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Weed Invasions: To Control or not to Control?*

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Abstract

When a weed invasion is discovered a decision has to be made as to whether to attempt to eradicate it, contain it or do nothing. Ideally, these decisions should be based on a complete benefit-cost analysis, but this is often not possible. A partial analysis, combining knowledge of the rate of spread, seedbank longevity and economic-analysis techniques, can assist in making the best decision. This paper presents a model to decide when immediate eradication of a weed should be attempted, or whether weed control should be attempted at all. The technique is based on identifying two 'switching points': the invasion size at which it is no longer optimal to attempt eradication, and the invasion size at which it becomes optimal not to apply any form of control. It is shown that seed longevity is a critical factor constraining the feasibility of eradicating large invasions.

Key Words: invasive species; eradication; containment; economics; weed control; switching point.

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INTRODUCTION

Invasive species are recognized as one of the main threats to global biodiversity (Vitousek *et al.*, 1996), and also are responsible for large economic losses to agriculture (Liebman *et al.*, 2001) and commercial forestry (Liebhold *et al.*, 1995). Therefore, when a new invasion is discovered it must be decided whether to attempt eradication.

Any eradication effort must be accompanied by containment to prevent invaders from escaping into other areas. Containment can be accomplished by establishing a barrier zone around the invasion. The economics of barrier zones, in the context of insect populations, has been studied by Sharov and Liebhold (1998). These authors explored the question: "how extensive must a population be before eradication is no longer a viable approach?" (p. 834). They evaluated the net benefits of eradication or containment relative to the do-nothing option. In this paper we follow a similar approach, but apply the method to plant invasions. This complicates the analysis because plants produce seeds that can survive for several years, even decades, before germination. Seeds are not detectable by normal search procedures, thus a seed must germinate into a seedling before it can be found and eliminated. It follows that eradication can only occur if new plants are destroyed before flowering, and that areas previously cleared of weeds must be revisited for a number of years to eliminate new seedlings. The number of repeat visits depends on the expected longevity of the seedbank.

Agencies in charge of weed control would benefit from a rapid-assessment tool to assist in making decisions when new invasions are discovered. To make it applicable, the weed-spread model underlying such a tool must be based on a small number of parameters and these parameters must be relatively easy to estimate, at least at a general level. The simple geometric model of Sharov and Liebhold (1998) has appeal in this context because of its simplicity, but it has some drawbacks. Higgins and Richardson (1996) emphasize the importance of accounting for the plant-environment interaction. Ideally, this interaction should be evaluated based on quantifying the effects of the environment on demographic parameters such as fecundity, survival and dispersal. Although the model developed here does not account for these interactions explicitly, it allows us to represent different types of weed-environment combinations by modifying the rate of spread and seed longevity.

The rate of spread of an invasion can be slowed, contained or reversed by targeting the invasion front. Sharov and Liebold (1998) define the invasion front, or population front, as: "The farthest point where the average density of individuals is greater than or equal to the carrying capacity" (i.e., the density of defoliating populations of Gypsy moth). In the present study the invasion front is defined as the area in which mature invasive plants able to produce seeds are found, irrespective of their density. The growth of the invasion front can be slowed down or reversed using a barrier zone, defined as "the area adjacent to the population front in which any pest-management activity is performed targeted at modification of the rate of population spread" (Sharov and Liebhold, 1998).

The analysis presented below is based on estimating the net benefits of managing the spread of a weed population. The net benefit depends on the size of the area invaded, the rate of spread, the seed-bank longevity, the benefits obtained from the current land use and the costs of pursuing the control options being evaluated. A control option may represent a single method or a 'package' consisting of a combination of methods, such as done in integrated weed management (Odom et al, 2003). A model is developed and used to estimate two 'switching points': the point at which eradication is no longer an optimal option and the point at which it becomes optimal to do nothing. The model is initially applied to a woody perennial weed (Scotch broom, *Cytisus scoparius*). Key parameters are later modified to evaluate their effect on the position of the switching points.

METHOD

The invasion is assumed to spread in a circular pattern and its size is measured by its radius. The decision as to whether to eradicate or contain the invasion is based on evaluating the present value of net benefits of each option over time. In the absence of control the population will spread at a maximum rate V_{max}. The rate of spread (v) can be reduced below V_{max} by establishing a barrier zone. The range of possibilities is illustrated in Figure 1.

