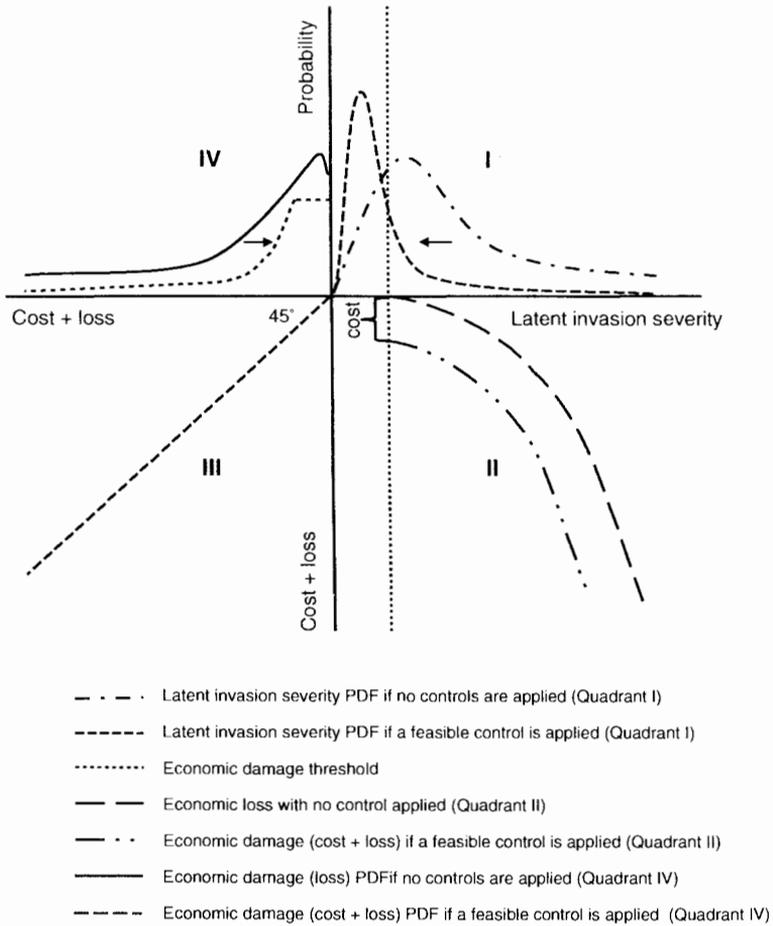


Figure 24.1 A stylized risk management model shows how invasion controls shift the latent invasion severity PDF and the economic damage PDF towards smaller values.

damage in current and (discounted) future periods (e.g. Olson and Roy, 2002). This learn-then-act strategy is most appropriate for post-invasion controls where established nonnative forest organisms are slow-spreading, the efficacy of control options is well understood, and reasonable estimates of economic losses are available. In contrast, this strategy is less appropriate for severe, fast-moving invasions or for pre-invasion control policies when little is known about the latent invasion severity, the efficacy of control strategies, or potential economic damages for a suite of potential invaders.

The risk management framework for controlling biological invasions in forests is limited in many applications by its stringent information requirements. Further, it is relatively insensitive to potentially catastrophic outcomes which may be difficult to characterize in a probabilistic framework. When the parameters of either the latent invasion severity or economic damage PDFs are unknown or highly uncertain, or when invasions are severe and fast-moving, other decision-making frameworks can be used.

A framework for making decisions under ignorance (when the decision maker has no knowledge of relevant probabilities) is the *maximin* rule. Under this rule, control  $x$  is preferred

to another control  $y$  if and only if the worst possible outcome from  $x$  is better than the worst possible outcome from  $y$  (Kelsey and Quiggan, 1992).

An alternative framework for making decisions under ignorance is based on the idea that decision makers characterize possible outcomes in terms of how surprised they would be if each outcome came true (Shackle, 1966; Katzner, 1990). Potential surprise functions are similar to inverse subjective probability functions, although they do not need to sum to one over the range of possible outcomes (Horan et al., 2002). Several possible outcomes can be associated with each control, and decision makers choose the control that minimizes the degree of surprise for attention-gaining (ascendant) outcomes (the *focus loss*).<sup>3</sup> Similar to *maximin*, the *focus-loss* framework shifts the decision-makers' attention from expected outcomes toward the catastrophic tail of the outcome distribution.

