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Bioeconomics of Managing the Spread of Exotic Pest Species with Barrier Zones

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Exotic pests are serious threats to North American ecosystems; thus, economic analysis of decisions about eradication, stopping, or slowing their spread may be critical to ecosystem management. The proposed bioeconomic model assumes that the rate of population expansion can be reduced (even to negative values in a case of eradication) if certain management actions are taken along the population front. The area of management can be viewed as a dynamic barrier zone that moves together with the population front. The lower is the target rate of spread, the higher would be both benefits and costs of the project. The problem is to find the optimal target rate of spread at which the present value of net benefits from managing population spread reaches its maximum value. If a population spreads along an infinite habitat strip, the target rate of spread is optimal if the slope of the cost function versus the rate of spread is equal to the ratio of the average pest-related damage per unit time and unit area to the discount rate. In a more complex model where the potential area of expansion is limited, two local maxima of net benefits may exist: one for eradication and another for slowing the spread. If both maxima are present, their heights are compared and the strategy that corresponds to a higher value of net benefits is selected. The optimal strategy changes from eradication to slowing the spread and finally to doing nothing as the area occupied by the species increases. The model shows that slowing the spread of pest species generates economic benefits even if a relatively small area remains uninfested. The cost of slowing the spread can be estimated from a model of population expansion via establishment of isolated colonies beyond the moving front. The model is applied to managing the spread of the gypsy moth (*Lymantria dispar*) populations in the United States.

KEY WORDS: Barrier zone; bioeconomics; biological invasion; gypsy moth; model

1. INTRODUCTION

Invasion of exotic pests is a serious threat to North American ecosystems.[1,2] The risk of organism movement across natural geographic barriers is growing due to the increasing transportation activity. And introduced species are more likely to be pests than are native species.[3] After a new exotic pest species becomes established and initial eradication attempts have failed, a decision should be made whether to continue eradication efforts, or switch to a confinement strategy that would stop or slow the population spread. In this article, I suggest the use of economic analysis for making a decision.

The subject of the bioeconomic theory is the optimal management of renewable biological resources.[4,5] Initial bioeconomic models in fisheries used the concept of maximum sustainable yield, which implies a stable equilibrium. However, natural populations often have nonequilibrium dynamics, such as limit cycles or chaos.[6] Exotic species may expand their range in space by forming moving waves.[7] Economic assessment of these transition processes requires incorporation of discount rates into the

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cost-benefits analysis. Discount rate is the instantaneous rate of decrease in value of any costs and benefits over time. For example, a postponed payment is beneficial for a person because he can use additional time to get the money. In the same way, we prefer to get money now rather than 5 year later. If future value is adjusted according to the discount rate it is called the present value. The present value of an activity equals the net expected revenues weighted by the exponential function of time at which these revenues are obtained:[4]

$$\int_0^T P(t)\exp(-\alpha t)\,dt, \tag{1}$$

where $P(t)$ is the net revenue at time t, α is the discount rate, and T is the time horizon. The time horizon may be infinite, and in this case a criterion of convergence is required. Revenues, $P(t)$, can be both positive and negative. Typically, discount rates vary from 2% to 7% per year.

Bioeconomic theory has been applied to pest management, but in most cases only short-term revenues have been considered.[8,9] For example, the concept of the economic injury level, which is the cornerstone of integrated pest management, is usually applied to one growing season.[10,11] In most agricultural programs, the time span from investment in pest management to crop harvest is short, and there is no need to use the concept of present value because inflation is negligible during this period. Thus, most optimization models in pest management concentrated on maximizing the difference between benefits and costs in the same year.[12–14]

Traditionally, pest eradication and confinement programs have been based upon qualitative understanding of economic effects. Attempts to apply economic models to justify eradication measures often failed because of insufficient information and unjustified simplifications.[15,16] For example, side effects of large-scale pesticide treatments were ignored in cost-benefit analyses of several eradication programs.[15] Monitoring systems were often inefficient, and the range of a species could be underestimated. However, new technologies (effective traps, geographic information systems, etc.) provide tools for a sound economic analysis of eradication and confinement activities. Information on the ecological effects of many invading pest species has substantially increased over the last decade, making economic analyses possible.

In this article, I focus on the use of only one kind of strategy against established exotic pests: barrier zones. I define a barrier zone as any pest management activity performed in the area adjacent to the population front and targeted at modifying the rate of population spread. If the population front moves (foreword or backward), then the barrier zone should move too, in accordance with the definition. Barrier zones can be used not just for stopping the spread of a pest species, but also for slowing the spread, and for eradication.

Barrier zones have been used against several insect species. In 1923, a barrier zone was established along the Hudson River to prevent the spread of the gypsy moth, *Lymantria dispar* (L.), in the United States.[17] It was managed until 1941 when it finally became infested. The barrier did not stop the advance of the population front, but the rates of spread were considerably reduced.[18] Currently, the USDA Forest Service is conducting the Slow-the-Spread (STS) program to slow the expansion of gypsy moth populations to the west and south by early detection and eradication of small isolated colonies ahead of the moving front.[19] In the Appalachian Mountains, where sufficient historical data was available, the average rate of spread has been reduced from 21 to 8.6 km/yr.[20]

After the screwworm (*Cochliomya hominivorex* Coquerel) was successfully eradicated from the United States in 1966, a barrier zone was set along the border of Mexico to prevent the reinvasion of this cattle parasite.[21] Screwworm populations were managed using sterile insect release. Later, the eradication program was expanded to Mexico and Central American countries with a goal to move the barrier zone toward Panama.

Before africanized honeybees (*Apis mellifera* L.) entered the United States, there was an attempt to stop their spread in Mexico.[22] In 1985, the USDA established a Bee Regulated Zone in the Tehuantepec region. However, this zone was soon invaded and the goals of the project were transformed into slowing the spread. It is believed that the project has postponed the invasion of africanized honeybees by 2 years.

The boll weevil (*Anthonomus grandis* Boheman) was successfully eradicated in Virginia, both Carolinas, Georgia, Florida, Alabama, California, and Arizona.[23] However, further eradication was more difficult than expected because of increased insect resistance, decreased abundance of natural enemies, and other environmental and economic factors. Whether complete eradication of the boll weevil in the United States is possible or not, it is important to keep the pest from spreading back into areas where it has been eradicated. Thus, barrier zones are maintained along the borders of the area where eradication was successful.

In this article, I present a bioeconomic model of a barrier zone that determines economic benefits from using a barrier zone (Section 2), and optimizes the management of a barrier zone (Section 3). The model is then applied it to the problem of gypsy moth spread in North America as a case study (Section 4). The gypsy moth is a good example for this analysis because: (1) there is an ongoing project on slowing the spread of this species,[24] and (2) historical data collected with pheromone-baited traps are extensive in both space and time.

2. MODEL OF ECONOMIC BENEFITS FROM USING BARRIER ZONES

In this section, I describe a model of economic benefits from modifying the rate of spread of an invasive pest species with a barrier zone.[25] In the simplest version of the model (Section 2.1), I assume that the barrier zone together with the population front move along an infinite habitat strip with a uniform rate, which is smaller than the natural rate of spread. The slower is the target rate of spread, the higher is the cost because more intensive pest management is needed within the barrier zone. The model determines the optimal target rate of spread that maximizes net benefits. Then the model is generalized for a nonuniform population spread in a limited area (Section 2.2), and finally a particular case of spread in a rectangular area is examined in detail (Section 2.3).

