STRATEGIES FOR CONTROLLING WEEDS IN NATURAL ECOSYSTEMS: A DYNAMIC OPTIMISATION APPROACH

Doreen Odom*, Oscar Cacho*, J.A. Sinden* and G. R. Griffith*+

*** Graduate School of Agricultural and Resource Economics,**
University of New England, Armidale,
and + NSW Agriculture, Armidale

Abstract

Scotch Broom is a serious environmental weed in Barrington Tops National Park and the surrounding areas. It poses a significant threat of reducing the diversity of flora in invaded ecosystems and generating a false understorey. It also harbours feral pigs, which perpetuate the cycle of disturbance. To address problems caused by Scotch Broom in the 10000 hectares already invaded and the threat of further invasion, it is vital to understand why this species is able to invade and persist in Australian ecosystems. Such understanding will be the key to developing effective management strategies, both to prevent further invasions and to suppress dominance of Scotch Broom.

The budget available for weed control, pests control, and other activities in the Park, is limited and so managers must identify control strategies that are efficient and sustainable. A deterministic dynamic programming model is developed for this purpose in this paper. A simulation model, which captures Broom population dynamics, was developed first and takes account of two state variables, which are then incorporated in the dynamic program. The dynamic programming model contains these two state variables and five control variables. The state variables are the area occupied by Scotch Broom and the seed bank. The control variables are excluding tourists, manual pulling, herbicide application, feral pig control and biological control. We acknowledge the help of the NSW National Parks and Wildlife Service for providing us with the information required by the models.

The National Parks and Wildlife Service already has an effective containment strategy for Broom. In the present paper, we attempt to develop a management strategy that covers the park area and surrounding agricultural areas.

Preliminary results are presented and further information requirements are discussed.

Key words: Scotch Broom; flora diversity; dynamic programming; optimal control strategies

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1. Introduction

Barrington Tops National Park is approximately 100 kilometres north west of Newcastle, which is the major city in the industrialised Hunter Region of New South Wales. Barrington Tops is a basalt-capped granitic plateau, 1500 metres above sea level. It has an annual precipitation of about 1700mm (Lawless 1991) some of which falls as snow each winter. The vegetation is predominantly Eucalyptus woodland.

The Barrington Tops National Park is a unique area of outstanding international significance because of its scientific, recreational and educational values. It contains the core of one of the five major regions of rainforest present in New South Wales, provides refuge for a whole group of species which might be expected to occur only on mountains of higher altitudes, supplies a major proportion of high quality water needed for residential, industrial and agricultural purposes in the Hunter and Manning regions, and it demonstrates the development of a section of the Great Escarpment and its relationship between the Barrington Volcano and subsequent erosion. On the other hand it offers rugged mountain scenery and outdoor recreation, which at key points, is accessible by vehicles. Visitors to the Park can undertake a variety of activities such as bushwalking, camping, picnicking, car touring, fishing, photography, horse riding and nature study. The surrounding State forests also provide a range of recreation facilities (Trudgeon & Williams 1989).

Scotch Broom occurs as a weed in New South Wales, parts of Victoria, Tasmania and in parts of South Australia. In New South Wales, it occurs predominantly along the Great Dividing Range over 600 metres above sea level, with the most extensive infestation covering 10,000 hectares of the basalt plateau on Barrington Tops.

Scotch broom normally flowers in its third year (Smith & Harlen 1991) and produces large numbers of seeds that mostly fall within 1 metre of the parent plants (Smith & Harlen 1991: Paynter *et al.* 1996). Seeds may be dispersed up to 5 metres further by ants (Bossard 1990) and a variety of other seed vectors may occasionally disperse an unknown, but small portion of seeds over much greater distances (Smith & Waterhouse 1988: Smith & Harlen 1991).

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It is not clear how long broom seed banks persist: Hosking, Smith & Sheppard (1996) note that more than 80% of seeds buried in nylon mesh bags were still alive and dormant after 45 months. However, Bossard (1993) found that only 7% of seeds remained ungerminated when buried for 3 years at a depth of 4 cm.

There is evidence that plants live longer in exotic habitats. Scotch broom has an average life expectancy of 20-25 years in Barrington Tops (Hosking *et al.* 1998), but stands can live for more than 25 years.