### Stages of a biological invasion

A key point not illustrated in Figure 24.1 is that biological invasions proceed by stages where each stage is associated with one or more management actions and a vector of economic costs and losses (Figure 24.2). Economic analysis proceeds by seeking efficient strategies either within a stage or across stages.

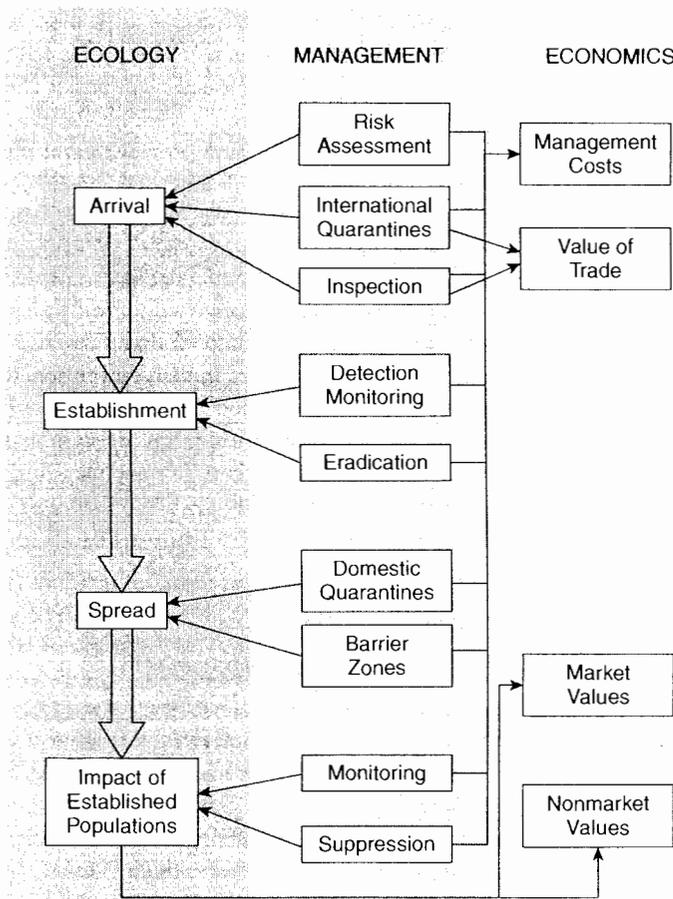


Figure 24.2 Each stage of a biological invasion induces management responses and economic impacts.

### ***Stage 1: Arrival and introduction of nonnative forest pests***

International trade is the major pathway for the introduction of nonnative forest pests. The importation of live plants is the most probable pathway of introduction for most damaging forest insects and pathogens established in the United States, and nearly three-quarters of plant shipments infested with exotic organisms pass through US ports undetected (Liebhold, Brockerhoff, Garrett, Parke and Britton, 2012). Wood packing materials are the most common pathway of introduction for wood-boring forest insects, and the use of these shipping materials is an increasing concern (Aukema et al., 2010; Strutt, Turner, Haack and Olson, 2013).

#### ***Economic models: Preventing arrival and introduction***

A general economic strategy for preventing the introduction of invasive species is to internalize the costs of biological invasions using tariffs combined with improved port inspections (Perrings et al., 2005). Economic optimization reveals that the importing country should set the tariff at the Pigouvian level, equal to the sum of expected damages from contaminated units not detected during inspections plus the costs of inspections (McAusland and Costello, 2004). When it is possible to estimate the probability of a successful invasion, each biosecurity facility should optimally set the marginal cost of undertaking preventive measures equal to marginal expected benefits, taking into account the probability that a species will invade through a different facility (Horan et al., 2002).

Economic models focusing on a single stage of the invasion process cannot provide globally optimal solutions because they ignore potential trade-offs among defensive actions across the stages of an invasion. Optimal allocation among prevention and control depends on the nature of prevention and control cost curves and the decision-maker's preferences over risky events. Research has shown that under some conditions, invasive species can be managed most cost-effectively using greater investments in prevention relative to control because damages can be catastrophic (Leung et al., 2002). Other research has shown that if decision makers are risk-averse and if control options are thought to be more certain than prevention, then control may be preferred to prevention (Finnoff, Shogren, Leung and Lodge, 2007). Recent innovations in the analysis of trade-offs among invasion stages include the development of spatial models of prevention, detection and control (Sanchez-Albers, Fischer and Coleman, 2010). The primary lesson is that focusing on a subset of transmission pathways, on only one or two controls, or on a single region, misses important interactions that are critical in identifying cost-effective policy recommendations.