2.1. Uniform Spread in an Infinite Habitat Strip

The simplest version of the model assumes that a pest species spreads along an infinite habitat strip (Fig. 1). This assumption may be valid if the population has spread far enough away from the introduction point but a large area is not infested yet. In this case, the optimal solution would be a constant target rate of population spread. Thus, a traveling wave technique can be used to determine the rate of spread.

If there is no barrier zone, then the species spreads at its maximum rate of $v_{\max}$. In a space-time diagram, damage occurs in the area below the line $x = tv_{\max}$ (Fig. 2). With a barrier zone, the rate of spread is reduced to v; then damage occurs in the area below the line $x = vt$. Thus, benefits from slowing the spread occur in the shaded area between lines $x = tv_{\max}$ and $x = vt$ (Fig. 2). Benefits are discounted with time (i.e., immediate benefits are more valuable than postponed benefits). The present value of benefits from slowing the spread per unit length of the population front is

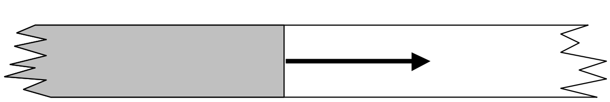

Fig. 1. Spread of a population along an infinite habitat strip.

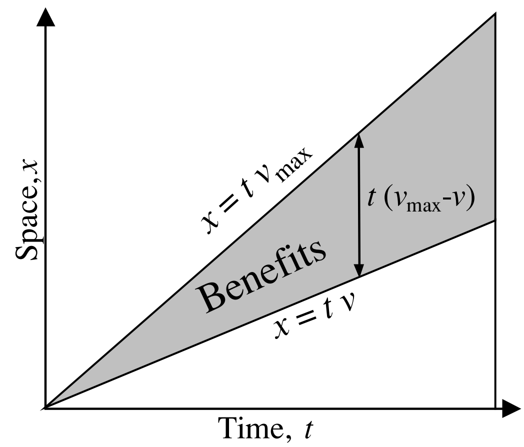

Fig. 2. Space-time diagram of benefits from slowing the spread of a pest species.

$$B = \int_0^\infty t\,D(v_{\max} - v)e^{-\alpha t} = \frac{D(v_{\max} - v)}{\alpha^2}, \qquad (2)$$

where D is the damage per unit area per year, and α is the discount rate per year.

The cost of the barrier zone per unit length along the population front, $C(v)$, represents the minimum cost of maintaining the target rate of population spread, v, which implies that all activities in the barrier zone are optimized. The smaller is the target rate of spread, v, the higher is the cost of the program (Fig. 3A). If the spread is not managed, then the cost would be zero, and the population would spread with its natural rate, $v_{\max}$; hence, $C(v_{\max}) = 0$. $C(0)$ is the cost of stopping the spread.

The present value of net benefits, NB, is equal to benefits B minus costs that are discounted with time

$$NB = B - \int_0^\infty C(v)e^{-\alpha t} = \frac{D(v_{\max} - v)}{\alpha^2} - \frac{C(v)}{\alpha}. \qquad (3)$$

The optimal solution corresponds to the maximum of net benefits, NB. Thus, the optimal target rate of

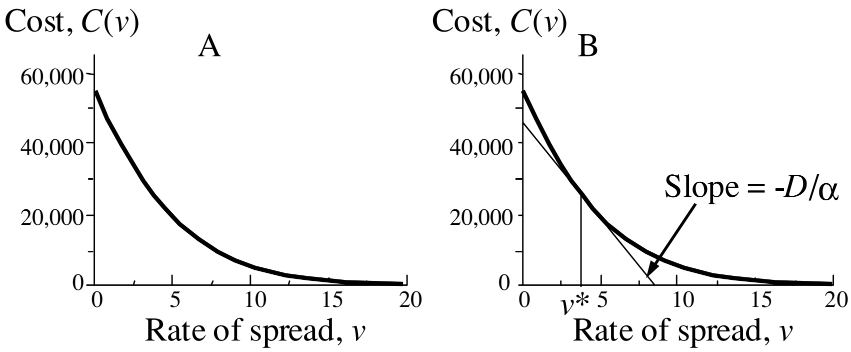

Fig. 3. Cost, $C(v)$, of slowing the spread per unit length of the barrier zone as a function of target rate of population spread, v (A); determining the optimal target rate of spread, v^* (B).

population spread can be found by solving the equation $dNB/dv = 0$. The solution is

$$\frac{dC}{dv} = -\frac{D}{\alpha}. \tag{4}$$

This equation means that the slope of the cost function should be equal to the ratio of damage rate, D, to the discount rate, α. In Fig. 3B, the line with a slope of $-D/\alpha$ touches the cost function at the point that corresponds to the optimal target rate of spread, v^*.

If damage, D, is high, then the slope, D/α, is steep; hence, the target rate of spread is low. Pest management in the barrier zone should be aggressive to achieve this rate of spread. But if damage is low, then the slope, D/α, is gentle; hence, the target rate of spread is large, and little pest management is needed in the barrier zone. Equation (4) may have no solution for positive rates of spread if the damage is too low (Fig. 4A), or too high (Fig. 4B). In the former case, the optimal strategy is to do nothing. In the latter case, a solution may exist for some negative rate of spread. A negative rate of spread means that the population front retreats due to barrier-zone management. Eventually, it leads to eradication of the species. If damage is so high that there is no solution of Equation (4) even for negative rates of spread, then eradication should be done in one step in the entire area rather than with a barrier zone.

Equation (4) assumes unlimited operational funds for the project, which may not be realistic. In practice, the cost of the optimal strategy for slowing the spread may exceed available funding. In this case, slowing the spread it is still beneficial, but the target rate of spread should be increased to reduce the cost.

2.2. Nonuniform Spread in a Limited Area

The model described above has serious limitations. It cannot be applied to populations that have just established or have spread already through most of their potential area. Sharov and Liebhold[25] developed two more realistic models: (1) population spread in a rectangular area from one side to the opposite side, and (2) spread in all directions from the center (Fig. 5). In both cases, the optimal target rate of population spread is a function of time rather than a constant. Thus, more complex optimization methods are needed.

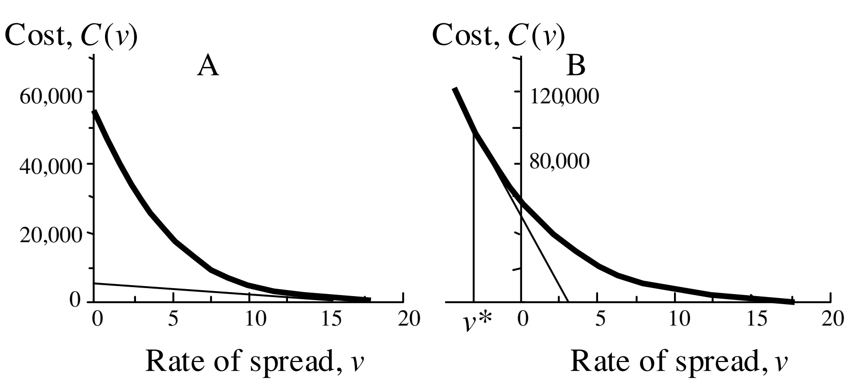

Fig. 4. Two cases where Equation (4) has no solution for positive rates of spread: (A) damage is too low and doing nothing is the best strategy; (B) damage is too high and eradication (negative rate of spread, (v_1) is the best strategy.

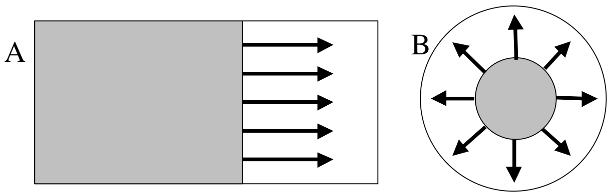

Fig. 5. Population spread in a rectangular area (A), and radial spread in all directions (B).