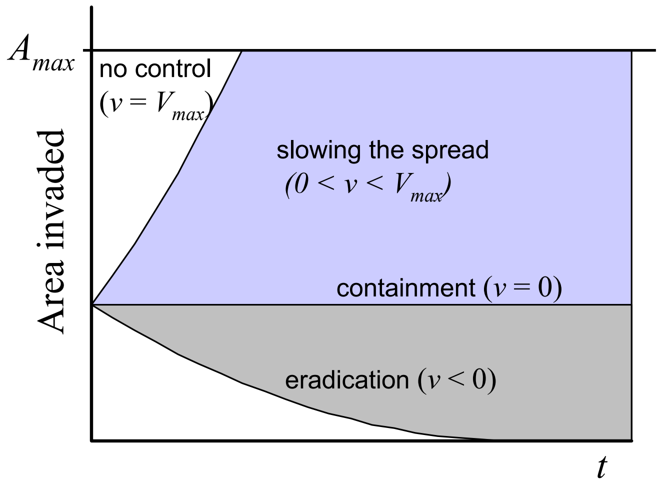

Figure 1. The benefits of slowing down, containing and eradicating an invasion are determined by the value of the shaded areas between the no-control and each of the control lines.

When no control is undertaken, the area invaded increases at rate V_{max} until the entire area at risk (A_{max}) is invaded. Partial control can slow the spread and, although the entire area at risk will be eventually invaded, this option has value. Delaying the transition to a fully invaded environment means that benefits from the uninvaded area are obtained for a longer period and the costs of treatment are delayed. Slowing the spread also enhances the possibility of making eradication feasible if new technologies become available in the future. Total containment of the invasion is illustrated by a horizontal line (Figure 1), where the area invaded remains constant indefinitely (the rate of spread is zero). Finally, eradication is illustrated by a negatively-sloped curve, where the rate of spread is negative and the weed population will eventually be eliminated.

Figure 1 illustrates that a barrier zone can be stationary or moving. A stationary barrier zone represents total containment, where the rate of spread is maintained at zero and the perimeter of the invasion front remains constant. A moving barrier zone may represent slow eradication, where the barrier zone moves back towards the introduction point as the invasion front retreats, or it may be associated with slowing the spread where the invaded area increases at a slower rate than under no control.

The distance from the introduction point to the invasion front at any time t is denoted by x_t. This is the radius of the invasion circle and is a measure of the severity of the invasion. $A(x_t)$ is the area in which the entire population of mature plants is found and is calculated as:

$$A(x_t) = \pi x_t^2 \tag{1}$$

The rate of spread (v_t) is the derivative of x_t with respect to time:

$$v_t = \frac{dx_t}{dt} \tag{2}$$

When v is negative, the size of the invasion decreases with time and will eventually result in eradication. The net benefits associated with maintaining a given rate of spread $v < V_{max}$ must be evaluated relative to the do-nothing option:

$$NB(v, x_0) = PB(v, x_0) - PB(V_{max}, x_0) \tag{3}$$

Where $NB(v)$ is the net benefit of maintaining rate of spread v and $PB(\cdot)$ is the net present value of benefits obtained from a given level of control over a planning period of T years:

$$PB(v, x_0) = \sum_{t=0}^{T} \left[B_t(v, x_0) - C_t(v, x_0) \right] \cdot \delta^{-t} \tag{4}$$

where δ is the discount factor (1+r) for the discount rate r, B_t are annual benefits and C_t are annual costs. The annual benefits obtained from the uninvaded area under a given rate of spread v are:

$$B_t(v) = \beta \left[A_{\max} - A(x_t(v)) \right] \tag{5}$$

where the coefficient β represents the annual benefit per unit of uninfested area.

The cost of maintaining a given rate of spread is derived from inputs of labor, materials and chemicals. The amounts of these inputs depend on the area treated. The area treated is the sum of the barrier zone area (A_B), the area where repeat treatments are applied (A_R) and the area where established plants are being eliminated (A_E):

$$C_t(v) = \left[A_B(x_t(v)) + A_R(x_t(v)) + A_E(x_t(v)) \right] \left(L\, c_L + H\, c_H \right) \tag{6}$$

Where L is labor, c_L is the cost of labor, H is the amount of chemicals used and c_H is the cost of chemicals. Note that $C(V_{max}) = 0$ and that this simplified model assumes that density does not affect control costs.

