ECONOMIC ISSUES IN THE MANAGEMENT OF PLANTS INVADING NATURAL ENVIRONMENTS: SCOTCH BROOM IN BARRINGTON TOPS NATIONAL PARK

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Abstract

Scotch broom (*Cytisus scoparius, L.*), is an exotic leguminous shrub, native to Europe, which invades pastoral and woodland ecosystems and adjoining river systems in cool, high rainfall regions of southeastern Australia. Broom has invaded 10,000 hectares of eucalypt woodland at Barrington Tops National Park in New South Wales, and is having a major impact on the natural ecology of the sub-alpine environment. It is extremely competitive with the native flora, retarding their growth and in many areas blanketing the ground and preventing growth of many understorey species in open forest areas.

An active program to manage this invasion is being implemented by the National Parks and Wildlife Service. The management issues include whether eradication or containment is economically desirable, and when biological control is economically desirable. Management choices depend on the marginal costs of increments of government intervention, effects of uncertain budgets on the control of broom, choice of control measures and effects of uncertain values of biodiversity. These issues are addressed through the application of a detailed bioeconomic model of broom management.

Key words: Scotch broom, economic issues, management issues, natural environments, bioeconomic model.

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1. Introduction

Government agencies, particularly the National Parks and Wildlife Services, manage most of Australia’s remaining natural ecosystems. The agencies are funded mainly from general government revenue, and any income they receive is usually paid into that revenue. They are, therefore, highly dependent on the political process for funds. Given the non-commercial nature of most nature conservation activities, political factors play a much greater role in determining effort and methods used to control weeds on public land than on private land (Hartley and Tisdell 1981).

Due to deficiencies in political mechanisms and the failures of economic markets, the actual quantity of weed management in natural ecosystems is unlikely to be optimal from an economic viewpoint. There may well be insufficient control of weeds because of lack of funding and because of the external, unpriced nature of the benefits. Because of the need to protect the natural ecosystem and its flow of services, the methods of control within a Park are limited relative to methods available for areas outside the Park. They may also be limited because of particular government practices, customs and regulations.

Particular policy issues therefore arise in the management of weeds in a natural ecosystem:

- Should the government intervene in the management of the weed?
- What combination of control measures best meets community objectives?
- When is biological control an economically desirable measure?
- When is eradication, as opposed to containment, economically desirable?
- How important is biodiversity protection in the choice of management strategies?
- What are the benefits of a certain budget for the coming years?

The main goal of this paper is to develop management strategies for controlling Scotch broom in Barrington Tops National Park. In approaching this goal we aim to analyse the above policy issues through the application of a detailed bioeconomic model of broom management for this Park. Therefore the paper has been organised as follows: we first develop the dynamic model for broom management. Then, we specify the economic optimisation problem. We present results and discussion for each policy issue. Finally we summarise the results and suggest some conclusions.

2. A dynamic model for broom management

Following current land-use patterns on Barrington Tops, it is assumed that a tract of land of 80,000 hectares is presently available for biodiversity protection, recreation and livestock production (Odom *et al.* 2001). We have omitted watershed protection and soil conservation as services of the natural environment because no data on the quantity and quality of flows are available. From the aspect of broom management, the land can be defined in terms of four state variables: the fraction of sites occupied by broom; the fraction of sites that are unsuitable for broom establishment; the fraction of open sites (areas suitable for broom but not yet colonised); and the average number of viable seeds per site. These variables describe the initial state of the land to facilitate the model, it is also assumed that the given control measures can be applied to the whole area (Odom *et al.* 2001).

2.1 Park outputs

The three outputs of the Park are measured as follows: biodiversity is measured in terms of percentage of species preserved; recreation is measured in terms of number of group visits per year; and agricultural output is measured as the proportion of potential annual yield actually achieved (Odom *et al.* 2001). These activities are not always mutually exclusive, so a specific area was not allocated to each, but rather an overall area of the Park was allocated according to the current situation.

The net annual benefit obtained from the area in year t (B_t) is defined as:

$$B_t = B_{bio}(w_t) + B_{rec}(w_t) + B_{agr}(w_t) - u_t \cdot c_u \qquad (1)$$

where, B_{bio} B_{rec} and B_{agr} are the benefits (as price × quantity) provided by each of the three outputs. The values of the outputs are functions of weed density (w_t), with $dB_j/dw_t < 0$ for all $j = bio, rec, agr$. The last term in equation (1) represents the costs of broom control, where *(u)* is a vector of control measures and *(c)* is a vector of per-unit costs of control.

The quantities of biodiversity and recreation output are described by the function:

$$v_j = P_j \frac{V_{\max j}(x_{\min j} - w_t)}{k_{mj} + (x_{\min j} - w_t)} \text{; for } j = bio, rec \tag{2}$$

where v_j is the production of output *j*, P_j is the price, $V_{\max}$ is the maximum output possible, $x_{\min}$ is the weed concentration at which v_j become zero, and k_m is a half-saturation constant. The value of agricultural output is described by the function:

$$v_{agr} = P_{agr} V_{\max agr} \left(1 - \exp\left(k_{m agr}(x_{\min j} - w_t)\right)\right) \tag{3}$$

where variables and parameters are defined as above. Agricultural output is measured as a 'yield index', the proportion of potential yield actually achieved. Values of the parameters $V_{\max}$, $x_{\min}$ and k_m (Table 1) were estimated in consultation with National Parks and Wildlife Service staff and were also based on research by Panetta and James (1999). The resulting functions are shown in Figure 1.