In both cases the present value of total benefits from slowing population spread is

$$TB = D \cdot \iint_S L(x(t)) \exp(-\alpha t)\, dt\, dx, \qquad (5)$$

where D is the average damage caused by the pest per unit area per unit time, $L(x)$ is the length of the population front after it moved by distance x from the introduction point, and S is the shaded area in Fig. 2. If the population spreads in a rectangular area (Fig. 5A), then the length of the population front, $L(x)$, is a constant. But if the population spreads in all directions from one point (Fig. 5B), then the length of the front increases linearly with increasing distance from the center: $L(x) = 2\pi x$.

Sharov and Liebhold[25] showed that Equation (5) is equal to

$$TB = \frac{D}{\alpha}\left[\int_0^{x_{\max}} L(x) \exp(-\alpha x / v_{\max})\, dx - \int_0^{\infty} v(t) L(x(t)) \exp(-\alpha t)]\, dt\right], \qquad (6)$$

where $x_{\max}$ is the most distant point in the uninfested area, and $x_0 = x(t_0)$ is the starting location of the population front.

The cost of the entire barrier zone at time t is $C(v(t))L(x(t))$. The present value of total costs for the entire project starting from current time, t_0, equals

$$TC = \int_0^{\infty} C(v(t)) L(x(t)) \exp(-\alpha t)\, dt. \qquad (7)$$

Combining costs and benefits (Equations (6) and (7)) we get the present value of total net benefits

$$TNB = \frac{D}{\alpha}\int_0^{x_{\max}} L(x) \exp(-\alpha x / v_{\max})\, dx - \int_0^{\infty}\left[\frac{D}{\alpha} v(t) + C(v(t))\right] L(x(t)) \times \exp(-\alpha t)\, dt. \qquad (8)$$

The function $x(t)$ is considered a control function, and total net benefits, TNB, is an objective variable to be maximized. The first term in Equation (8) does not depend on function $x(t)$. Thus, the optimal strategy can be found by minimizing the second term in Equation (8). This minimum can be estimated using analytical or numerical methods, depending on the complexity of functions $L(x)$ and $C(v)$. Total net benefits may have several local maxima. In this case it is necessary to select the local maximum with the highest value of TNB.

2.3. Spread in a Rectangular Area

If a population spreads in a rectangular area (Fig. 5A), then the length of the population front, $L(x)$, is a constant. The second term in Equation (8) has a minimum if and only if the integral

$$\int_{t_0}^{t_{\max}} \left[\frac{Dx'(t)}{\alpha} + C(x'(t))\right] \exp[-\alpha(t - t_0)]\, dt \qquad (9)$$

has a minimum, where $t_{\max}$ is the time when the population reaches the end of its potential area (if $v > 0$), or when it is completely eradicated (if $v < 0$). The optimal function $x(t)$ can be found by using the Euler equation[26]

$$\frac{d}{dt}\left(\frac{\partial F}{\partial x'}\right) - \frac{\partial F}{\partial x} = 0, \qquad (10)$$

where $x' = v = dx/dt$ and

$$F(t, x, x') = \left[\frac{Dx'}{\alpha} + C(x')\right] \exp[-\alpha(t - t_0)]. \qquad (11)$$

The Euler's equation (Equation (10)) yields the following differential equation, which can be used for estimating the optimal target rate of population spread

$$v' = \left(D + \alpha \frac{dC}{dv}\right)\left(\frac{d^2C}{dv^2}\right)^{-1}, \qquad (12)$$

where $v' = dv/dt = d^2x/dt^2$ is the acceleration of spread.

Equation (12) generates a family of lines that deviate up and down from the stationary solution v^* determined by Equation (4) (Fig. 6). Branches of lines between values 0 and v^* correspond to minimum net benefits and will not be considered further. Lines with the rate of spread $>v^*$ and <0 have maximum net benefits. Lines with a $v > v^*$ correspond to slowing the spread, and lines with $v < 0$ correspond to eradication. To find a particular solution of Equation (12) we used two boundary conditions: one for slowing population spread, and another for eradication. Both boundary conditions describe the situation at the moment when pest management is used for the last time.

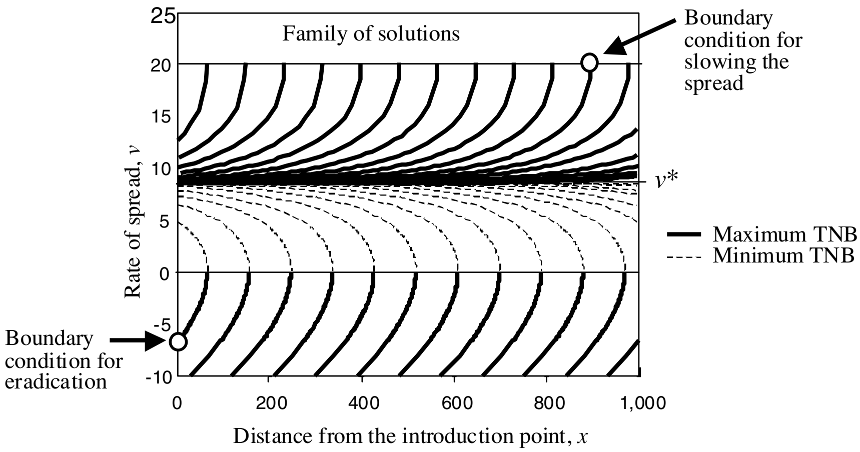

Fig. 6. Family of solutions of Equation (12).

This is either abandoning of slowing the spread when the population front comes too close to the end of the area that potentially can become infested, or completing the eradication program.

The boundary condition for slowing the spread is derived as follows. Let us assume that the distance to the end of the area is Δx, and the rate of spread is controlled at v for the last time before abandoning the barrier zone. The time interval left for keeping the barrier zone is Δt, which is much smaller than $\Delta x/v_{\max}$. The present value of total net benefits (Equation (8)) is approximately equal to

$$TNB = \frac{D \cdot L}{\alpha}(v_{\max} - v)[1 - \exp(-\alpha \cdot \Delta x / v_{\max})] \cdot \Delta t - L \cdot C(v) \cdot \Delta t, \quad (13)$$

where the first term represents benefits, and the second term represents costs. Slowing population spread is terminated when the derivative $dTNB/dv = 0$ at $v = v_{\max}$. Applying these conditions to Equation (13), we get

$$-C'(v_{\max}) = \frac{D}{\alpha}\left[1 - \exp\left(-\alpha \frac{\Delta x}{v_{\max}}\right)\right]. \quad (14)$$

The boundary condition for slowing population spread is the following: management of the rate of spread terminates when the distance to the end of the area is equal to Δx (Equation (14)).

Now we derive the boundary condition for eradication. Let us assume that the population has been reduced to such a small size that we can ignore the damage component of total net benefits and assume a constant (negative) rate of spread. Time left until complete eradication is proportional to $(-1/v)$. Thus, total costs are proportional to $[-C(v)/v]$. The optimal rate of spread corresponds to a minimum of this expression, which can be found by setting the derivative $= 0$:

$$v\frac{dC}{dv} - C(v) = 0. \quad (15)$$

The optimal rate of spread, v, at the end of eradication ($x = 0$) is the solution of Equation (15). This is the boundary condition for eradication.