The area of the barrier zone is:

$$A_{Bt}(x_t) = \pi\left[(x_t + b)^2 - x_t^2\right] \tag{7}$$

Where b is the width of the barrier zone, which must be equal to or greater than V_{max} when containing or eradicating the weed to ensure that all seedlings arising from dispersed seeds are eliminated. If the invasion is being slowed down ($0 < v < V_{max}$) then $dx/dt > 0$ and the area of the barrier zone increases over time. If the invasion is being eradicated, $v < 0$, implying that $dx/dt < 0$ and A_B decreases over time to gradually reach a value of zero. In this case, as the barrier zone shrinks it is necessary to revisit areas that have been previously part of the barrier zone. The number of repeat visits depends on the seed longevity (S_L) and the areas previously treated:

$$A_R = \begin{cases} \sum_{\tau=t-S_L}^{t} \pi\left[(x_\tau + b)^2 - (x_{\tau-1} + b)^2\right] & \text{if } v < 0 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

The area where established plants are being eliminated in a given year is associated with the reduction in the radius of the invasion:

$$A_E = \begin{cases} \pi\left[x_t^2 - (x_t + v)^2\right] & \text{if } v < 0 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

To determine the optimal course of action, equation (3) is maximized by setting the level of control (u) expressed as the reduction in the rate of spread, with the relationship:

$$v = V_{\max} - u \tag{10}$$

The assumptions regarding parameter values, costs and benefits are presented in Table 1.

Table 1. Base-parameter values

Parameter	Value	Description	Source
V_{max}	0.1 – 4.0	maximum rate of spread (km/yr)	a
SL	7 – 20	seed longevity (years)	a
X_{max}	50	radius of total area (km)	
A_{max}	$\pi \cdot (X_{max})^2 \cdot 100$	total area (ha)	
L	80	time for 1 worker to search & treat an invaded hectare of land (hours/ha)	b
c_L	35	wage rate ($/hour)	b
c_H	8	cost of chemicals ($/100L of mix)	b
H	90	quantity of chemicals (100L mixes /ha)	b
B	120	annual benefit of uninvaded area ($/ ha)	
r	0.06	discount rate	

a. Odom *et al.* (2003); b. *pers. comm*. Schroder (2004)

In the model above, the net benefits of control (eradication or containment) depend on the costs of implementing the control strategy, the benefits from the land-use threatened by the invasion, and the biophysical characteristics of the weed, including the rate at which the weed population spreads and the longevity of the seed bank. As a starting point for this analysis, the model was calibrated to the general biophysical characteristics of a Scotch broom (*Cytisus scoparius,* L.) invasion. Scotch broom is a leguminous flowering shrub, native to Europe, that produces large numbers of seeds and has successfully invaded pastoral and woodland ecosystems and adjoining river systems in cool, high rainfall regions of southeastern Australia (Sheppard and Hosking, 2000 in Odom *et al.*, 2003). Broom is an effective weed species as its seeds may be dispersed up to 5 m without help from seed vectors and to much greater distances by a variety of seed vectors including ants, feral pigs, cattle and humans (Smith and Harlen, 1991). Hence, spread rates (V_{max}) of 0.1 km and 4.0 km per year were simulated in this study.

A fair amount of uncertainty exists about the persistence of Broom seeds. Odom *et al.* (2003) assume a seed-bank decay rate of 50% in their model, which implies that a non-replenishing seed bank will decay over 12 to 20 years depending on its initial density. Therefore, two seed-bank-longevity values (SL), 7 and 20 years, were used in this analysis.

The costs of control vary depending on the control method used, which is influenced by the type of weed and the environment being invaded. Methods of controlling weeds include manual removal, herbicide and cut-and-paint techniques. The parameters used for costs (Table 1) are the quantity of chemicals used per hectare of invasion (H), the cost of chemicals (c_H), the quantity of labor required to manually pull the weeds and to spray the chemicals (L) and the wage rate (c_L). Initially it was assumed that the weeds are discovered in a natural environment and so the search and treatment techniques used have to be limited to more focused, labor-intensive techniques to ensure that the natural environment is not harmed in the process of weed removal. Therefore, the quantity of labor used in this application of the model is greater than what would be used in a cropping environment.