Scotch broom is extremely competitive with the native flora, retarding its growth and in many areas blanketing the ground and preventing growth of many understorey species in open forest areas. There is a build up of long-lived seed in the soil that germinate rapidly when the canopy and / or ground surface is disturbed. Removal of mature plants is therefore rapidly followed by reinfestation from newly germinating seed.

In addition, within Barrington Tops National Park, tracks have been blocked and access to watercourses prevented. On agriculture land, Scotch broom invades pasture; decreasing productivity and restricting access to watercourses.

Herbicidal control of Scotch broom is possible, but extremely expensive and unless residual herbicides are used (Wapshere & Corey 1999), the effect is only temporary. Residual herbicides present problems for agricultural land and are inappropriate for national parks.

Mechanical control is virtually impossible as the site is then left open to broom regeneration. Grazing by sheep contains infestations preventing further spread, cattle are not successful and both are unsuitable for use in conservation areas.

The objective of this paper is to answer certain policy questions of relevance to the agency attempting to manage the Broom problem in Barrington Tops National Parks. The policy questions include (1) What are the best combinations of park outputs; (2) What is the best choice of decisions and inputs for the National Parks and Wildlife Service; and (3) in general, how can they manage uncertainty? To address these issues, the paper is organised as follows: we first review the application of dynamic programming in natural ecosystems; the dynamic programming model for Broom is then presented; followed by the results and sensitivity analysis of some parameters. Then we discuss the implications of the results and possible extensions to the model from which conclusions are then drawn.

2. A review of dynamic programming in natural ecosystems

Dynamic programming is usually thought of as a numerical solution technique. Equally important ways to think of dynamic programming are as a problem solving approach and as a way to characterise a solution (Taylor & Duffy 1994). Knowledge of dynamic programming is useful for anyone interested in the optimal management of agricultural and natural resources, for two reasons (Kennedy 1986). First, resource management problems are often problems of dynamic optimisation, and dynamic programming offers insights into the economics of dynamic optimisation. Conditions for the optimal management of a resource can be derived using the logic of dynamic programming, taking as a starting point the usual economic definition of the value of a resource, which is optimally managed through time. The economic definition is that of maximising net present value of the stream of benefits and costs. The second reason is that, dynamic programming provides a means of solving dynamic and stochastic resource problems numerically.

In order to achieve better strategies for controlling weeds in natural ecosystems, we must choose annual decisions, in terms of the type and quantity of management, to achieve levels of biodiversity preservation and recreation capacity over time, with stochastic outcomes to decisions. Dynamic programming is well suited to meet these needs.

Maguire (1986) develops a model to show how decision making under uncertainty may be used to integrate ecological theory, objective data, subjective judgements and financial concerns in the management of endangered species populations. The model analyses whether to translocate animals among small, isolated sub-populations to avoid problems of inbreeding depression or managing species as a single larger population. It demonstrates the nature of trade-offs between population security and financial cost and promotes the assessment of trade-offs.

The analysis involves the development of probabilistic models relating the outcomes of alternative actions to random events in the environment, and the assessment of values reflecting preferences for different outcomes according to one or more decision criteria.

Kennedy and Jakobsson (1993) developed an optimal model for timber harvesting in the montane ash forest of the Central Highlands of Victoria.

The objective was to find the sequence of harvesting decisions made at 50-year intervals, which maximises the expected present value of returns from timber production and possum habitat preservation in each of a large number of future 50-year periods.

The model included two stochastic events, which may occur over the 50 years between one decision stage and the next. One is an intense wildfire, which destroys much of the forest, and the other is survival of the possum to the next decision stage.

Clark and Butler (1999) developed a dynamic model of Western Sandpiper migration; one of the world's most abundant shorebird species, which migrates from winter sites in the southern United States and Central and South America to breeding grounds in Western Alaska and Eastern Siberia. Their objective was to explain the timing and variation in annual migration patterns, from a typical subtropical wintering site to the specie's Alaskan breeding grounds. They assumed that individual female sandpipers employ migration strategies that maximise their expected lifetime reproduction.

The model incorporates environmental factors assumed to affect migration decisions, which include wind speeds, site-specific predation risks, and the timing of food availability on the breeding grounds and at the two most northerly stopover sites.

Shea and Possingham (2000) developed an optimal release strategy model for biological control agents. A stochastic dynamic programming approached linked to a metapopulation model, was used to find optimal release strategies (number and size of releases), given constraints on time and the number of biological agents available.