A typical solution of Euler's equation with boundary conditions is shown in Fig. 7. The horizontal axis is the location of the population front relative to the introduction point; the total length of the potential area is 1,000 km in this example. The vertical axis is the target rate of spread. The upper branch of the graph corresponds to slowing the spread because the rates of spread are positive, and the lower branch corresponds to eradication because rates of spread are

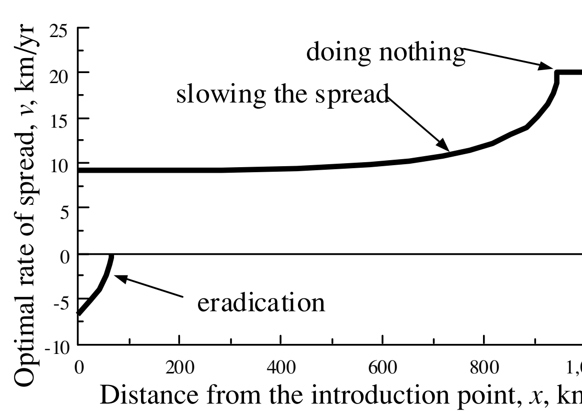

Fig. 7. Optimal management of a barrier zone for a population that spreads in a rectangular area of 1,000-km length from one side to the opposite side. Management strategy depends on the location, x, of the population front from the introduction point.

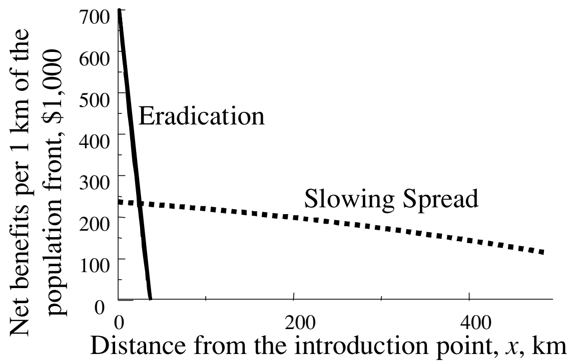

Fig. 8. Net benefits from slowing the spread and eradication as a function of distance from the introduction point, *x*.

negative. As the population front approaches the end of the potential area, slowing the spread is no longer necessary. The optimal target rate of spread becomes equal to 20 km/yr, which is the rate of unmanaged spread in this example.

If the population has occupied most of its potential area, then the only solution is slowing the spread or doing nothing (upper branch in Fig. 7). But if the pest has just arrived and has not spread far enough, then both slowing the spread and eradication are possible solutions. These two strategies correspond to two local maxima of net benefits. Euler's equation does not tell us which of these solutions is the best. Thus we need to compare net benefits for these strategies.

Fig. 8 shows net benefits from slowing the spread and eradication as a function of distance from the introduction point, x. Net benefits from eradication decrease rapidly with increasing distance; this means that eradication is most profitable when the population has not spread far enough from the introduction point. Net benefits from slowing the spread change very little with increasing distance from the introduction point. The intersection of two lines in Fig. 8 indicates the maximum range size of an infestation that can be eradicated. If the population is larger, then slowing its further progression generates greater net benefits than eradication. Stopping the spread is never an optimal strategy (unless there are natural barriers) because it generates lower net benefits than either eradication or slowing the spread.

3. MODEL OF BARRIER ZONE MANAGEMENT

Models of barrier zone management are needed to estimate the cost function, $C(v)$, for varying target rates of population spread. Although modeling of population spread is a well-developed area in theoretical ecology,[27–30] there are only few models that simulate the effect of barrier zones. Marsula and Wissel used a reaction-diffusion model to determine the number of sterile male insects released to prevent the spread of a pest species.[31] This model was applied to the barrier zone against the screwworm. The limitation of this model is that it considers a continuous distribution of pest populations. Thus, the entire barrier zone should be treated, which may be prohibitively expensive for other species.

Moody and Mack simulated the spread of an invasive plant species via establishment of isolated colonies beyond the population front.[32] They showed that eradication of small colonies can substantially reduce the rate of population expansion. Shigesada *et al.* also modeled the spread of populations that produce isolated colonies, but they did not examine the effect of colony eradication.[33] Sharov and Liebhold derived a traveling wave equation for populations that expand their area via establishment of isolated colonies.[34] If not treated in time, these colonies grow, coalesce, and eventually contribute to the population spread (Fig. 9). This model resembles metapopulation models because it considers individual colonies rather than individual organisms. It is based on the following assumptions:

1. The probability of establishment of a new colony, $b(x)$, decreases with increasing distance, x, from the population front (Fig. 9).
2. The numbers of individuals, $n(a)$, in a colony increases with colony age, a.
3. At the population front, the average density of individuals, N, is equal to the carrying capacity, K.

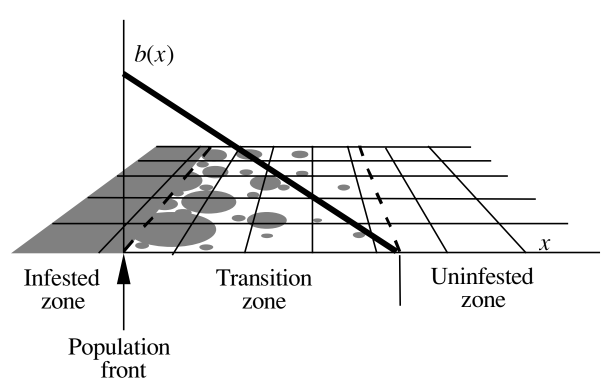

Fig. 9. Model of population spread via establishment of isolated colonies; $b(x)$ is the probability of colony establishment as a function of distance from the population front (from Reference 34).

A traveling wave equation can be derived by assuming a constant velocity of spread, v. As the colony grows from age 0 to a, the distance between this colony and the population front decreases by av. Thus, the number of colonies, $m(a, x)$ of age a at distance x from the population front is

$$m(a, x) = b(x + av). \qquad (16)$$

The number of individuals, $N(x)$, at distance x from the population front is

$$N(x) = \int_0^\infty m(a, x)\, n(a)\, da. \qquad (17)$$

At the population front, $N(0) = K$. Combining this condition with Equations (16) and (17), we get the traveling wave equation

$$\int_0^\infty b(av)\, n(a)\, da = K. \qquad (18)$$

The rate of spread can be determined by solving this equation analytically or numerically.

If isolated colonies are detected and eradicated within the barrier zone, then the colonization function $b(x)$ is truncated by the beginning of the barrier zone (Fig. 10). Obviously, the end of the barrier zone should correspond to the maximum distance from the population front where isolated colonies may become established. By substituting the new $b(x)$ function into Equation (18), we can estimate the expected reduction in the rate of spread due to pest management in the barrier zone.

If the probability of colony establishment, $b(x)$, is a linear function of distance from the population front (see Fig. 9), and the function of colony growth is exponential, then the model predicts a decreasing rate of spread as the width of the barrier zone increases (Fig. 11).

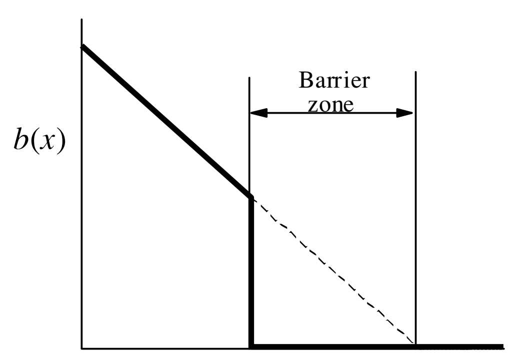

Fig. 10. The probability of colony establishment, $b(x)$, becomes truncated by the beginning of the barrier zone (from Reference 34).