2.2 Control measures

For simplicity, the only costs considered are those of weed control and these depend on the control method. Six control options are possible, and a number identifies them:

0. no control
1. exclude tourists
2. pull weeds out manually
3. apply herbicides
4. control wild pigs
5. biological control

In the model, a control strategy is represented by a 1x5 vector of zeros and ones. A zero in a given position indicates no control and a one indicates that the corresponding control is being applied. For example, u = [1 0 0 1 0] indicates that both tourist exclusion (1) and pig control (4) are being undertaken. There are 32 (that is 2^5) control strategies, each representing a unique combination of controls applied simultaneously. In the model, the 32 possible strategies are contained in a matrix U (32×5) of control vectors:

$$U = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ & & \cdots & & \\ 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \tag{4}$$

For modelling purposes we can select any row of U and insert it as the control vector u in equation (1). Control strategies are identified by their row number within U.

2.3 Population dynamics

The dynamics of broom population growth are represented through the difference equations:

$$w_{t+1} = w_t + f(w_t, s_t, u_t) \tag{5}$$

$$s_{t+1} = s_t + g(w_t, s_t, u_t) \tag{6}$$

where w_t is weed density and s_t is the size of the seed bank at time t. The functions $f(.)$ and $g(.)$ represent a biological model from Rees and Paynter (1997) that simulates the spread of broom. In the biological model there are four state variables: weed density; sites unsuitable for colonisation; sites open for colonisation; and the size of the seed bank. The parameter values of the population dynamics model are presented in Table 2.

The transition of a given tract of land from an unsuitable to a suitable site for broom depends on the probability of disturbance (p_{dist}), which is affected by factors such as the presence of tourists and wild pigs. As mentioned earlier, the simulation model operates with four state variables and hence contains four difference equations. Only two of those state variables, weed density (w_t) and seed bank (s_t), are directly relevant in the economic model; w_t affects biodiversity, recreation value and agricultural output directly (equation 1), whereas s_t affects the potential for the weed population to increase in future years. The other two state variables (sites open for colonization and sites unsuitable for colonization) influence the dynamics of the weed population but are not directly relevant to the decision model. They are used to define the state of the system.

The control methods directly affect four biological parameters: the probability that a site is disturbed (p_{dist}); the probability that a seedling survives the first year (p_s); the probability that a seed is retained in the parental site (f_h); and weed density (w_t). The effects of the control methods on these parameters are shown in Table 3.

Values of the parameters (Table 3) represent multipliers (or proportions of the base values from Table 2). Parameter values of 1.0 indicate no effect, and so these values appear in the first row for the no-control option (Table 3). The second row (exclude tourists) reduces the probability of disturbance (p_{dist}) to 0.2 and the probability that a seed becomes a seedling (p_s) to 0.33 of their original values, but increases the probability that a seed is retained in the parental site (f_h) to 1.23 times its original value. The remaining rows of Table 3 can be interpreted in a similar manner.

These values were estimated on the basis of the biological and management relationships between the control method and the parameter, ie. whether the parameter is expected to increase or decrease with a particular control and by how much. The effects of treatment on broom were constructed from a basic lifecycle of scotch broom and associated treatments to the various stages of the plant. When the control methods were combined, the effects on the parameters were estimated from two assumptions. If the controls affect different stages of the weed life cycle, then the parameter values were added, but if the controls affect the same stage of the weed life cycle, then the parameter values were added in a partial manner (R. Jones and T. Nordblom personal communication, 2001) [1].

2.4 The nature of the model

The bioeconomic model is developed by using a numerical, deterministic, dynamic programming technique, which integrates an economic model of broom management with a biophysical simulation model of broom spread.

The economic model describes the costs and benefits associated with broom control, for a particular area of Barrington Tops National Park which is being treated to reduce the spread. The biophysical simulation model describes the population dynamics of broom based on a simplified representation of an age-structured model. As an input to the biophysical simulation model, econometric models were used to analyse the spread of broom and generate data to modify the values and relationships of the biological parameters (Odom, Griffith, Schroder and Sinden 2003).

The bioeconomic model takes account of broom population dynamics, the effectiveness and cost of control measures, and the value of the land-use outputs (biodiversity, recreation and grazing). The dynamic programming model includes weed density and seed bank as state variables, combinations of control measures and a budget constraint for the control measures. The model is used to derive optimal control rules for any given state of the weed population. Because of the nature of the problem, the dynamic programming model is solved until it converges and an optimal decision rule is obtained. An optimal decision rule provides a package of control measures that can be used to address the problem each year, depending on the current weed density and seed bank.

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3. Economic Optimisation

The objective of the analysis is to choose the sequence of control strategies (u_t) that maximises the present value of a stream of annual net benefits, given an initial state (w_0,s_0) of the weed invasion. The optimisation problem for a planning horizon of T years is:

$$V_t(w_t, s_t) = \max_{u_t}\left[B_t(w_t, u_t) + \delta V_{t+1}(w_{t+1}, s_{t+1})\right] \qquad (7)$$

Subject to:

$$w_{t+1} = w_t + f(w_t, s_t, u_t) \qquad (8)$$

$$s_{t+1} = s_t + g(w_t, s_t, u_t) \qquad (9)$$

where δ is the discount factor $(1+r)^{-1}$ for the given discount rate r. The recursive equation (7) shows that current net benefits (B_t) are affected by both weed density and control strategies; whereas future net benefits (V_{t+1}) are affected by both weed density and seed banks. The recursive solution of (7) is executed from t=T to t=1, subject to the state transition equations (8) and (9).