The values for the cost parameters described above are derived from empirical observations of a Broom control program undertaken in the Barrington Tops National Park in NSW Australia (Schroder, 2004, pers. comm.) Between 25 and 350 100-litre herbicide mixes may be required to treat an invasion of Broom, depending on its density, and the cost of each 100L mix ranges between \$7 and \$11, depending on herbicide type. Therefore, H is assumed to be 90 and its price per 100L mix (c_H) is assumed to be \$8. The labor required (L) to manually pull the weeds from one hectare of broom infestation may be between 90 and 160 hours, depending on the density of the invasion, and the wage rate ranges between \$30 and \$40 per hour. Based on this information base-case values assumed for L and c_L were 80 hours and \$35 per hour, respectively.

The benefits of weed control depend on the maximum size of the area at risk (A_{max}) and the benefits (B) in terms of net revenue, recreation and biodiversity generated from the current land use. The maximum area at risk of invasion, assumed to be a circle with a 50km radius (X_{max}), is representative of a large, uninterrupted area of natural vegetation. The benefits from the uninvaded land are relatively easy to calculate if it is used in agricultural production. For example, the gross margin for wheat grown in the Central Wheatbelt of Western Australia is about \$170 ha^{-1} and that for Canola is approximately \$190 ha^{-1} (Ag West, 2003). The benefits derived from natural environments, however, are more difficult to estimate. Odom *et al.* (2003) used a value of \$100,000 per species per year as a base value for biodiversity protection. This value lies between a minimum of \$2,300 per species per year, which the Queensland government was prepared to pay to preserve natural vegetation (Morton *et al.,* 2002, in Odom *et al.*, 2003) and a maximum value of \$233,220 per species per year based on the willingness to pay of households in New South Wales and derived from contingent valuation studies (Lockwood and Carberry, 1998, in Odom *et al.*, 2003). Sawtell (1999) estimated the consumer surplus from recreation in the Barrington Tops National Park at \$1,380,000 per year using the travel-cost method, which when divided by the 80,000 hectares of the park gives a per hectare value of \$17.25 per year. Since it is difficult to convert biodiversity values from per-species to per-hectare basis, a base value of \$120 ha^{-1} was assumed for B and the sensitivity of optimal outputs to changes in this value was tested.

CRITICAL DECISION POINTS

The net benefit for any target rate of spread (v) can be calculated by substituting equations (4) to (9) into equation (3) and solving for the given value of v and the size of the invasion when discovered (x_0). The net benefits of containment and the net benefits of eradication are shown as functions of x_0 in Figure 2. These curves were obtained by setting $v = x_0$ (eradication) or $v = 0$ (containment) and solving equation (3). Net benefits are estimated relative to the no-control (or do-nothing) option, so $NB = 0$ for this option, represented by the horizontal axis.

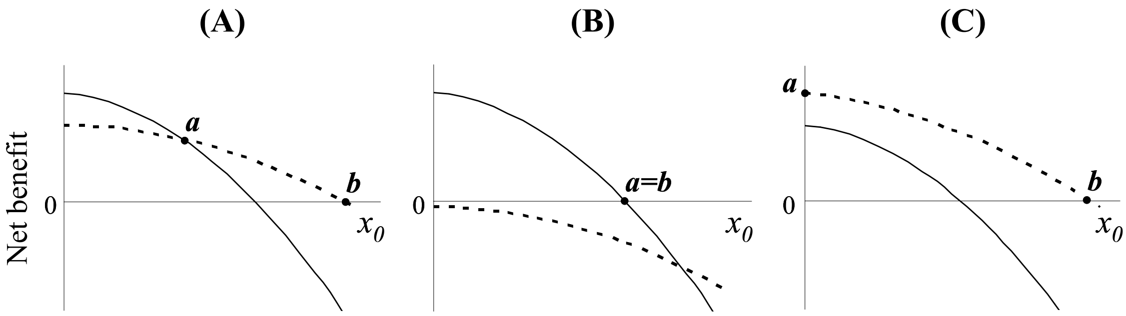

Figure 2. The net benefits of eradication (solid line) and containment (dotted line) for three possible cases resulting from different combinations of costs and benefits as represented in equation (3); x_0 is the radius of the invasion when it is first discovered. The two critical (switching) points are where eradication is no longer optimal (*a*) and where the do-nothing alternative becomes better than any form of control (*b*).