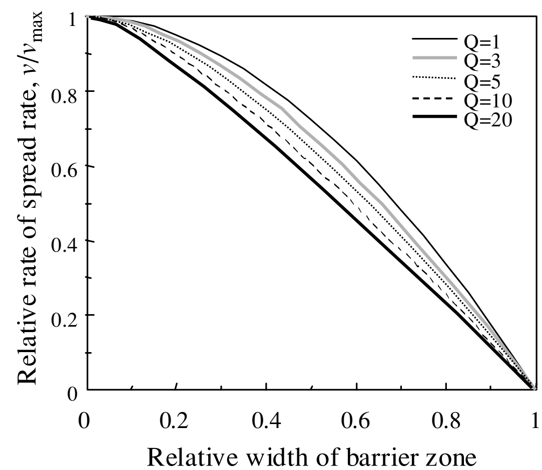

Fig. 11. Reduction in the rate of population spread due to barrier zone, as predicted by the model; relative width of barrier zone is the ratio of the barrier zone width to the width of the transition zone, W, where colonies can become established (Fig. 9); parameter $Q = rW/v_{\max}$ (modified from Reference 34).

If the population spreads via establishment of isolated colonies, then there is no need to treat the entire barrier zone. Instead, treatment is limited to areas occupied by colonies, which may be a small fraction of the entire barrier zone.

As the density of samples (or traps) increases, colonies become detected earlier, and treatment costs are smaller. But sampling costs would increase because more samples are needed. Thus there is a trade-off between monitoring and treatment costs. The optimal density of traps corresponds to the minimum sum of treatment and monitoring costs.[35]

The following simple model determines the cost function, $C(v)$, under three assumptions. First, the average number of colonies to be treated annually is assumed independent of sample density. This should be true if most new colonies originate from the generally infested area rather than from other isolated colonies. A second assumption is that the probability to detect a colony depends solely on the number of traps within that colony. Then the average area of a colony at the time of detection should be proportional to z^2. And third, treatment cost per unit area is a constant. The optimal distance between samples (or traps) in the monitoring grid, z, can be determined by minimizing the total cost of monitoring and treatment

$$C(z) = \frac{w \cdot c_{\text{sample}}}{z^2} + p z^2 n_{\text{treat}} c_{\text{treat}}, \qquad (19)$$

where w is the width of the barrier zone, which is determined using the graph in Fig. 11; z is the distance between samples (or traps) in the monitoring grid; c_{sample} is the cost of an individual sample (or trap); c_{treat} is treatment cost per unit area; $p = 1/k$, where k is the number of traps needed to detect a colony; and n_{treat} is number of colonies to be treated annually, which is determined by equation

$$n_{treat} = \int_{x_1}^{x_2} b(x)\,dx, \tag{20}$$

where x_1 and x_2 are distances from the beginning and end of the barrier zone to the population front. The first term in Equation (19) is the cost of monitoring, and the second term is the cost of treatments. The optimal distance between samples and minimum cost are found by solving the equation $dC/dz = 0$. The solution is

$$z = \sqrt[4]{\frac{w \cdot c_{sample}}{p \cdot n_{treat} \cdot c_{treat}}}, \tag{21}$$

$$C_{min} = 2\sqrt{w \cdot c_{sample} \cdot p \cdot n_{treat} \cdot c_{treat}}. \tag{22}$$

Costs for monitoring and treatment appear equal for the optimal distance between samples.

Equation (22) considers the cost of detection and eradication of isolated colonies, which is sufficient for slowing the spread. But if the target rate of spread is very small or negative, then it may be necessary to treat large areas of continuously distributed pest populations. Even if no isolated colonies become established, the population front moves slowly forward because of local dispersal of organisms. Let us assume that this rate of spread equals v_{slow}. To reduce the rate of spread below v_{slow} it is necessary to eradicate continuous pest populations within a band $(v_{slow} - v)$ wide per year. Thus, the total cost of the barrier zone including possible treatment of areas with continuous species distribution is

$$C(v) = \max[0, c_{treat} R(v_{slow} - v)] + 2\sqrt{w \cdot c_{sample} \cdot p \cdot n_{treat} \cdot c_{treat}}, \tag{23}$$

where R is the average number of treatments sufficient for species eradication. These treatments are not necessarily done in 1 year, and they may be patchy. For example, the entire area is treated in the first year, and then remaining spots are detected and treated individually later. The reason for using the max() function is that expression $(v_{slow} - v)$ can be negative if the target rate of population spread, v, is greater than the rate of population spread due to only local dispersal of organisms, v_{slow}. Equation (23) yields the value of the cost function $C(v)$ for the given target rate of population spread, v.

More complex models of barrier management can be used if necessary. It may be important to use different treatment agents depending on the size of treatment block. For example, chemical and even bacterial pesticides should not be used over large continuous areas because of possible adverse effects on nontarget organisms. Only species-specific treatments can be applied in large blocks, such as viruses, pheromones, or sterile insect releases. These treatments may appear more expensive than chemical or bacterial pesticides.

4. CASE STUDY: MANAGING GYPSY MOTH SPREAD IN NORTH AMERICA

4.1. Population Spread and its Management

The gypsy moth was accidentally introduced to North America near Boston in 1869 and since that time it has been expanding its range to the west and south.[36] According to the map of host-plant availability (Fig. 12), the gypsy moth occupies only 1/3 of its potential range.[37] The rate of spread in 1966–1990 was 20.78 km/yr in counties where the mean minimum January temperature was above 7°F.[18] Gypsy moth females in America are flightless, which explains why the spread is slow compared with other insect species. Transportation of gypsy moth egg masses and other life stages by humans is probably the most important dispersal mechanism, which leads to the establishment of isolated colonies beyond the population front.[17,18]

After the invention of pheromone traps it became possible to detect isolated colonies with very low population densities. Management of gypsy moth spread via eradication of isolated colonies started in 1990 in the mountains of Virginia and West Virginia within the Appalachian Integrated Pest Management (AIPM) project.[38] In 1993, the USDA Forest Service initiated the STS pilot project.[19,24] It operated in the mountains of Virginia and West Virginia, and in the coastal plain of North Carolina. The Upper Peninsula of Michigan was also a part of the project, but no treatments were done there. In 1998, the program became operational and was expanded over the entire population front from North Carolina to Wisconsin (Fig. 12).[24]

In the STS program, a 2-km grid of pheromone traps is used to detect isolated colonies in a 100-km

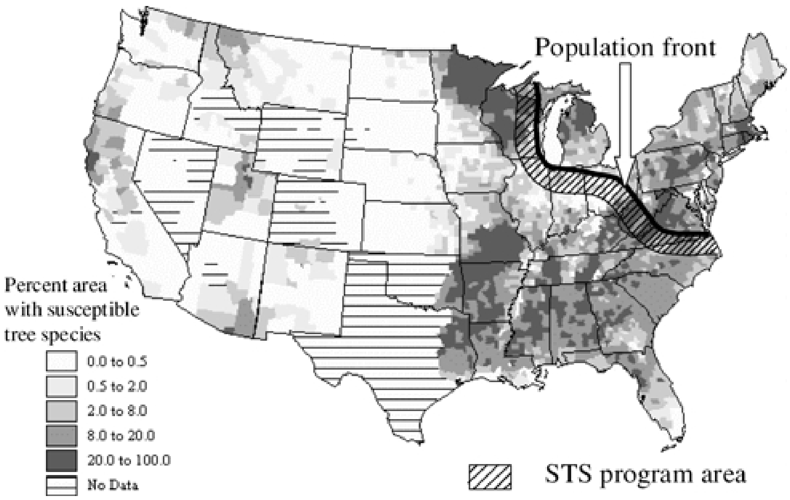

Fig. 12. Distribution of susceptible host trees for the gypsy moth (modified from Reference 37), location of the population front in 2000, and the area of STS program.

band along the population front (Fig. 12). The intertrap distance was optimized using a model[35] similar to the one presented here. Equation (21) yields the optimum intertrap distance of 1.31 km. The actual intertrap distance is greater than the optimal one because of cost constraints. If moth counts in traps indicate a possible colony, then a delimiting grid with 0.5-km intertrap distance is set to determine the boundary of a colony before treatment. This allows targeting of aerial treatments. Areas for delimiting grids and treatments are initially selected by a computer, based on several quantitative criteria. Then a map of these areas is posted on the Internet,[39] and representatives of each state use it for planning their actions for the following year. These plans are discussed and finalized at the project level. At the end, the plan of project activities is compared with initial computer recommendations to make sure that no important actions were missed.