### ***Stage 2: Establishment of nonnative pests***

The probability of successful establishment depends on the frequency and size of arrivals (propagule pressure), spatial habitat suitability and temporal environmental fluctuations (Leung, Drake and Lodge, 2004; Von Holle and Simberloff, 2005) which are highly stochastic. Most preventative strategies are based on reducing propagule pressure. However, if new species are repeatedly introduced through similar or novel invasion pathways, Allee effects and stochastic population dynamics are much less likely to cause initial populations to go extinct, thereby increasing the likelihood that isolated populations become established.

*Economic models: Surveillance and eradication  
of newly established populations*

Surveillance systems to detect newly established species that evade port inspections are critical to reducing the potential for ecological and economic damage. Cost-effective surveillance systems for newly established populations balance the intensity and cost of surveillance (which increase with the level of effort) with the costs of damage and eradication of newly detected populations (which may be less if detected early) (Epanchin-Niell and Hastings, 2010). Economic models that account for this trade-off have assumed the pest location is unknown (Mehta, Haight, Homans, Polasky and Venette, 2007), small invasive populations establish ahead of an advancing front (Homans and Horie, 2011) or that the likelihood of detection increases with the size of an infestation (Bogich, Liebhold and Shea, 2008).

Research effort has also focused on the properties of optimal one-time surveillance across multiple sites when species' presence is uncertain prior to detection, accounting for heterogeneity in species presence and detectability across sites (Hauser and McCarthy, 2009). Other models of one-time surveillance have investigated the impact of uncertainty regarding the extent (rather than simply the presence) of an infestation (Horie, Haight, Homans and Venette, 2013).

Economic models of long-term surveillance programs have been developed using dynamic optimization algorithms and indicate that greater surveillance effort is warranted in locations that have higher establishment rates, higher damage and eradication costs or lower sampling costs (Epanchin-Niell, Haight, Berec, Kean and Liebhold, 2012). Active research is underway in which invasion dynamics are uncertain. This line of research recognizes that surveillance may not provide correct information, and researchers have used partially observable Markov decision process to address optimal invasive species surveillance (Regan, McCarthy, Baxter, Panetta and Possingham, 2007) and monitoring and control strategies (Haight and Polasky, 2010). More generally, partially observable decision models have been used to allocate management resources for networks of cryptic diseases, pests and threatened species (Chadès et al., 2011).

***Stage 3: Spread of nonnative pests***

The spread of a biological invasion results from the combination of three factors: (1) pest population growth, (2) dispersal of organisms and (3) spatial characteristics of the environment. The classic reaction-diffusion model of a biological invasion predicts circular traveling waves that spread outwards from the point of invasion origin and a linear relationship between the square root of the invaded area and time – that is, the range expands at a constant rate (Holmes, Lewis, Banks and Veit, 1994; Shigesada, Kawasaki and Takeda, 1995). Despite the apparent simplicity of this model, it has been successfully used to explain the spread of nonnative forest species such as the gypsy moth (Liebhold, Halvorsen and Elmes, 1992).

Several modeling approaches have been developed that take into account local and long-distance dispersal due to factors such as transportation networks. The stratified diffusion model describes range expansion in terms of the effective range radius, which is the square root of the invaded area (integrated across all colonies) divided by the square root of pi (Shigesada et al., 1995). Building on this idea, the temporal and spatial dynamics of economic damages resulting from a biological invasion were analyzed using the area of economic damage (AED) occurring in 'economic colonies' (Figure 24.3) (Holmes, Liebhold, Kovacs, and Von Holle, 2010). Although applications of the stratified diffusion model are largely backward looking, gravity models and random utility models have been used to make predictions of invasions when

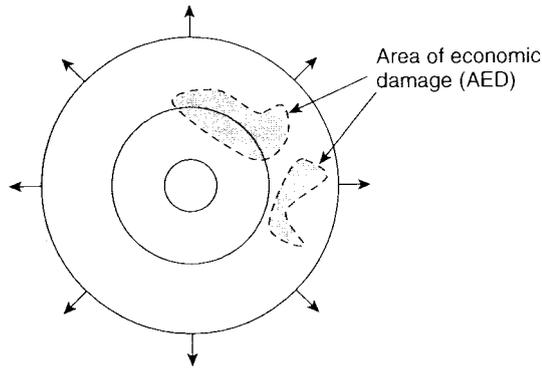


Figure 24.3 Economic damage disperses by local and long-distance pathways over successive time periods. The integrated AED in 'economic colonies' is used to compute the effective range radius and the rate of spread of economic damage associated with a biological invasion.

human-mediated dispersal is important (Chivers and Leung, 2012). Each takes into account distance as well as the 'attractiveness' of alternative locations, and therefore can incorporate differential traffic to each site and their consequences on patterns of spread.