The preferred course of action when an invasion is discovered is that which maximizes *NB* for the given invasion size. In figure 2A, *NB* is maximized by eradicating the invasion if its initial radius (x_0) is to the left of point *a*. If x_0 is to the right of point *a* it becomes optimal to contain the invasion. The net benefit of containment decreases as the invasion radius increases to reach zero at point *b*, to the right of this point it is optimal not to control the invasion, as the net benefit of containment becomes negative. Points *a* and *b* (Figure 2) are the two critical points at which it is no longer optimal to eradicate (*a*) or where it becomes optimal to do nothing (*b*). Hereafter these critical points are termed 'switching points', as they represent the invasion sizes at which there is a switch in the optimal course of action. Figure 2A presents the standard case where both eradication and containment are optimal over some interval, Figures 2B and 2C present two alternative cases. If the net benefit of containment is negative throughout, then it is never optimal to contain and switching points *a* and *b* overlap at the intersection with the horizontal axis (Figure 2B). This means there is a single switch from eradication to no control. Another case is when the containment curve is above the eradication curve throughout (Figure 2C). In this case it is never optimal to eradicate, switching point *a* occurs at x_0=0 and switching point *b* occurs at the intersection with the horizontal axis. At this point there is a switch from containment to no control.

RESULTS AND DISCUSSION

The model was used to estimate the optimal control strategy for any given invasion size of Scotch broom under a range of spread rates (V_{max}) and seed-bank longevities (*SL*). The main outputs of this analysis are the two switching points *a* and *b* as previously explained (Figure 2). Switching point *a* is the area at which it is no longer optimal to eradicate the invasion. Switching point *b* represents the area where it becomes optimal to apply no control.

Scotch broom spreads at rates of between 5 meters and a few kilometers per year so optimal control strategies were calculated for an invasion spreading at 4 km yr^{-1} (Figures 3A and 3B) and one spreading at 0.1 km yr^{-1} (Figures 3C and 3D). Since uncertainty exists about the longevity of the seed bank in different environments the model was also run for two values of *SL*: 20 years (Figures 3A and 3C) and 7 years (Figures 3B and 3D). Note that now area (in hectares) is used to define invasion size instead of radius (as above in Figure 2) as the former is a more intuitive measure of invasion size and it is more closely related to labor and chemical inputs.

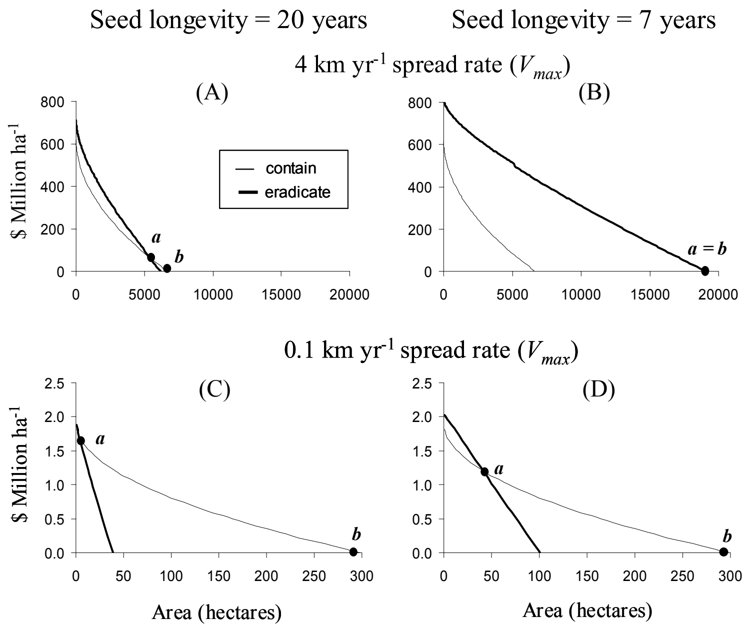

Figure 3: Net benefits of eradication and containment as functions of the area invaded; switching point *a* shows the maximum area at which eradication is optimal, switching point *b* shows the area where it becomes optimal to do nothing.