The success of the STS program has been demonstrated in several ways. First, the rate of population spread was reduced by >50% in Virginia and West Virginia after 1990 when the strategy of treating isolated colonies was initiated (Fig. 13, see also Reference 20). Second, most treatments were successful, and most isolated colonies eradicated in the STS program never appear again.[24] Third, there is a strong scientific foundation to the strategy implemented in the STS, and model predictions match well with actual program results.[34]

4.2. Model Parameters

The area that can potentially support gypsy moth populations (Fig. 12) is distinctly subdivided into two portions: the northern region (Michigan, Wisconsin, and Minnesota), and the southern region (to the south from Iowa, Illinois, and Indiana). Probably, the gypsy

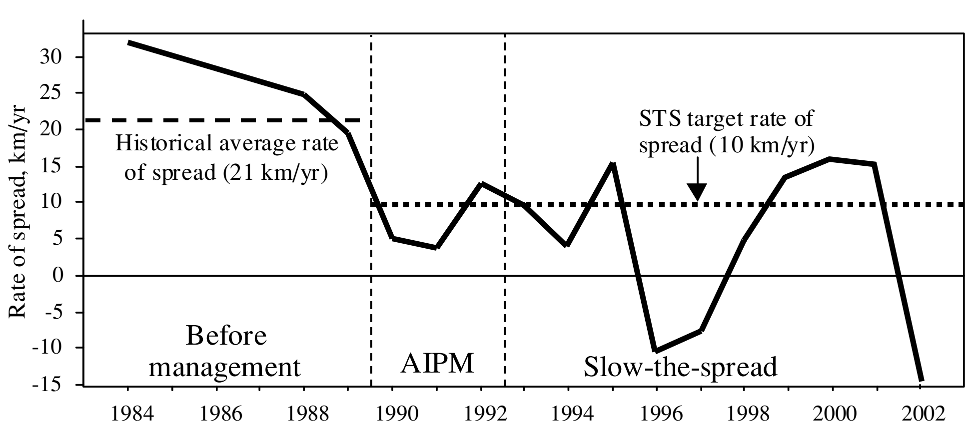

Fig. 13. Annual rates of gypsy moth spread in Virginia and West Virginia.

moth will spread independently in these two regions. In this analysis we consider the southern region only, which is the largest one. We assume the length of the population front $L = 1{,}000$ km; this is the approximate distance from Lake Erie to the ocean shore in North Carolina. The gypsy moth has already spread ≈1,000 km from the point of introduction, and the depth of the potential range that remains uninfested is ≈1,500 km (Fig. 12). Thus, $x_{max} = 2{,}500$ km.

The rate of uncontrolled spread is $v_{max} = 21$ km/yr.[18] Parameters of the colonization function $b(x)$ were estimated from historical trap catch data in the mountains of Virginia and West Virginia.[34] The function $b(x)$ decreased linearly from the value of 0.0017 per 1 km^2/yr at the population front to the zero value at the distance of 250 km. The exponential rate of population growth in isolated colonies is $r = 1.7$, as derived from egg mass surveys.[34]

Annual damages caused by the gypsy moth populations per unit area, D, was estimated using the economic analysis of Leuschner *et al.*[40] The major component of damage was the effect on residential areas, assessed using the analysis of willingness to pay to avoid the impact. However, damage costs were overestimated because defoliation was assumed to occur every year. After the adjustment to the frequency of defoliation the average damage is $D = \$380$ per 1 km^2/yr.[25]

Average trapping costs in the STS program in 1994–1995 were $c_{trap} = \$64$ per trap (including trap management, data analysis, and overheads), and average treatment costs were \$25/acre ($c_{treat} = \$6{,}177/km^2$).[35] Parameter $p = 4.1$ in Equations (21)–(23) was adjusted to match the area treated annually within the STS program.[35] Eradication of high-density gypsy moth populations requires five treatments, as follows from the model of Sharov and Colbert.[41] Thus, $R = 5$ in Equation (23). The rate of population spread in the case if no isolated colonies become established is assumed to be $v_{slow} = 3$ km/yr, which follows from the application of Skellam's model to the gypsy moth.[18]

Row *et al.*[42] recommended using a discount rate of 0.04 per year. However, it may be necessary to use a higher discount rate because of the uncertainty in model parameters. The error in model predictions tends to increase with time. If the discount rate is small, the present value of total benefits is too sensitive to benefits in the far future, which are predicted with a substantial error. As a result, the error of the total net benefits value may be large, and decisions based on the model may have a high risk. Thus, we

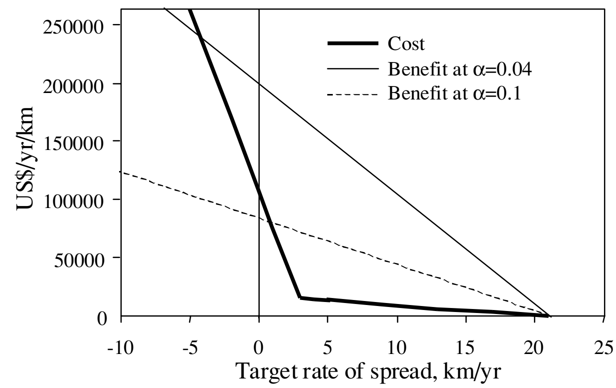

Fig. 14. Cost, $C(v)$, and benefit, αB, for the gypsy moth barrier zone per year per 1-km length of the barrier zone, at discount rates $\alpha = 0.04$, and $\alpha = 0.1$. The difference between benefits and costs has a maximum at the target rate of spread $v = 3$ km/yr.

will use two discount rate values: $\alpha = 0.04$, and $\alpha = 0.1$. The second value is more conservative because the risks associated with uncertainty of predictions are smaller.

4.3. Model Results

The cost of maintaining the barrier zone estimated using Equation (23) is shown in Fig. 14. Costs are relatively low if the target rate of spread is >3 km/yr. To achieve lower target rates of spread (<3 km/yr) it is necessary to eradicate high-density gypsy moth populations over large continuous areas, and thus the cost increases rapidly.

The optimal target rate of slowing gypsy moth spread appears at 3 km/yr for both discount rates $\alpha = 0.04$, and $\alpha = 0.1$ (Fig. 14). The discount rate has no effect on the optimal target rate of spread because the cost function bends sharply at $v = 3$ km/yr. This bend is a simplification assumed in our model, but in reality this transition should be smooth; then model solutions would be sensitive to the discount rate value. In the STS project we use a higher target rate of population spread, 10 km/yr. The deviation from the model is associated with funding limits and also with simplified model assumptions. In the model we assume that newly established colonies are always small in their range, as in the case of egg mass transportation to a new area. However, occasionally we observed formation of much larger colonies that are difficult to treat. It is not clear how these colonies are formed. Possibly they resulted from wind-borne dispersal of small larvae,[43] but more research is needed to answer this question.