### *Economic models: Slowing the spread of established populations*

When a nonnative species becomes established, various strategies can be used to affect the expansion of its range, including reduction of the chances of accidental movement of organisms to uninfested areas via domestic quarantine, detection and eradication of isolated colonies or control activities to slow or stop the spread of the core population. Research has focused on developing optimal control strategies for slowing or eradicating population growth, addressing questions of when, where and how much control should be applied (see Epanchin-Niell and Hastings, 2010, for a review).

Invasive species control models generally include pest population dynamics with an objective of minimizing the sum of discounted control costs and invasion damages over time. The most basic models of invasive species dynamics focus on the numbers of individuals or area of infestation and ignore spatial description (Sharov and Liebhold, 1998; Eiswerth and Johnson, 2002; Saphores and Shogren, 2005). A general principle emerging from this research is that, if the invasive species stock is initially greater than its optimal equilibrium level, then the highest level of management effort should be initially applied and then decline over time until the steady state is reached (Eiswerth and Johnson, 2002). When controlling a population front, the optimal strategy changes from eradication to slowing the spread to doing nothing as the initial area occupied by the species increases, the negative impact of the pest per unit area decreases or the discount rate increases. Stopping population spread is not an optimal strategy unless natural barriers to population spread exist (Sharov and Liebhold, 1998).

These basic population models have been extended to account for uncertainty in invasion growth. The optimal control strategy is obtained using discrete-time stochastic dynamic programming (Eiswerth and van Kooten, 2002; Olson and Roy, 2002) or a real options framework in continuous time (Saphores and Shogren, 2005; Marten and Moore, 2011).

Recently, spatially explicit models of invasive species dynamics have gained prominence. These models define the landscape as a set of discrete patches, define control activities for each

patch and predict the growth and dispersal of the invasive species among patches as a function of the selected controls (e.g. Hof, 1998; Albers, Fischer and Sanchirico, 2010; Blackwood, Hastings and Costello, 2010; Epanchin-Niell and Wilen, 2012; Kovacs, Haight, Mercader and McCullough, 2013). Although these spatial dynamic models are complicated to solve, they can provide pragmatic guidance to forest managers. For example, managers should (1) use landscape features that alter the shape of the initial invasion in order to reduce the length of exposed invasion front and look forward over space to slow the spread and (2) steer the invasion front away from the direction of greatest potential damages or in the direction where the costs of achieving control are low (Epanchin-Niell and Wilen, 2012).

### **Economic impacts from nonnative forest pests**

One of the primary challenges of applying optimization models to post-invasion management of biological invasions in forests is that the analyst needs first to specify pest population dynamics and second to describe how pest dynamics are coupled with a proper measure of economic impacts. Welfare economic theory should guide the choice of empirical methods used to measure economic impacts, which may be transitory, cyclical or persistent.<sup>4</sup> Determining the temporal relationship between a nonnative forest pest, its host and the flow of market or nonmarket goods and services is necessary to establish scope for economic analysis.

#### *Timber market losses*

If reduction in the volume of timber harvest is a small percentage of total harvest volume and can be fully offset by timber harvest of nonimpacted timber species, and if compensatory growth on nonimpacted healthy trees will eliminate all lost timber harvest volumes from a biological invasion within a given period, timber prices will remain fixed and only forest landowners with impacted stands will experience economic losses (Aukema et al., 2011). In contrast, if a biological invasion is severe enough to shift timber supply (e.g. via pre-emptive or salvage harvest), timber demand (e.g. via substitution of alternative species) or both, prices will be variable and three types of models may be used for analysis: (1) market trends, (2) partial equilibrium models and (3) computable general equilibrium (CGE) models.

#### *Timber market trends*

The simplest approach to evaluating timber market dynamics is to qualitatively describe market forces using time-series data on timber prices and quantities (Zivnуска, 1955). If in successive years timber prices increase and quantity decreases, economic theory stipulates that market supply has shifted back (and it is not possible to state what has happened to demand). Other shifts in supply and demand are implicit with other combinations of price and quantity changes.