Solution of this system for a range of values of the state variables (w_t and s_t) yields an optimal decision rule for each of the values, which can later be used to retrieve the optimal trajectory of control measures for any given initial state (w_0, s_0).

All prices and costs are expressed in Australian dollars ($). The prices of outputs (P_j) were obtained from three different sources. The benefits of biodiversity protection were set at a basic value of $100,000 to represent the worth of one species'. This estimate was obtained from two studies. Morton *et al.* (2002) reported that the Queensland government was prepared to spend $200 million, as a lump sum, to preserve native vegetation. They reported that 26 species would be saved per $1 million of expenditure. Therefore the cost of saving one species would be $38,462 or an annual equivalent at 6% of $2,308 per species. Hence, if government expenditure represents the minimum the community would pay, a species is worth $2,308 per year. An upper limit can be derived from contingent valuation studies. Lockwood and Carberry (1998) used this method to value endangered species, and estimated a lump-sum willingness to pay of $1.69 per household per species. For 2.3 million households in New South Wales, this works out to be a lump sum of $3.89 million per species, or at an annual sum of $233,220 per species at a 6% discount rate.

The value of $2,308 is based upon actual expenditure therefore it is likely to be a minimum value and the top value of $233,220 is based on the willingness to pay surveys and so is likely to be the maximum. The value of $100,000 per species per year lies between the two values of $2,308 and $233,220. The sensitivity of the model solutions to changes in this value was tested by using a range of values from $0 to $500,000.

Other surveys to value endangered species have given much higher contingent values. Kennedy and Jakobsson (1993) estimated a value of $40 per head per year for Leadbeater’s Possum in the state of Victoria. This would give a total of $194 million for all 4.854 million Victorians. Loomis and White (1996) reviewed surveys of willingness to pay in the United States of America. Their average of $140 per household per year would give a value of $322 million per year per species. These values may indicate that the value of $233,220 may itself be an under-estimate. But for the present analysis, the latter value is taken as the upper limit.

Benefits for recreation on Barrington Tops in terms of dollars per visit and number of visits were obtained from Sawtell (1999) and confirmed by Tier (2001). Benefits from recreation have been measured in terms of number of group visits; on average Barrington Tops National Park receives 10,000 group visits per year (Manidis Roberts 1995). Sawtell (1999) used the travel-cost method to estimate the economic value of recreation use in Barrington Tops National Park. She estimated that the consumer surplus from one group visit is $138 and therefore the consumer surplus per year will be $1,380,000 from 10,000 group visits. Tier (2001) also used the travel-cost method to measure the benefits of recreation, and estimated a willingness to pay of $110 per group visit.

Prices for agricultural output, in terms of gross margins, were obtained from NSW Agriculture (Davies 2000), based on a grazing enterprise in the area.

The model was solved for a planning horizon (T) of 45 years. The numerical deterministic dynamic programming technique was implemented in the Matlab (Mathworks 1999) program with the discount rate of 6%. The choice of 6% was based on the principle of social time preference, and rates recommended by Australian Governments (Sinden and Thampapillai 1995).

The model was solved for the base case parameters (Tables 1 to 4), with no constraint on the budget available to control weeds. An extended version of the model was also solved by incorporating a budget constraint

$$u_t.c_u \leq K \qquad \text{for all } t = 0,...T \tag{10}$$

where the term on the left is the annual cost of control and K is the budget available. The basic value of the budget constraint was $K = 50{,}000$.

4. Results and Discussion

4.1 Should the government intervene in the management of Scotch Broom?

Net present value (NPV) is the economist's indicator of welfare. A management program with a positive NPV offers a positive increase in welfare, and the program with the highest increase in NPV offers the highest increase in welfare. The decision to intervene can therefore be made from the NPV of the management strategies, and the choice of the optimal quantity of intervention can be made in the same way.

The analysis of the broom problem showed that:

- a NPV of $186.92m was obtained from the unconstrained version of the single state-variable (weed density only) model, and
- a NPV of $174.78m was obtained from the same model with a budget constraint of $50,000.

Welfare is therefore increased with intervention and it is increased most when there is no constraint on the budget available for control. This conclusion is supported by the analysis with the model for two state variables (weed density and seed bank) (Odom *et al.* 2003).

The desirability of different levels of intervention is indicated by the relative sizes of the benefits and costs in the optimal solutions. In the single state-variable model, the total discounted cost of controlling broom over the whole planning horizon was $1,020,797 for the unconstrained version, and $514,296 for the constrained version. The budget constraint of $50,000 per year therefore saved $506,501 on the cost of controlling broom in present-value terms, but resulted in a reduction in net benefits of about $12.14m (the difference between the net present values of $186.92m and $174.78m). Thus an extra outlay of $506,501 leads to an extra net return of $12.14m, giving a net benefit-cost ratio of 24 to 1. The results of the two state-variable model also indicate a large reduction in net benefits as compared to the cost saved, when the budget constraint is imposed.