According to Equation (14), slowing the rate of gypsy moth spread is economically beneficial up to 37 km from the end of the potential species range for $\alpha = 0.04$, and 39 km for $\alpha = 0.1$. Equation (15) has no solution, which indicates that eradication of the gypsy moth population in one step is more beneficial than the gradual backward movement of the barrier zone. Benefits from eradication are greater than benefits from slowing the spread only at the initial stages of invasion when the population front has extended by <62 km for $\alpha = 0.04$, and <16 km for $\alpha = 0.1$.

Parameters of this bioeconomic model are based on our current knowledge; some of them are rough estimates and may change after more detailed research. Thus results have some degree of uncertainty and should be updated as new information become available. The effect of specific parameters on the model output can be explored using sensitivity analysis. We already published the results of sensitivity analysis of the population spread model[34] and the bioeconomic model.[35]

5. DISCUSSION

Any bioeconomic analysis is based on the assessment of costs and benefits. But when a new exotic species arrives, there is a lack of understanding of potential damage and possible management costs. If the pest species is potentially dangerous, eradication is the first logical option even if economic assessment is not available. But as information about the species accumulates, a reasonable evaluation of costs and benefits of the project is needed.

Cost-benefit estimations are never absolutely certain. We take the best knowledge and evaluate potential strategies. As we learn more about the species, the model and the strategy are updated. It is important to consider all major cost components, which include manufacturing and application of pesticides and pest monitoring. Additional components may be public relations, potential lawsuits, and risk to human health.[44]

If the eradication project has smaller net benefits than slowing the spread, then it should be transformed into a slowing-the-spread program. Termination of eradication projects is often politically charged; thus, the benefits of some projects may have been overestimated and costs underestimated in order to keep these projects going. But it is wrong to view the termination of an eradication project as a total failure. Even if eradication was not achieved, the project might have postponed the spread of the pest species by several years. Postponing or slowing the spread of a pest species generates economic benefits, as shown by the model. Transition from an eradication objective to slowing the spread is an adjustment in the pest control strategy that makes it more effective in a given situation.

This study demonstrates the value of bioeconomic analysis in planning programs that implement barrier zones for managing the spread of pest species. Our model specified optimal strategies for slowing population spread and eradication, which may help to avoid suboptimal decisions based on intuition. For example, Dahlsten *et al.* stated that "insects that have already colonized parts of the United States, or any large land mass or continent, probably should not be the targets for eradication programs in other sections of the country because of their potential for recolonization."[45] Our analysis demonstrates that this statement is wrong. Eradication of small isolated colonies of gypsy moth within barrier zones is not only feasible, but it is economically justified because the model predicts positive net benefits under realistic assumptions.

The model shows that eradication can be successfully implemented mainly against recently established species whose range is limited. Only in rare cases, like the screwworm, is eradication environmentally safe and not prohibitively expensive so that it can be applied to large populations. Of course, as species-specific pest control agents become less expensive, greater numbers of species can be successfully eradicated over large areas. The economics of many eradication programs were never thoroughly evaluated. For example, the boll weevil eradication project has continued since 1977 and only partial success has been achieved.[46] If chemical pesticides are used in eradication programs it is necessary to account for side effects on nontarget species. For example, intensive pesticide treatments against the boll weevil in Texas suppressed natural enemies, and as a result, serious outbreaks of secondary pests occurred.[46]

Slowing population spread is a relatively new tool in pest management. It was not seriously considered before because of the emphasis on eradication or stopping the spread of exotic pests. Our model demonstrates that considerable benefits from slowing population spread may exist even if only a small portion of potential range remains uninfested. In the case of the gypsy moth, the reduction of the spread rate is achieved by eradicating small isolated colonies beyond the expanding population front. Because these colonies are usually small, treatment can be confined to small patches, and thus, the program has a very limited impact on nontarget organisms. Also we found that a new method of mating disruption with synthetic pheromones is effective in low-density populations. This method is ecologically safer than chemical and bacterial pesticides because it is specific to the gypsy moth and has no nontarget effects.

Models presented in this article have several limitations. One of them is the assumption of a uniform spread over time. Many species have cycles in their population dynamics. During an outbreak, spread rates may be higher because of an increased number of dispersing organisms. Moreover, some species have density-dependent dispersal that results in a higher proportion of migrants leaving high-density populations.[47] Our data suggest that spread rates of the gypsy moth increased during outbreaks of 1992–1995 and 1999–2001 (Fig. 13); however, more data are needed to confirm this relationship. Another limitation is that the model does not consider spatial variation in parameter values (e.g., the maximal rate of spread and management costs), although these parameters may depend on local conditions, such as the proportion of area with favorable habitats, human population density, roads, and other factors. Our model can be a prototype for more detailed specific models to be used as guides for the management of particular pest populations. These specific models may address limitations discussed above, but they will be more complex and will need numerical optimization (e.g., dynamic programming) rather than the Euler's equation.

Control of natural resources may depend considerably on social factors; thus, the model presented in this article cannot automatically generate decisions. Rather, it provides information on the economic viability of barrier-zone projects, which may affect decisions in a political arena.[16] Large-scale pest management projects are usually expensive and thus affected by budget constraints. For example, theoretically it may be optimal to eradicate the pest population in one step, but this may require more funds than available. Shifting funds from other programs may cause more damage to these programs than potential gains from the eradication program. A compromise may be reached by extending the eradication project over a longer period. Even if the program is already in an operational stage, it still can be affected by unforeseen social or environmental factors. If a more serious pest species becomes established in the country, then it may be necessary to move a portion of funds to manage this new species.