Although the market trend model is simple to implement, its application can provide useful insights. For example, consider data on chestnut lumber prices and quantities (Figure 24.4) for years spanning the onset and spread of the chestnut blight (1904–1943).<sup>5</sup> The chestnut blight was first identified in New York City during 1904, and at that time, chestnut accounted for about one-quarter of the lumber produced in New England and about 15 percent of lumber production in the Appalachian region. As can be seen in Figure 24.4, the volume of chestnut lumber produced in the United States increased rapidly from 1904 to 1909 and then gradually decreased as chestnut timber inventories were exhausted. Although real chestnut lumber prices varied during this period, they remained remarkably stable. These trends are

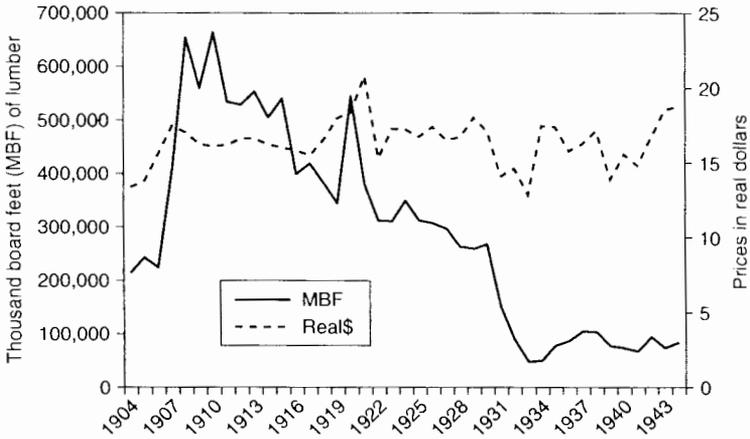


Figure 24.4 Time-series of chestnut lumber prices and quantities in the United States, 1904–1943. Source: Steer (1948).

consistent with a reduction in lumber supply due to a declining timber inventory and a gradual reduction in chestnut lumber demand as hardwood products firms substituted other timber species.

#### PARTIAL EQUILIBRIUM MARKET MODELS

A more informative analysis of the impacts of forest pests on timber markets can be conducted in cases where shifts in timber supply and demand can be estimated or simulated using empirical functions provided by prior studies. These models estimate quasi-rents for timber producers and consumers in an intermediate market and do not include impacts on other groups, such as final consumers.

A conceptual model describing timber market impacts of catastrophic mortality from forest insects and other forest disturbances has been developed and used to provide empirical estimates of supply shocks on producer and consumer surplus (Holmes, 1991; Prestemon and Holmes, 2000). The market model describes a short-run, outward shift in timber supply as damaged timber stocks are salvaged, and then a backwards shift in supply as damaged stocks are exhausted and supply is provided by a diminished timber inventory. As shown in Figure 24.5, the market equilibrium immediately preceding a disaster corresponds with price  $P_0$  and quantity  $Q_0$  (point *a*) based on supply curve  $S_0(I_0)$ , a function of initial inventory  $I_0$  and an initial demand curve,  $D_0(I^*)$ . The volume of timber salvage,  $V$ , induces an inelastic salvage supply curve as the opportunity cost of holding damaged stocks is very low. During salvage operations, market supply shifts outwards to  $P_T$  and  $Q_T$  (point *b*). The volume supplied from undamaged stands ( $Q_u$ ) is found where  $P_T$  intersects the undamaged supply curve  $S_1(I_1)$ , point *d*. The salvage volume,  $V$ , gradually shifts back as salvage volumes are exhausted, leaving a new equilibrium of supply and demand at  $P_1$  and  $Q_1$  (point *c*). In the short run, economic surplus is transferred from forest owners with damaged stands to owners with undamaged stands and to wood-consuming firms. However, in the longer run, if standing inventories are significantly reduced, wood-using firms may lose economic surplus to the point that they go out of business.