The model operated within a decision-making framework and derived rules of thumb that will enable biocontrol workers to choose between management options, depending on the current state of the system. The optimal strategy ranges from a few large releases, through a mixed strategy (a variety of release sizes), to many small releases, as the probability of establishment of smaller inocula increases.

3. A dynamic programming model for Broom management

The nature of the approach is presented in Figure 1. The approach begins with the development of a biophysical simulation model, which captures broom population dynamics and takes account of the environmental conditions, the weed density (representing the state variable in time **t**), and the broom control methods (control variables). The simulation model, together with the state transition function representing the transition from the initial state to the next state (**t+1**) and the return function (which includes returns from biodiversity, recreation and agriculture in time **t)** are incorporated in the dynamic programming model. The results are the choices of control measures and quantities of outputs, which will then enable us to draw some policy implications for natural ecosystems.

Following land use on Barrington Tops, we assume that, a tract of land of 80,000 hectares is presently used for biodiversity protection, recreation and livestock production. From the aspect of broom management the land can be defined in terms of four variables; the fraction of sites occupied by broom, the fraction of sites that are unsuitable for broom establishment, the fraction of open sites, and the average number of viable seeds per site. These classes or variables describe the initial state of the land. The four classes ignore the actual spatial arrangement of broom plants in the present state of the model. We also assumed that the same inputs could be applied to the whole area.

The three outputs are assessed as follows. Recreation is measured in terms of number of group visits, biodiversity in terms of number of species preserved, and agricultural output is measured as percentage of potential yield.

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

$$B_t = V_{bio}(w_t) + V_{rec}(w_t) + V_{agr}(w_t) - \mathbf{u}_t \cdot \mathbf{c_u} \tag{1}$$

where V_{bio} V_{rec} and V_{agr} are the benefits provided by each of the three outputs, namely biodiversity, recreation and agriculture. The values of the outputs are functions of weed density in time t (w_t), with $dV_j/dw_t < 0$ for all $j = bio, rec, agr$. The last term in the equation represents the costs of broom control, where **u** is the control measure and **c** is the per unit cost of the control.

3.1 The management decisions

For simplicity, the only costs considered are those of weed control, which depends on the control methods used. Six control options are possible, and they are identified by a number:

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

In the model, the particular control applied is represented by a 1x5 vector of zeros and ones, a zero in a given position indicates no control, while 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. In the current version of the model, control methods are mutually exclusive in a given year, so there are six possible controls, each represented by a row of the matrix:

$$\mathbf{U} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

The first row represents no control and the remaining rows are the control methods (1,…,5) as described above. The cost of control is calculated by multiplying the control vector $\mathbf{u}_t$ by the (5x1) cost vector $\mathbf{c_u}$.

3.2 Population dynamics

Broom population dynamics are introduced through the difference equation:

$$w_{t+1} = w_t + f\left(w_t, \mathbf{u}_t\right) \qquad (3)$$

The function *f(•)* represents the biological model to simulate the spread of broom from Rees and Paynter (1997). In this model there are four state variables: weed density, sites unsuitable for colonisation, sites open for colonisation, and the size of the seed bank. The assumed parameter values for the simulation model of broom growth in the Barrington Tops National Park are presented in Table 1, and the initial conditions of the area 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 presence of tourists and wild pigs. The simulation model operates with four state variables and hence contains four differential equations. But only one of those state variables, weed density (w_t), is relevant in the economic model, because this is the factor that directly affects biodiversity, recreation value and agricultural output. This is therefore, the only state variable considered in the remainder of the paper.

3.3 Maximisation of returns

The objective of the analysis is to choose a sequence of decision variables or management inputs (u_t) that maximises the present value of a stream of annual net benefits, given the initial state.

The problem of maximising the net present value of the stream of benefits obtained from the park over a planning horizon of T years can be solved through dynamic programming. The recursive equation is:

$$V_t(w_t) = \max\left[B_t(w_t, u_t) + \delta V_{t+1}(w_{t+1})\right] \tag{4}$$

where B_t is the one-period return function (as in equation 1) and δ is the discount factor $(1+r)^{-1}$ for the given discount rate r. The first term in this equation represents benefits in the present year and the second term represents benefits from the future. The recursive solution of (4) is executed from $t = T$ to $t=1$, subject to the state transition equation (3).