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REFERENCES

1. Sailer, R. I. (1983). History of insect introductions. In C. L. Wilson & C. L. Graham (Eds.), *Exotic Plant Pests and North American Agriculture* (pp. 15–38). New York: Academic Press.
2. Liebhold, A. M., Macdonald, W. L., Bergdahl, D., & Mastro, V. C. (1995). Invasion by exotic forest pests: A threat to forest ecosystems. *Forest Science Monographs 30*. Bethesda, MD.
3. Simberloff, D. (1986). Introduced insects: A biogeographic and systematic perspective. In H. A. Mooney & J. A. Drake (Eds.), *Ecology of Biological Invasions of North America and Hawaii, Ecological Studies 58* (pp. 3–26). New York: Springer-Verlag.
4. Clark, C. W. (1976). Mathematical bioeconomics. In *The Optimal Management of Renewable Resources*. New York: Wiley.
5. Allen, P. G., Botsford, L. W., Schuur, A. M., & Johnston, W. E. (1984). *Bioeconomics of Aquaculture*. Amsterdam: Elsevier.
6. Turchin, P., & Taylor, A. D. (1992). Complex dynamics in ecological time-series. *Ecology, 73*, 2.
7. Skellam, J. G. (1951). Random dispersal in theoretical populations. *Biometrika*, *38*, 196–218.
8. Hall, F. R. (1974). Bioeconomics of apple pests: Cost appraisal of crop injury data. *Journal of Economic Entomology*, *67*, 517–521.
9. Stern, V. M. (1975). The bioeconomics of pest control. *Iowa State Journal of Research*, *49*, 467–472.
10. Stern, V. M., Smith, R. F., van den Bosch, R., & Hagen, K. S. (1959). The integrated control concept. *Hilgardia*, *29*, 81–101.
11. Pedigo, L. P. (1985). Integrated pest management. In *McGraw-Hill Yearbook of Science and Technology 1985* (pp. 22–31). New York: McGraw-Hill.
12. Goh, B. S. (1980). *Management and Analysis of Biological Populations*. Amsterdam: Elsevier.
13. Shoemaker, C. A., & Onstad, D. W. (1983). Optimization analysis of the integration of biological, cultural and chemical control of alfalfa weevil (Coleoptera: Curculionidae). *Environmental Entomology*, *12*, 286–295.
14. Gutierrez, A. P., & Wang, Y. H. (1984). Models for managing the economic impact of pest populations in agricultural crops. In C. B. Huffaker & R. L. Rabb (Eds.), *Ecological Entomology* (pp. 729–761). New York: Wiley.
15. Dahlsten D. L., Garcia, R., & Lorraine, H. (1989). Eradication as a pest management tool: Concepts and contexts. In D. L. Dahlsten & R. Garcia (Eds.), *Eradication of Exotic Pests. Analysis with Case Histories* (pp. 3–15). New Haven, CT: Yale University Press.
16. LeVeen, E. P. (1989). Economic evaluation of eradication programs. In D. L. Dahlsten & R. Garcia (Eds.), *Eradication of Exotic Pests* (pp. 41–56). New Haven, CT: Yale University Press.
17. McFadden, M. W., & McManus, M. E. (1991). An insect out of control? The potential for spread and establishment of the gypsy moth in new forest areas in the United States. In Y. N. Baranchikov, W. J. Mattson, F. P. Hain, & T. L. Payne (Eds.), *Forest Insect Guilds: Patterns of Interaction with Host Trees*

(pp. 172–186). U.S. Forest Service General Technical Report NE-153.
18. Liebhold, A. M., Halverson, J. A., & Elmes, G. A. (1992). Gypsy moth invasion in North America: A quantitative analysis. *Journal of Biogeography*, *19*, 513–520.
19. Leonard, D. S., & Sharov, A. A. (1995). Slow the Spread project update: Developing a process for evaluation. In *Proceedings. USDA Interagency Gypsy Moth Research Forum 1995* (pp. 82–85). U.S. Forest Service General Technical Report NE-213.
20. Sharov, A. A., & Liebhold, A. M. (1998). Quantitative analysis of gypsy moth spread in the Central Appalachians. In J. Braumgartner, P. Brandmayer, & B. F. J. Manly (Eds.), *Population and Community Ecology for Insect Management and Conservation* (pp. 99–110). Rotterdam: Balkema.
21. Knipling, E. F. (1978). Eradication of plant pests—pro. *Bulletin of the Entomological Society of America*, *24*, 44–52.
22. Flakus, G. (1993). *Living with Killer Bees. The Story of Africanized Bee Invasion*. Oakland, CA: Quick Trading Co.
23. Smith, J. W. (1998). Boll weevil eradication: Area-wide pest management. *Annals of the Entomological Society of America*, *91*, 239–247.
24. Sharov, A. A., Leonard, D., Liebhold, A. M., Roberts, E. A., & Dickerson, W. (2002). Slow-the-Spread project: An overview. *Journal of Forestry*, *100*(5), 30–35.
25. Sharov, A. A., & Liebhold, A. M. (1998). Bioeconomics of managing the spread of exotic pest species with barrier zones. *Ecological Applications*, *8*, 833–845.
26. Elsgolts, L. E. (1962). *Calculus of Variations*. London: Pergamon Press.
27. Andow, D. A., Kareiva, P. M., Levin, S. A., & Okubo, A. (1990). Spread of invading organisms. *Landscape Ecology*, *4*, 177–188.
28. Bosch van den, F., Hengeveld, R., & J. A. J. (1992). Analyzing the velocity of animal range expansion. *Journal of Biogeography*, *19*, 135–150.
29. Hastings, A. (1996). Models of spatial spread: Is the theory complete? *Ecology, 77*, 1675–1679.
30. Neubert, M. G., & Parker, I. M. (this issue). Projecting rates of spread for invasive species. *Risk Analysis.*
31. Marsula, R., & Wissel, C. (1994). Insect pest control by a spatial barrier. *Ecological Modelling*, *75/76*, 203–211.
32. Moody, M. E., & Mack, R. N. (1988). Controlling the spread of plant invasions the importance of nascent foci. *Journal of Applied Ecology*, *25*, 1009–1022.
33. Shigesada, N., Kawasaki, K., & Takeda, Y. (1995). Modeling stratified diffusion in biological invasions. *American Nature*, *146*, 229–251.
34. Sharov, A. A., & Liebhold, A. M. (1998). Model of slowing the spread of gypsy moth (Lepidoptera: Lymantriidae) with a barrier zone. *Ecological Applications*, *8*, 1170–1179.
35. Sharov, A. A., Liebhold, A. M., & Roberts, E. A. (1998). Optimizing the use of barrier zones to slow the spread of gypsy moth (Lepidoptera: Lymantriidae) in North America. *Journal of Economic Entomology*, *91*, 165–174.
36. Liebhold, A. M., Mastro, V., & Schaefer, P. W. (1989). Learning from the legacy of Leopold Trouvelot. *Bulletin of Entomological Society of America*, *35*, 20–21.
37. Liebhold, A. M., Gottschalk, K. W., Mason, D. A., & Bush, R. R. (1997). Forest susceptibility to the gypsy moth. *Journal of Forestry*, *95*, 20–24.
38. Reardon, R. C. (1991). Appalachian gypsy-moth integrated pest-management project. *Forest Ecology and Management*, *39*, 107–112.
39. Sharov, A. A. (2001). Decision-support system for the Slow-the-Spread of the gypsy moth project. Available at: http://www.ento.vt.edu/∼sharov/stsdec/stsdec.html.
40. Leuschner, W. A., Young, J. A., Walden, S. A., & Ravlin, F. W. (1996). Potential benefits of slowing the gypsy moth's spread. *Southern Journal of Applied Forestry, 20*, 65–73.
41. Sharov, A. A., & Colbert, J. J. (1996). A model for testing hypotheses of gypsy moth, *Lymantria dispar* L., population dynamics. *Ecological Modelling*, *84*, 31–51.
42. Row, C., Kaiser, H. F., & Sessions, J. (1981). Discount rate for long-term Forest Service investments. *Journal of Forestry*, *79*, 367–369.
43. Taylor, R. A. J., & Reling, D. (1986). Density/height profile and long-range dispersal of first-instar gypsy moth (Lepidoptera: Lymantriidae). *Environmental Entomology*, *15*, 431–435.
44. Dahlsten, D. L., & Garcia, R. (Eds.). (1989). *Eradication of Exotic Pests. Analysis with Case Histories*. New Haven, CT: Yale University Press.
45. Dahlsten, D. L., Garcia, R., & Lorraine, H. (1989). Eradication as a pest management tool: Concepts and contexts. In D. L. Dahlsten & R. Garcia (Eds.), *Eradication of Exotic Pests. Analysis with Case Histories* (pp. 3–15). New Haven, CT: Yale University Press.
46. Coppedge, J. R. (1996). Eradication of the boll weevil in the United States through an areawide approach. In *XX International Congress of Entomology. Proceedings*, Firenze, Italy (p. 704), August 25–31, 1996.
47. Turchin, P. (1998). *Quantitative Analysis of Movement. Measuring and Modeling Population Redistribution in Animals and Plants*. Sunderland, MA: Sinauer.