Consider now the marginal or incremental cost of reducing weed density (Figure 2). The total cost of reducing weed density from the initial level of 0.5010 (point A) to a level of 0.3700 (point B) requires a budget of $250,000 per year. But the total cost of reducing the weed density from the same initial level to a density level of 0.4304 (point C) is only $50,000 per year. The higher budget for control leads to a higher reduction of weed density and therefore to lower levels of broom density. With a smaller budget, the reduction of broom density is smaller, and therefore the weed density remains at higher levels. The set of marginal costs of reducing the weed density are derived from Figure 2 and presented in Table 5.

The marginal cost of reducing the weed density clearly increases as the weed density decreases, as expected. The marginal cost of reducing the weed density level from 0.5010 to 0.4700 is $ 48,387 per year, and the marginal cost of reducing the weed density for the further increment, from 0.4700 to 0.4304, rises to $88,384. Further reductions in weed density lead to further increases in marginal costs.

If the weed density were reduced from 0.3700 still further toward 0.0000, the marginal costs would presumably continue to increase as density is reduced and so the budget requirement would continue to rise in an increasing manner.

Based on these results, treatment of broom leads to increases in welfare. Budgets in recent years appear to have been less than $50,000, but these results by themselves suggest that actual budgets devoted to broom control should be increased. But the estimates of NPV require that all benefits and costs are valued at the prices of competitive markets. The value of biodiversity typically lacks any kind of market price and this problem is addressed directly later in the results.

4.2 What combination of control measures best meets community objectives?

The overall objective of the National Parks and Wildlife Service with respect to broom control and recreation is, presumably, to achieve the optimal combination of biodiversity protection and recreational visits - - from the viewpoint of the community as a whole. As we have seen in the previous section, this objective requires reducing both the weed density and the seed bank and in the conduct of budget constraints. The next management issue is what combinations of controls should be employed at different budget levels?

With no budget constraint, the best combinations of measures proved to be:

- control of wild pigs and biological control for areas with low weed density and high seed density;
- pull weeds, apply herbicide and biological control for areas with high levels of weed density and low levels of seed density;

- pull weeds, apply herbicide, control wild pigs and biological control in areas where both weed density and seed density are at high levels; and
- control wild pigs alone in areas where both weed density and seed density are at low levels.

With a constraint of $50,000, the best combinations were:

- control wild pigs alone for areas with low weed density and high levels of seed density;
- apply herbicide alone for areas with high levels of weed density and low levels of seed density;
- pull weeds and apply herbicide in areas where both weed density and seed density are at high levels. Because of the budget constraint, the agency could only afford to apply these measures at 83% of their optimal level; and
- control wild pigs alone in areas where both weed density and seed density are at low levels.

The choice of control measures varies with weed density and seed density as expected. But the reduction of both weed density and the seed bank is limited by the budget and the agency can only use control measures that they can afford. Thus, the optimal sets of control measures depend on the budget as much as on the level of weed density and the seed bank.

4.3 When is biological control an economically desirable measure?

Biological control is the most environmentally friendly of the measures, and so is often preferred by biologists to control broom. In addition, biological control agents persist for many years and so should be suitable for controlling the broom seed bank with its long life span. But when is biological control economically desirable?

In the single state-variable model (with only weed density):

- biological control did not appear at all with a budget constraint of $50,000,
- biological control appeared in three out of nine cases when the budget constraint increased to $100,000, and

- biological control appeared as an optimal control measure in 78% of all strategies where there was no budget constraint.

In the two state-variable model (with both weed density and seed bank):

- biological control appeared in only five cases out of 81 (6%) with a budget constraint of $50,000 a year. These were areas with medium weed density (0.1410) and medium to high levels of seed density (1571- 3350 seeds/m^2), and
- biological control appeared as an optimal measure in 77 out of 81 cases (95%) when there was no budget constraint.

In terms of levels of weed and seed density:

- when there is no budget constraint, biological control is desirable at all levels of weed and seed density except where both the weed and seed density are at very low levels, and
- with a budget constraint, biological control is not desirable except where the weed density is medium and the seed density is medium to high levels.

The implications seem to be that the use of biological control is critically dependent on weed density and seed density being at medium to high levels, and on budget size. This occurs, of course, because biological control is very costly, but the only costs involved are at the initial stages.

4.4 When is eradication, as opposed to containment, economically desirable?

The topography of the Park has allowed broom to colonise inaccessible areas of very high altitude and may hide part of the broom population. Seeds are viable for more than 45 years, so it is technically difficult to eradicate the invasion. But is it economically desirable to try to eradicate it?

Without a budget constraint, the analysis suggests that it is optimal to reduce the weed density to a level of about 2% of the area of the Park (an area of 0.02 in Figure 3), with a steady cycle of fluctuations within a narrow range. In the unconstrained case therefore, the weed density should be reduced to a steady state level at about 0.02. But in the constrained case, also shown in Figure 3, the optimal weed density

increases markedly and settles at about 17% of the park area (an area of 0.17 in Figure 3).
The steep decrease in weed density for years one to ten with the unconstrained budget (Figure 3) implies the application of a high control budget in these early years. This will bring the population down to a level where it can be contained at lower cost in the longer term.

The optimal paths for seed density (Figure 4) are similar to those for weed density. In the unconstrained case, the seed bank first increases then decreases to attain a stable, fluctuating state of 126 seeds/m^2. In the constrained case, the seed bank keeps increasing and approaches 900 seeds/m^2 in occupied sites.

Clearly, it is not economically desirable to reduce the weed population to zero with the assumed initial conditions and under optimal management, even when the budget is unconstrained. A containment strategy should therefore be pursued.