The values of biodiversity and recreation are described by the function:

$$V_j = P_j \frac{\upsilon_j(\eta_j - w_t)}{\kappa_j + (\eta_j - w_t)}\text{; for } j = bio, rec \tag{5}$$

where, (V) is the production rate, (P) is the price for biodiversity or recreation, (υ) is the maximum number of species preserved, or recreational visits, (η) is the weed concentration, and (κ) is the half-saturation constant.

The value of agricultural output is described by the function:

$$V_{agr} = P_{agr}\upsilon_{agr}\left(1 - \exp\left(\kappa_{agr}(\eta_j - w_t)\right)\right) \tag{6}$$

where, (V) is the production rate, (P) is the price of agricultural output, (υ) is the maximum potential yield, (η) is the weed concentration, and (κ) is the half-saturation constant.

The parameter η affects the intercept on the vertical axis, κ determines the slope of the curve and υ determines the intercept on the horizontal axis (see Appendix 1). The values of these parameters were estimated in consultation with National Parks and Wildlife Service staff and were also based on research by Panetta and James (1999).

The prices of Park outputs (P_j) were obtained from three different sources. The benefits of biodiversity protection were estimated by the authors. The basic value of \$100,000 has been used to represent one specie's worth and variations in it will be tested on the sensitivity analysis. Benefits for recreation in terms of number of visits were obtained from Sawtell's (1999) research on Barrington Tops. Prices for agricultural output, as terms of gross margins, were obtained from NSW Agriculture, which were prepared by Davies (2000). The economic parameters are presented in Table 3.

3.4 The state transition equation

Assumptions regarding broom population growth, and the effect of control methods on biological parameters and state variables, affect the state transition equation, the equation is represented by a simulation model. The state transition equation for each of the six control options (including no control) is presented in Figure 2. The 45^o dotted line represents the steady state for any given population density (w_t) at a given time t. Points below the reference line represent strategies that will cause broom density to decrease, whereas points above the line represent strategies that will cause density to increase. The only line falling above the line is no control. All control methods cause w_t to decrease over time, but herbicide application is the most effective per unit of control applied, followed by manual pull. This is because herbicide application is assumed to kill 60% of the plants and manual pull eliminates 40% of plants. This assumption may need to be revised based on the cost of searching for broom plants at low densities relative to high densities.

4. Results

4.1 From the base model

The basic results were obtained with an initial level of weed density of 0.3, the biological parameters presented in Table 1, the economic parameters presented in Table 3 and 4, a discount rate of 5 percent and a planning horizon of 25 years. The results are presented in terms of the steady state of the park (long-run equilibrium density of broom), the park outputs at the equilibrium, and the optimal controls.

The path of optimal weed density over 25 years and the steady state equilibrium in the long run are shown by Figure 3, which illustrates different initial levels of broom density (0.1, 0.2, 0.3, 0.4, and 0.5 of the park area). The figure shows that the optimal level of broom density in the long run is 0.073 or 7.3%, of the park area, the point where all the four paths converge at year 25. This means that 7.3 per cent of the area is completely occupied by broom. With high levels of broom density like 0.4 and 0.5 the Park needs to spend more funds in controlling broom so that the level of weed density is reduced to the optimal level. This is shown by the steepness of the curves compared to low levels like 0.1 and 0.2.

The optimal levels of the three outputs are the long-run equilibrium levels that maximise net present value, and are calculated by equations (5) and (6). At the initial broom density of 0.3 of the area, the final optimal level of biodiversity protection was 81% of the initial number of species, the quantity of recreation was 7,500 group visits, and the value of agriculture was 84% of the potential yield.

A summary of outputs is presented in Table 5, using different initial levels of broom density. High levels of initial broom density lead to low outputs, and low initial levels of broom density lead to high outputs.

The results of Table 5 show that the optimal control applied was always herbicide application, under the present assumptions.

4.2 Sensitivity analysis

Sensitivity analyses were conducted for three parameters, namely, prices of outputs, effectiveness of herbicide application and cost of controls. The summary of these results is presented in Table 6.

Values of outputs. The values of outputs, to be tested, were the benefits of biodiversity and the agricultural gross margin. The value of species in the base result was $100,000. A lower price of $10,000 for biodiversity was used, and the changes in the level of outputs and the optimal control methods were observed. The optimal weed density was now 0.0615, which is a level lower than the base results. On the other hand the optimal control method changed to manual pull, implying that, control methods are also sensitive to biodiversity prices. In addition a higher biodiversity price of $150,000 was used but no changes were seen on the level of weed density or the control method compared to the base results.