The positions of switching points *a* and *b* depend on the relative values of spread rate and seed-bank longevity (Figure 3). The higher the value of V_{max} the larger the area at which switching points *a* and *b* occur. For example, when V_{max} is 4 km yr^{-1} switching point *a* occurs at areas between 5,000 ha and 19,000 ha, depending on *SL*, compared to between 5 ha and 300 ha when the spread rate is 0.1 km yr^{-1}. When V_{max} is high the benefits of controlling the spread of the weed population are larger (NPV up to $800 million) than when the rate of spread is low (NPV up to $2 million). This large difference in discounted net benefits occurs because benefits are estimated relative to the do-nothing option. Hence, at low values of V_{max}, the no-control option does not involve immediate, large losses of benefits from the uninvaded area and so control is only profitable at small invasion sizes. Whereas at large values of V_{max} immediate eradication prevents large losses of benefits compared with the no-control option and so the present value of net benefits of control are larger.

Another significant feature of the relationship between optimal control and spread rate is that switching points *a* and *b* are much closer when the spread rate is high (Figure 3A and B) than when it is low (Figure 3C and D). This indicates that a higher priority should be given to eradication than to containment when spread rates are high to prevent the potentially large losses in benefits, but once the invasion gets too large containment is generally not optimal and so the no-control option should be adopted. By the same reasoning, containing a weed population that spreads at a slow rate is less costly in present value terms than eradicating it.

Seed-bank longevity has no effect on the net benefits of containment (Figure 3, thin lines) but has a significant effect on the net benefits of eradication (thick lines). An increase in *SL* results in a large decrease in the present value of net benefits of eradication, because it increases the number of years that the costs of searching and treating an invaded area are incurred in order to ensure the weed has been eradicated. The effect of this on switching point *a* is a shift to the left from approximately 18,800 ha to 5,400 ha when the spread rate is 4 km yr^{-1} and from 40 ha to 5 ha when spread rate is 0.1 km yr^{-1}.

Effects of biological parameters

Figure 3 indicates that switching point *a* is negatively related to *SL* and positively related to V_{max}. The nature of these relationships is shown in more detail in Figure 4, created by changing values of V_{max} and *SL*, while holding all other parameter values constant. Data points where switching point *a* equals switching point *b* are indicated by a '*b*' (Figure 4).

As spread rate increases switching point *a* increases at an increasing rate, reaches a maximum (at a critical V_{max} which depends on *SL*) and then decreases with further increases in V_{max} (Figure 4A). The position of the maximum point shifts up (to larger areas) and to the left (lower V_{max}) as *SL* decreases. For example, when *SL* is only six years switching point *a* reaches a maximum area of about 24,000 ha at a relatively low spread rate of about 2.5 km yr^{-1}, whereas when *SL* is 20, the maximum area of eradication is only 5,300 ha and occurs when V_{max} is 4 km yr^{-1}. The strong effect of SL on the area associated with switching point *a* is more clearly illustrated in Figure 4B, which shows an exponential decrease in area where eradication is economically feasible.