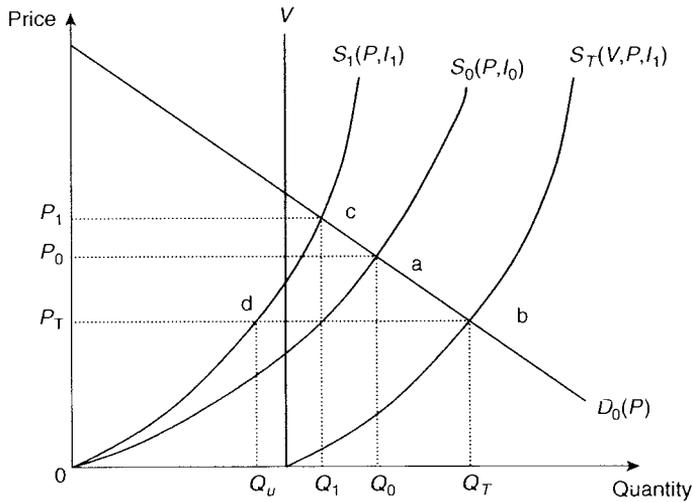


Figure 24.5 Timber market impact of a biological invasion where timber mortality is salvaged ( $V$ ) after being killed, shifting supply from  $S_0$  to  $S_T$ . Timber supply then shifts backwards ( $S_1$ ) as damaged timber stocks are exhausted and inventories of undamaged timber are diminished.

CGE MODELS

CGE models provide a mathematical representation of monetary flows through an economy as firms and households interact through the markets for inputs and products. It is generally assumed that consumers maximize utility, producers maximize profit and consumers and producers can substitute alternative inputs and final consumption goods as relative prices change and equilibrium is attained in each period. These models are critically dependent on the many assumptions that are made to operationalize them. CGE models have been used to estimate the regional economic impacts of indigenous (Patriquin, Wellstead and White, 2007) and nonnative forest pest outbreaks (McDermott, Finnoff and Shogren, 2013).

**Nonmarket losses from nonnative forest pests**

Forest ecosystems generate a constellation of benefits that are valued by people but are not bought and sold in markets. The proper economic measure of the value of a change in non-market forest benefits is what people are willing to pay to access, protect, enhance or restore a flow of benefits. The total value of nonmarket benefits associated with a change in forest conditions is the sum of use, option and passive use values. Although quantification of the economic benefits of controlling biological invasions in forests has historically emphasized protection of commodity production, recent research demonstrated that the economic benefits of invasion control efforts in US forests would largely result from the protection of nonmarket goods and services (Aukema et al., 2011).

Several economic tools are available for measuring the nonmarket value of natural resources (Champ, Boyle and Brown, 2003). Approaches for estimates are categorized by methods that use observed behavior, known as revealed preference methods, and methods based on responses to hypothetical questions, known as stated preference methods. Because revealed preference methods are based on observations of how people behave in situations that are linked with markets,

these methods are not able to provide estimates of passive use value. In contrast, stated preference methods are able to uncover estimates of total value.

### ***Revealed preferences for forest protection***

Two revealed preference methods have been used to study the economic impacts of forest pests – the travel cost method and the hedonic price method. If an insect or disease outbreak changes the condition of a forest recreational site and alters visitation rates, then the travel cost method can be used to estimate changes in economic welfare. Because several recreational sites may have related demand functions, the demand linkages among sites must be accounted for (Englin, Holmes and Sills, 2003). Several studies have used the travel cost method to estimate economic impacts of forest insects via the demand for forest recreation (reviewed in Rosenberger, Bell, Champ and Smith, 2012), although we are unaware of forest pest impact studies that consider substitution across recreational sites.

The hedonic price method is based on the idea that the price of a good represents the sum of values associated with the qualities or attributes that comprise the good (Champ et al., 2003). Where localized changes in forest health affect a relatively small proportion of properties in a housing market, the hedonic price function for the market remains unaffected, and the first-stage hedonic price function can be used to compute marginal changes in economic welfare.<sup>6</sup> This method has become increasingly popular for estimating the nonmarket impacts of nonnative forest pests in the United States, largely as a result of the increasing availability of spatially referenced remote sensing data on forest health and the availability of electronic records on housing prices and attributes. One of the key discoveries has been that the loss of forest health on one property causes economic spillovers onto neighboring properties (Holmes, Murphy, Bell and Royle, 2010). Estimates of percentage losses in property value from declines in tree health vary widely (Holmes, Murphy, et al., 2010; Kovacs, Holmes, Englin and Alexander, 2011; Price, McCollum and Berrens, 2010), and it is not yet understood what causes this variation.

### ***Stated preferences for forest protection***

Several studies have used stated preferences (contingent valuation or choice experiments) to estimate willingness to pay for forest health protection programs. The contingent valuation method was used to evaluate the benefits of programs protecting forests from nonnative forest insects in residential forests (Miller and Lindsay, 1993; Jakus, 1994) and in public forests (Holmes and Kramer, 1996; Moore, Holmes and Bell, 2011). These studies concluded that (1) the benefits of forest protection programs are generally several times larger than their costs, and (2) passive use values constitute a substantial proportion of the total value of forest protection in public forests.