As Figure 2 indicated, the total cost of controlling broom will be more than $300,000 per year if the weed density is reduced to zero or even close to zero. All the control methods are labour intensive and expensive, even in the accessible areas that are currently treated within the Park. But the total costs will, in fact, include more costs than are used here. These include the extra costs of searching for weeds in scattered and hidden areas, and extra costs of access to difficult areas.

4.5 How important is biodiversity protection, relative to other ecosystem services, in the choice of management strategies?

The size of the NPV in the solutions is of course sensitive to the value used for the benefit of biodiversity. For example, a low value of biodiversity of $10,000 per year per species gives a NPV of $57.22m, the base value of $100,000 gives a NPV of $186.95m, and a high value of $150,000 gives a NPV of $259.1m.

But the crucial management issue is what happens to the choice of control measure when the value of biodiversity changes? A change in the value, relative to the value of recreation services, captures a change in the importance of biodiversity in the management of the natural ecosystem. It also allows for a sensitivity analysis to analyse this issue. If the value of biodiversity were zero the weed density level would be 0.0099 (A in Figure 5), but when the value of biodiversity increases to $50,000 the optimal weed density reduces to 0.0089 (B). Further, when the value of biodiversity is $100,000 (C) and above, the weed density stabilises at 0.0077. The control measures vary with weed density and we found that:

- the optimal control measures proved to be stable (the same measures were indicated at the same levels) for values between $50,000 to $100,000, and
- the optimal control measures proved to be stable for values of $100,000 and above.

The value of biodiversity is likely to exceed $100, 000 and management choices are stable in this area – so the choices do not depend on the money value placed on a species in this analysis.

4.6 What are the benefits of a certain budget for the coming years?

The budgets of government agencies are characteristically uncertain, and budgets for weed control are no different. As a general planning principle, knowledge of future budgets would assist the agencies to manage the broom invasion. These kinds of assistance may be illustrated for the management of the broom invasion on Barrington Tops.

An obvious benefit of budget certainty is that the agency can determine an optimal package of control measures for an extended period of time (not just for a single year). It allows the agency to avoid the problems of annual changes in the management measures because of annual changes in budget. The results of the unconstrained and constrained versions of the model, discussed in Section 4.2, illustrate these problems. Consider the measures recommended through the model for the situation of mean weed density (0.287% occupied) and mean seed density (1571 seeds per square metre). With a budget constraint of $50,000 the optimal control measures are 83% of manual pull and herbicide application. Whereas without a budget constraint the optimal control measures are 100% of manual pull, herbicide application and biological control.

The optimal set of control measures for a given year, as determined through the model, depends on the budget available in the year and the expectations of a similar budget in future years. The results have shown large differences in NPVs and in control measures as the budget increase (Odom *et al*. 2003). The NPV, of course, increases with increases in the budget (Figure 6). For example:

- with a budget constraint of $100,000 per year the NPV is $183.08m at an initial level of weed density (0.5010), whereas,
- with a budget constraint of $50,000 per year the NPV is $174.78m same initial level of weed density.

Welfare to the community is maximised with a higher budget.

Budgets, weed density and seed bank are inter-related. The optimal reduction in the weed density is also affected by the amount of the budget. This information will help the agency to relate the weed density level to the budget required to reduce it to an optimal level. Because of the relationship between the state variables in the population dynamics model, the optimal state transition for weed density is affected by the prevailing seed bank, and the optimal state transition for the seed bank is affected by the prevailing weed density (Odom *et al.* 2002; Odom *et al.* 2003). Therefore the budget also affects the seed bank level. Thus the control of weed density has to go hand-in-hand with the control of the seed bank, and sufficient funds are required for both to occur.

5. Summary and Conclusion

Intervention in the management of broom in this natural ecosystem is clearly economically justified, and increases in the existing budgets appear to be justified. A combination of control measures, rather than any single measure, is almost always justified. Attempts to eradicate broom appear to be undesirable, so containment is the preferable strategy. Funding bodies should give assurances of future budget levels.

In this paper we have assumed certainty of all the parameters used in the bioeconomic model. Risks were not taken into account due to lack of data on uncertain events such as climate, rainfall, fire, windstorms etc. Another limitation is that sensitivity analysis of the effectiveness of biological control has not been undertaken, although it is considered important as an extension to the model.

Finally, lack of spatial data made it impossible to accommodate other issues, which would have been important in obtaining specific effects of control measures according to the different areas of the park.

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Figure 1: The relationship between weed density and the quantity of each Park output; biodiversity (A), recreation (B), agriculture (C).