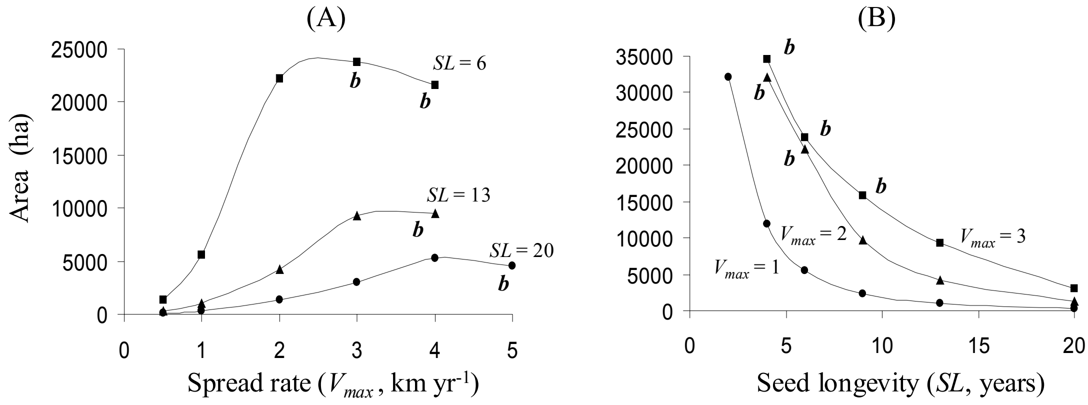

Figure 4: Sensitivity of switching point *a* to spread rate (V_{max}) and seed-bank longevity (*SL*).

These results indicate that when higher spread rates (V_{max}>1) and lower seed longevities (*SL* < 7) are combined, it is optimal to eradicate larger invasions (*Area* > 20,000 hectares) up to a maximum area when it then becomes optimal to switch to the no-control option. In other words, at high values of V_{max} and low values of *SL* switching points *a* and *b* are equal. This occurs because treatment and search costs associated with eradicating the seed bank decrease exponentially as seed longevity decreases, which makes eradication of larger invasions more feasible than containing them forever. However, high spread rates are associated with large containment areas and costs and so it becomes optimal to avoid these costs at large invasion sizes by adopting the no-control strategy. Finally, lower spread rates make containment strategies preferable to eradication at larger invasion sizes because the potential of the weed to cause widespread damage is relatively low (in present value terms) therefore the benefits of eradication are not as high and do not justify the associated large upfront costs.

Effects of economic parameters

As stated earlier, if the area at risk is a natural ecosystem the benefits (*B*) of preventing the spread of the weed are often not known or difficult to quantify. Therefore, it is useful to determine how optimal management, in terms of switching points, changes as the value of the land at risk changes. Labor costs (*L*) contribute most to the total costs of a control program, particularly in areas comprising rare or pristine natural ecosystems, where widespread application of herbicides is not an option.

Table 2 presents switching points *a* and *b* for various combinations of *B* and *L*. In these scenarios it was assumed that no chemicals are used, a valid assumption where the land under invasion is a sensitive natural environment. It was also assumed that the seed longevity is 20 years and the rate of spread of the weed population is 1 km yr^{-1}. All other parameter values were kept at the base-case values of Table 1.

As expected, switching points *a* and *b* decrease as labor inputs increase and as *B* decreases (Table 2). This decrease is less substantial for switching point *a* than for switching point *b* because the seed bank survives for a long time (which makes eradication costly), and the spread rate is low (which makes the costs of damage relatively low in present value terms). Therefore, unless the infestation is discovered early (it covers a small area) containment or no-control strategies are preferred over eradication.

Table 2. Sensitivity of optimal control to a range of labor-input requirements and benefits, at base-case parameter values where the seed longevity is 20 years and the rate of spread is 1 km yr^{-1}.

Benefits ($ ha^{-1})	Switching point *a*			Switching point *b*		
	Manual labor (hrs ha^{-1})			Manual labor (hrs ha^{-1})		
	80	130	180	80	130	180
30	661	254	113	707	**254**	**113**
60	661	661	531	5,809	1,320	**531**
120	707	707	707	57,256	11,122	4,072
180	755	755	707	212,372	45,239	14,527

Switching point *a* = the maximum area at which eradication is optimal
Switching point *b* = the area at which it becomes optimal to do nothing

When labor inputs are high and benefits of control low, switching point *a* equals switching point *b* (Table 2, figures in bold type). This is because the costs of controlling the weed (in present value terms) due to its long *SL* exceed the benefits of controlling its relatively slow rate of spread. Switching point *b* gets larger as the value of *B* increases or *L* decreases and exceeds switching point *a* for most combinations of *L* and *B*. In other words, when V_{max} is low and *SL* is high larger invasion sizes are more feasible to contain than to eradicate.

Discount Rate

A strategy of containment will incur costs for an infinite time horizon, whereas the decision to eradicate a weed population will involve relatively large upfront costs and a stream of future benefits which are discounted. Implications of using a high discount rate (10%) are illustrated in Table 3.