The choice experiment method differs from contingent valuation in that it focuses attention on trade-offs between various levels of environmental attributes and money (Champ et al., 2003). This method has been used to estimate willingness to pay for multiple attributes of state parks in Florida (United States), including preventing invasive plants from becoming abundant (Adams, Bwenge, Lee, Larkin and Alavalapati, 2011). Similar to the general conclusion from contingent valuations studies of forest health protection, statewide benefits of protecting parks from invasive plants were found to be several times larger than current expenditures on these programs.

### Aggregation of multiple economic impacts

Relatively few studies have been conducted that estimate aggregate economic impacts of invasive species at a national scale. Despite the success of these studies in drawing attention to the economic significance of biological invasions (Pimental, Lach, Zuniga and Morrison, 2000; Colautti, Bailey, van Overdijk, Amundsen and MacIsaac, 2006), their policy relevance has been limited by lack of a theoretically consistent economic framework (Born, Rauschmayer and Brauer, 2005; Holmes et al., 2009).

Recent research (Aukema et al., 2011) has reported an improved method for estimating aggregate economic impacts from multiple biological invasions based on the idea that economic damages are random variables that can be depicted using economic damage PDFs (Figure 24.6A). The level of economic damage associated with each historically occurring pest is categorized as low, medium or high, and it is assumed that the probability that a new pest will fall into any of the damage categories is equal to the integral of the corresponding area under the damage PDF. Because the shape and scale of the damage PDFs are unknown, alternative functions are generated using alternative parameter values (Figure 24.6B). The relative probability of

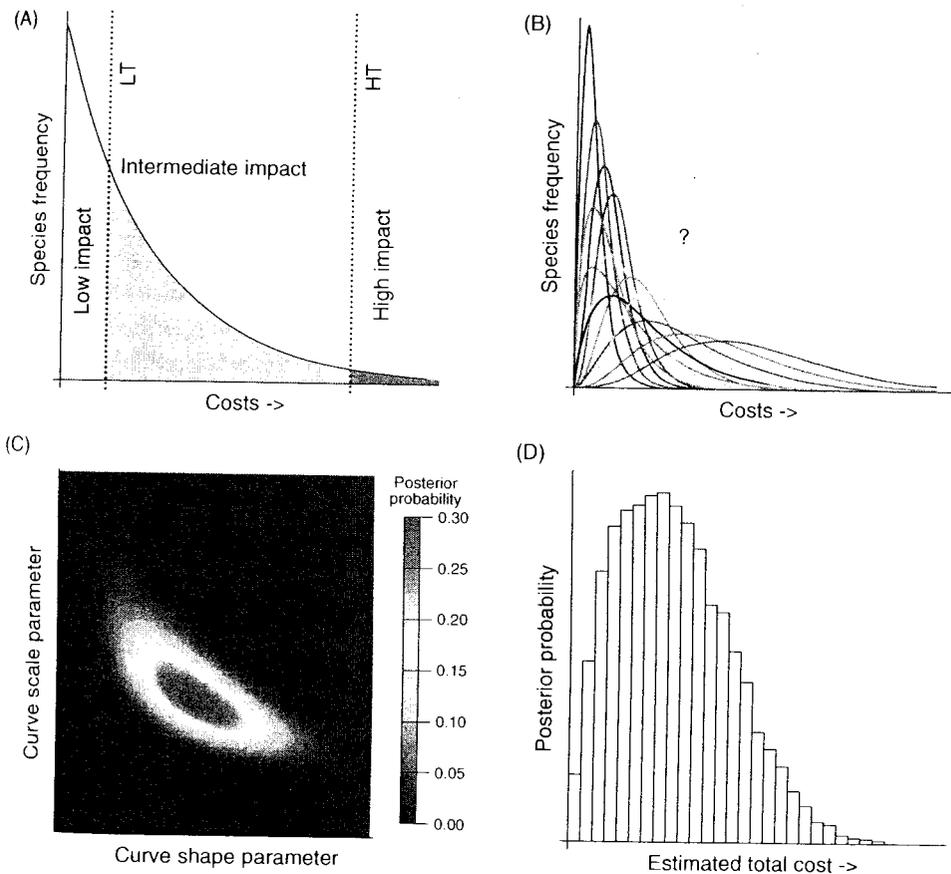


Figure 24.6 A Bayesian framework for estimating aggregate economic damages resulting from multiple biological invasions.