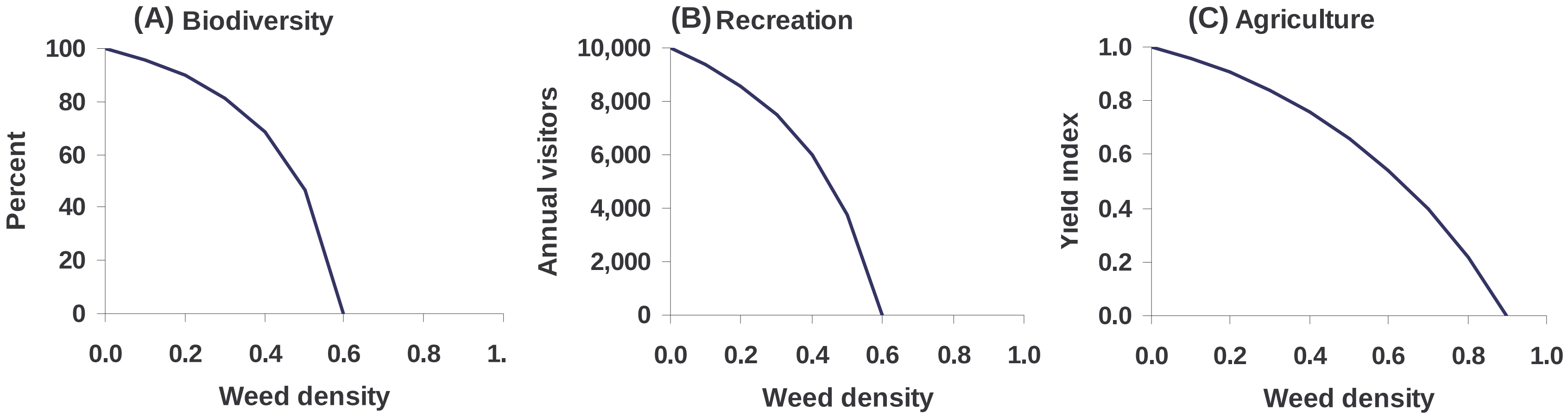

Figure 2: The marginal cost of reduction in weed density

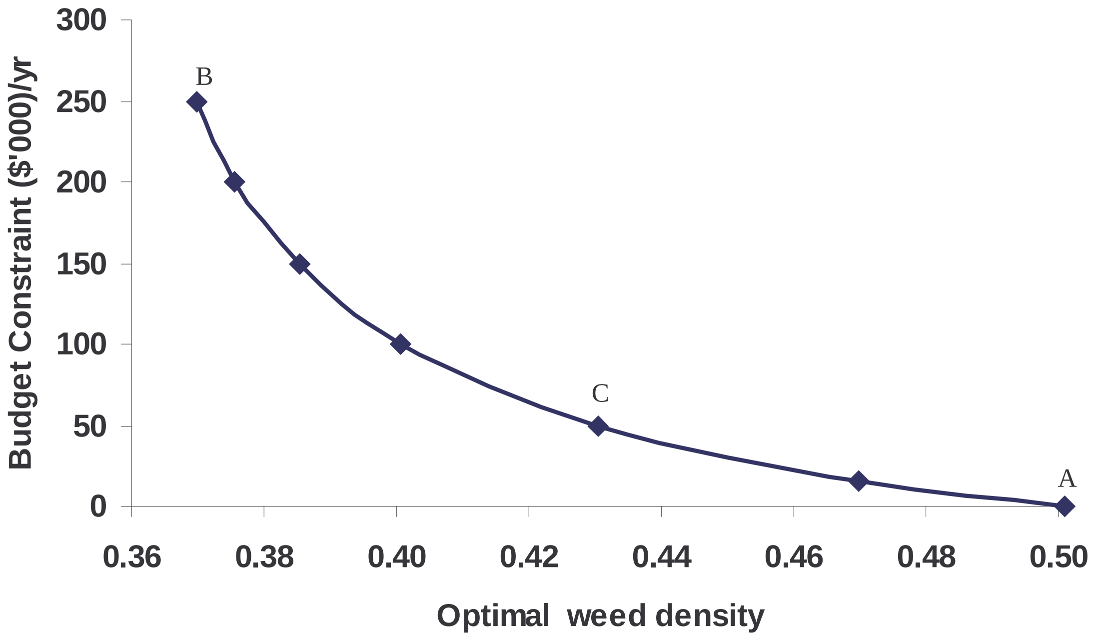

Figure 3: The optimal path for weed density

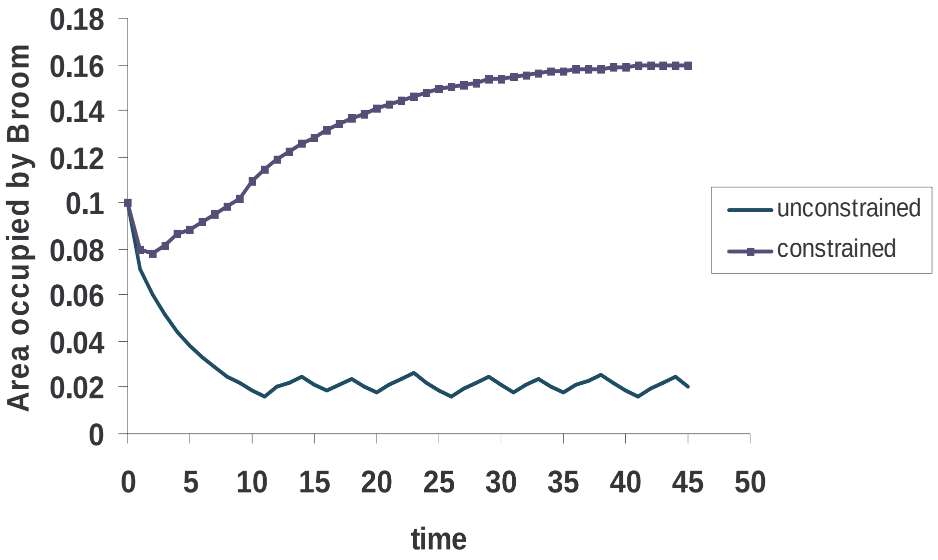

Figure 4: The optimal path for seed density

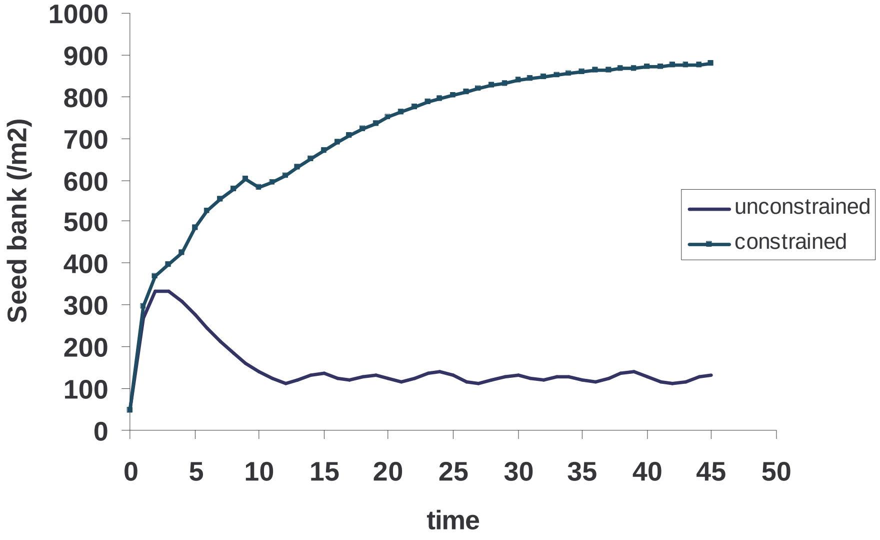

Figure 5: The relationship between the value of biodiversity and the optimal weed density