Table 3. Sensitivity of optimal control to a range of labor-input requirements and benefits at a 10% discount rate, where the seed longevity is 20 years and the rate of spread is 1 km yr^{-1}.

Benefits ($ ha^{-1})	Switching point *a*			Switching point *b*		
	Manual labor (hrs ha^{-1})			Manual labor (hrs ha^{-1})		
	80	130	180	80	130	180
30	113	20	1	**113**	**20**	**1**
60	227	201	79	962	**201**	**79**
120	227	227	227	9,852	1,963	661
180	254	227	227	51,875	7,390	2,463

Switching point *a* = the maximum area at which eradication is optimal
Switching point *b* = the area at which it becomes optimal to do nothing

An increase in discount rate from 6% to 10% decreases the area to which eradication is optimal by between 66% and 99%. This large decrease, especially at low values of B and high values of L, occurs because the benefits associated with eradication are experienced in the future and are therefore discounted more heavily than the costs, which are experienced upfront and for the duration of the seed-bank longevity. Consequently eradication becomes less feasible at higher discount rates and is only optimal at very small areas, where the upfront costs will be low.

Switching point b also decreases at a higher discount rate (by between 82% and 99%). When switching point b equals switching point a (numbers in bold), the decline occurs for the same reasons as given above.

Implications for Management Decisions

Results based on a perennial plant with a slow rate of spread (1 km yr^{-1}) and high seed longevity (20 years) indicate that the maximum area at which eradication is optimal ranges between 113ha and 755ha depending on the value of the invaded land and the amount of labor required to control the invasion (Table 2). The relatively small window for eradication obtained in this study is compatible with arguments presented by several authors regarding the importance of discovering invasions early if eradication is to be feasible (i.e., Groves and Panetta, 2002; Rejmanek and Pitcairn, 2002). However, our sensitivity analysis identified combinations of parameters resulting in areas as high as 25,000ha being eradicable when SL is low, provided the budget allows for it.

The range of areas over which containment is optimal ($a-b$), was found to be strongly affected by benefits (B) and labor (L) per unit area. At low B and L combinations the area where containment should be undertaken ranges from 661ha to 707ha; whereas at high B and L combinations the range is 707ha to 14,527ha. This implies that there is a small window of opportunity to discover and contain an invasion in land of relatively low value; whereas in high-value land this window is much larger. The term “land value” in the context used here does not refer to price in the land market, as it includes non-marketable values provided by natural ecosystems.

Not surprisingly, the discount rate used in the evaluation is an important consideration when dealing with weed invasions. Results for two different discount rates show that the window for eradication decreases considerably as the discount rate increases. An increase in the discount rate from 6% to 10% causes switching point a to decrease from a range of 113-755ha (Table 2) to a range of 1-254ha (Table 3).

SUMMARY AND CONCLUSIONS

In this paper we develop a simple model to represent the spread of a weed invasion. The model is designed as a first step in developing rapid-assessment tools to evaluate alternative management strategies when new invasions are discovered. The critical variables in the model are the expected rate of spread of an uncontrolled invasion, the longevity of the seedbank, labor and chemical inputs required to control the invasion, and the benefits lost as a consequence of the invasion. Control consists of establishing a barrier zone along the perimeter of the invasion and, if appropriate, eliminating the established weed population. For any given invasion size the desirable course of action is determined by selecting the strategy that maximizes net benefits, measured in present value terms and with a planning horizon of 50 years. Net benefits are measured relative to the do-nothing option.

Two critical decision points (switching points) were identified. Switching point a is the invasion size at which eradication ceases to be a desirable option. Switching point b is the invasion size at which it becomes optimal to do nothing. The distance $b-a$ represents the range where containment is the optimal option. We identified cases where a=b, indicating that, when the invasion is large enough it is optimal to switch from eradication to giving up control altogether, with no containment as an intermediate option. These cases occurred for weeds that spread rapidly (at speeds of 4 km yr^{-1}) and that have relatively short seed longevity (7 years or less).

The dollar value of benefits lost per hectare invaded was shown to have an important influence on switching-point values, as was the amount of labor per hectare required for weed control. Overall, seedbank longevity appears to be the main constraint on eradication of large invasions.

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