Source: Aukema et al. (2011).

each set of parameters being true is determined using Bayesian statistical methods (comparing model predictions to the observed data on pest frequencies and economic damage estimates). The resulting collection of posterior PDFs then yields estimates of parameter uncertainty (Figure 24.6C). Additionally, in order to include model or structural uncertainty, different families of curves can be considered (e.g. gamma, log-normal, power or Weibull distributions) and integrated into the analysis using Bayesian model averaging. Finally, the output from these analyses is used to generate the posterior predictive distribution of damage (Figure 24.6D).

Using this aggregation method, the authors found that the greatest impacts of recent biological invasions in US forests are largely borne by local governments and residential landowners. Wood-boring insects were found to cause the largest annual economic impacts, inducing nearly \$1.7 billion in local government expenditures and approximately \$830 million in lost residential property values. Timber impacts were typically an order of magnitude smaller than impacts on local governments and residential households.

## Conclusions and discussion

Biological invasions have historically caused major disruptions in the flow of valued goods and services provided by forest ecosystems. Unless trans-boundary biosecurity programs are improved, new invasions are anticipated to impact ecological and economic systems well into the future. Although optimization models have recently been developed that focus attention on economic efficiency across the stages of a biological invasion, calibration of these models is severely limited by the dearth of theoretically consistent measures of economic damages. Better information on economic costs, losses and the efficacy of control programs across multiple spatial scales is needed to provide improved information to decision makers.

Several research themes are suggested. First, the importance of protecting nonmarket values provided by healthy forests has recently been recognized in both microeconomic and aggregate economic studies and substantial research effort is warranted to address many unanswered questions. Topics include (1) understanding sources of variation in first-stage hedonic functions and estimation of second-stage hedonic demand functions for healthy residential forests, (2) understanding the importance of passive use forest protection values in relation to use values across a broad spectrum of public forest ecosystems and (3) understanding whether preferences for forest health protection are stable or variable across generations.

Innovative methods are also needed for estimating timber market impacts of biological invasions. One approach that (to our knowledge) has yet to be utilized by forest economists is estimation of econometric general equilibrium supply and demand functions, as described by Just and Hueth (1979).

A greater number of microeconomic studies of market and nonmarket values associated with protecting forest health are needed for improving models of aggregate economic impacts of biological invasions in forests. Although progress has been made in developing aggregate economic damage functions, it is not known if aggregate damage functions are stable or, if not, what factors shift damage functions over time. The development of systems for updating aggregate damage estimates as new information becomes available is recommended.

Linkages between the costs of pre-invasion and post-invasion controls and forest ecosystem damages avoided are poorly understood and deserve greater research attention. Until more knowledge is gained on this topic, balancing costs and benefits as prescribed by economic analysis will remain an elusive goal.

Finally, almost nothing is known about how forest health protection decisions are actually made. Research is needed to shed light on the degree to which, and under what circumstances,

decision makers think in probabilistic terms or rely on alternative modes for making decisions. We suggest that stated preference methods (such as choice experiments) or the use of economic experiments might be fruitfully employed to understand how decision makers assign weights to alternative pest management programs and outcomes, and how they update their thinking as knowledge is gained about the nature of individual or multiple biological invasions.

## Notes

- 1 In practice, nonsmooth PDFs could be used, such as a triangular distribution which only requires estimates of the minimum, maximum, and mode.
- 2 Control effort may also reduce the economic loss associated with each level of invasion severity, causing a change in the shape of the loss function.
- 3 The focus loss is determined by the tangency between the potential surprise function and the corresponding iso-ascendency contour (Katzner 1990).
- 4 Transitory economic impacts can occur when a pest functionally eradicates its host, forest ecosystems provide compensatory growth of other tree species, and people substitute alternative goods or services as conditions of relative scarcity change. Cyclical economic impacts result from oscillatory pest population dynamics, and forests recover between outbreaks. Persistent impacts occur when a pest and its host coexist over long periods of time, due to factors such as slow rates of spread or genetic improvement in host trees.
- 5 Lumber prices were deflated to 1913 prices using the consumer price index, which was initiated in that year. Prices prior to that year shown in Figure 24.4 are nominal prices.
- 6 If data on forest conditions are available for several housing markets, then it may be possible to estimate the second-stage demand function for forest conditions.

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