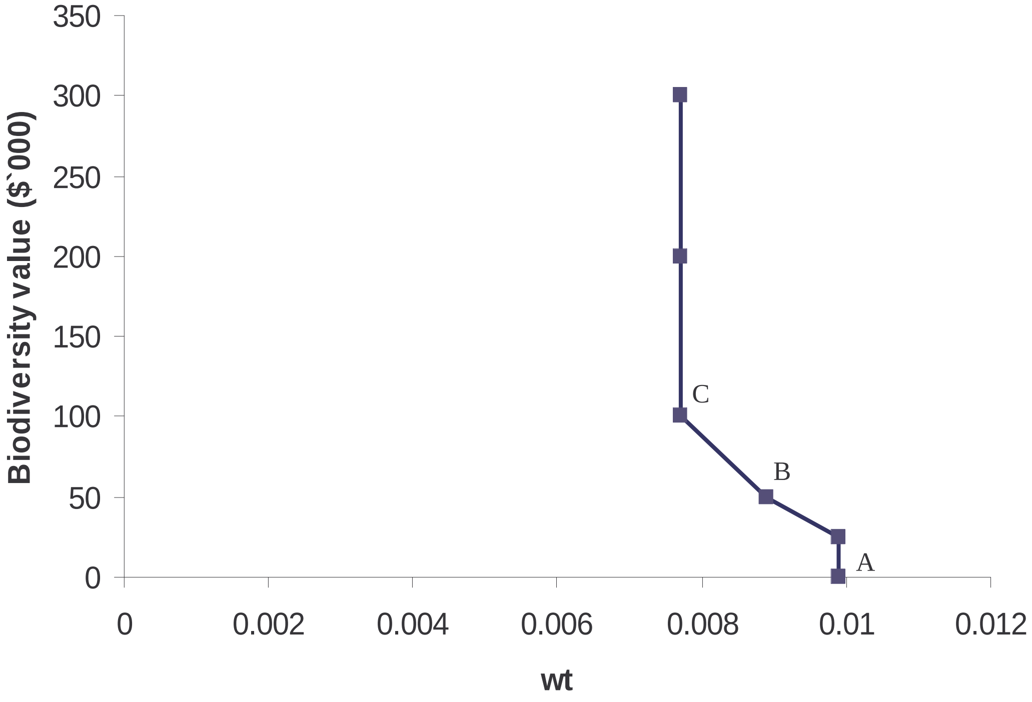

Figure 6 : The NPV under budget constraint

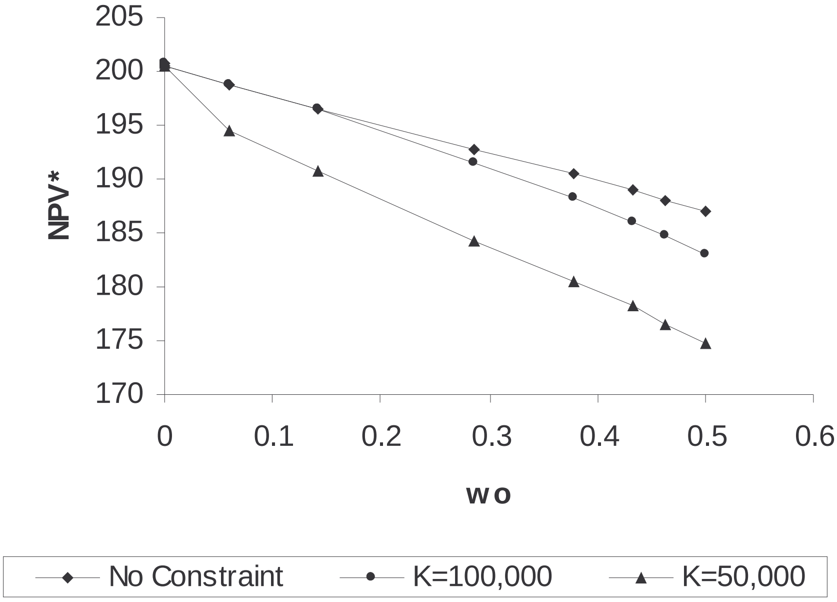

Table 1: Parameters of park output functions

Park output	Parameter				Equation
	$V_{\max}$	k_m	$x_{\min}$	p	
Biodiversity	130	0.18	0.6	1.0×10^5	(2)
Recreation	1.50×10^4	0.3	0.6	138	(2)
Agriculture	1.2	-2.0	0.9	1.68×10^6	(3)

Table 2: Parameters of the population dynamics model

Parameter	Value	Description
p_{dist}	0.05	probability that a site is disturbed
p_g	0.04	probability that a seed becomes a seedling
p_s	0.3	probability that a seedling survives the first year
P_d	0.5	probability that a seed is lost from the seedbank (decay)
A_{min}	3	minimum age for reproduction of broom
A_{max}	20	maximum plant age
$\boldsymbol{F}$	5300	seed production per site (number per m^2)
f_h	0.73	probability that seed is retained in the parental site
p_{so}	1.0	probability that site becomes suitable for colonisation after senescence
f_r	0.6	fraction of broom plants that are reproductive
z_{max}	0.05	fraction of broom plants in the maximum age class

Sources: Rees & Paynter (1997); Downey & Smith (2000); Sheppard, Hodge, Paynter & Rees (2001); Paynter, Downey & Sheppard (2001)

Table 3: Control strategies and their effects on parameter values

	Controls applied[1]					Multiplier			
Strategy	1	2	3	4	5	P_{dist}	P_s	f_h	w_t
1	0	0	0	0	0	1.00	1.00	1.00	1.00
2	1	0	0	0	0	0.20	0.33	1.23	1.00
3	0	1	0	0	0	1.40	0.33	0.55	0.80
4	0	0	1	0	0	1.60	0.30	0.27	0.60
5	0	0	0	1	0	0.20	0.67	1.23	1.00
6	0	0	0	0	1	0.20	0.07	0.04	0.60
7	1	1	0	0	0	1.30	0.17	0.96	0.80
8	1	0	1	0	0	1.50	0.14	1.10	0.60
9	1	0	0	1	0	0.10	0.51	0.62	1.00
10	1	0	0	0	1	0.10	0.30	1.21	0.60
11	0	1	1	0	0	0.90	0.18	0.42	0.50
12	0	1	0	1	0	1.30	0.51	0.96	0.80
13	0	1	0	0	1	1.30	0.30	0.53	0.50
14	0	0	1	1	0	1.50	0.52	1.10	0.60
15	0	0	1	0	1	1.50	0.27	0.25	0.40
16	0	0	0	1	1	0.10	0.64	1.21	0.60
17	1	1	1	0	0	0.80	0.02	0.80	0.50
18	1	1	0	1	0	1.20	0.34	0.34	0.80
19	1	1	0	0	1	1.20	0.13	0.94	0.50
20	1	0	1	1	0	1.40	0.36	0.50	0.60
21	1	0	1	0	1	1.40	0.15	1.08	0.40
22	1	0	0	1	1	0.00	0.47	0.60	0.60
23	0	1	1	1	0	0.80	0.36	0.82	0.50
24	0	1	1	0	1	0.80	0.15	0.40	0.30
25	0	0	1	1	1	1.40	0.49	1.08	0.40
26	0	1	0	1	1	1.20	0.47	0.94	0.50
27	1	1	1	1	0	0.70	0.19	0.21	0.50
28	0	1	1	1	1	0.70	0.32	0.80	0.30
29	1	0	1	1	1	1.30	0.32	0.46	0.40
30	1	1	0	1	1	1.10	0.31	0.32	0.50
31	1	1	1	0	1	0.70	0.02	0.80	0.30
32	1	1	1	1	1	0.60	0.16	0.19	0.30

[1] Controls: 1=exclude tourists, 2=pull weeds, 3=apply herbicide, 4=control wild pigs, 5=biocontrol.

Table 4: Base-case assumptions

Item	Units/Value
Costs of control options	*($/year)*
1. exclude tourists	5,000
2. manual pull	15,000
3. apply herbicide	45,000
4. control pigs	15,000
5. biological control	76,848
Initial conditions of the area	*Fraction*
Area occupied by broom	0.125
Sites that are unsuitable for broom	0.400
Sites that are suitable for broom	0.600
Areas open for colonisation	0.475 [a]

[a] Areas suitable for broom but not yet colonised

Table 5: Marginal cost of reductions in weed density

Reduction of weed density	Change in the weed density	Change in annual cost of control ($)	Marginal annual cost of control ($)*
0.5010 to 0.4700	0.0310	15,000	48,387
0.4700 to 0.4304	0.0396	35,000	88,384
0.4304 to 0.4005	0.0299	50,000	167,224
0.4005 to 0.3855	0.0150	50,000	333,333
0.3855 to 0.3755	0.0100	50,000	500,000
0.3755 to 0.3700	0.0055	50,000	909,091

* The annual cost of a 1 per cent (0.1) change in weed density