The results of agricultural prices did not show any changes from the base results. A lower gross margin of $50 was used but the results had no change. In addition a higher gross margin of $300 was then used but no changes were identified on the final level of weed density or the optimal control method.

Effectiveness of herbicide. The assumption that herbicide application reduced broom density by 60%, was changed to 20%, in order to test the effectiveness of herbicide application. The results showed an increase in the level of the final weed density to 0.1175 implying that with low herbicide effectiveness, a reduction of the weed density is lower than the base results. At the same time, the optimal control method also changed to manual pull, which is now more effective than herbicide application. A higher rate of 80% for herbicide effectiveness was then used and the result showed a decrease in the level of the final weed density to 0.0002, implying that with higher herbicide effectiveness, a reduction of the weed density is much bigger. The results also showed that with higher herbicide effectiveness the optimal control method changed to excluding tourists. Hence both weed density and control methods are sensitive to herbicide effectiveness.

Cost of controls. The effects of both lower and higher costs of herbicide and biological control were tested. A higher herbicide price of $120 per hectare was used, and the results showed an optimal weed density of 0.0994 which is higher than the base result, implying that the weed density has not been reduced as much due to the increase in the cost of herbicide. The optimal control method shifted from herbicide application as shown by the base results to manual pull. A lower price of $2 per hectare was then used, and the results showed no changes on both the level of weed density and the optimal control method compared to the base results. Thus both long-term weed density and optimal control methods are only sensitive to higher herbicide costs.

A lower cost of $20,000 for biological control for the whole area was then used. The result showed a slight fall in the weed density to 0.0715, which left herbicide application as the optimal control method. With a higher cost of $120,000 for biological control, the results showed no changes on both the level of weed density and the optimal control method. Hence weed density is only slightly sensitive to the cost of biological control.

In summary the base results indicates that we should use herbicide throughout to control broom and the weed density will drop to 0.0736 of the area, with the park outputs of 81% for biodiversity protection, 7,500 group visits to the park and 84% of the agricultural potential yield. We are surprised that the results of using a lower value for biodiversity were contrary to the logic that, higher levels of preservation leads to lower levels of weed density and lower levels of preservation leads to higher levels of weed density. Instead our results showed that lower biodiversity price lead to lower levels of weed density.

5. Discussion

This paper has presented an initial application of a basic dynamic programming model for the management of Scotch broom. As shown in Table 6, long-term weed density, optimal control methods and the outputs varied with changes in economic parameters. We now consider extensions to the model that may be appropriate.

(a) Separate applications are needed for different kinds of land, ie. agricultural land, crown reserve land and different parts of the Park according to different density of broom.

(b) The assumption of mutually exclusive control methods will have to be relaxed, to allow combinations of controls to be applied simultaneously. Then, the decision problem can include the question what combinations of controls should be used? Before this can be implemented, it is necessary to determine possible interactions between the control methods.

(c) Another extension is to consider how the effects of control options vary with weed density. We have assumed the effects of control options to be constant, whereas the effects of the control measures may vary with the density of weeds. For example, an expenditure of $10,000 for manual pull in scattered broom might not be effective, but $10,000 in high or medium density broom will be much more effective.

(d) Exogenous variables, which also may be important, have not yet been built into the model. This includes the number of pigs and their effect on broom density, as well as the effect of the number of tourists in spreading broom.

(e) Four state variables are relevant to the problem, but the model only uses one (ie. weed density). This was considered to be the most obvious and relevant one to start with. Is there a need to extend the model to the four state variables? For example, should the size of the seed bank be included in the economic model? Preliminary simulation runs indicated that, because of the large number of seeds produced per broom plant, the seed bank reaches a saturation point very fast and hence the dynamics of the system can be adequately captured by weed density alone. This result may be caused by the nature of the biological model (Rees & Paynter, 1997), which assumes that equilibrium has been reached between state variables. The other two state variables, open sites which are suitable for colonisation and sites unsuitable for colonisation, are less observable for the economic model. They are not included in the state variables at present, but they are used in the simulation model.

(f) Scientists appear to accept that biological control is appropriate for Scotch broom. To model this measure, we would need to include an additional state variable in the model to track changes in the population of the control agents. The interaction between the weed population and the biological control agent would need to be modelled explicitly.

(g) Finally, since the problem of weeds is dynamic and includes uncertainties, the model might well be extended to include stochastic elements.

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Figure 1. The nature of the approach

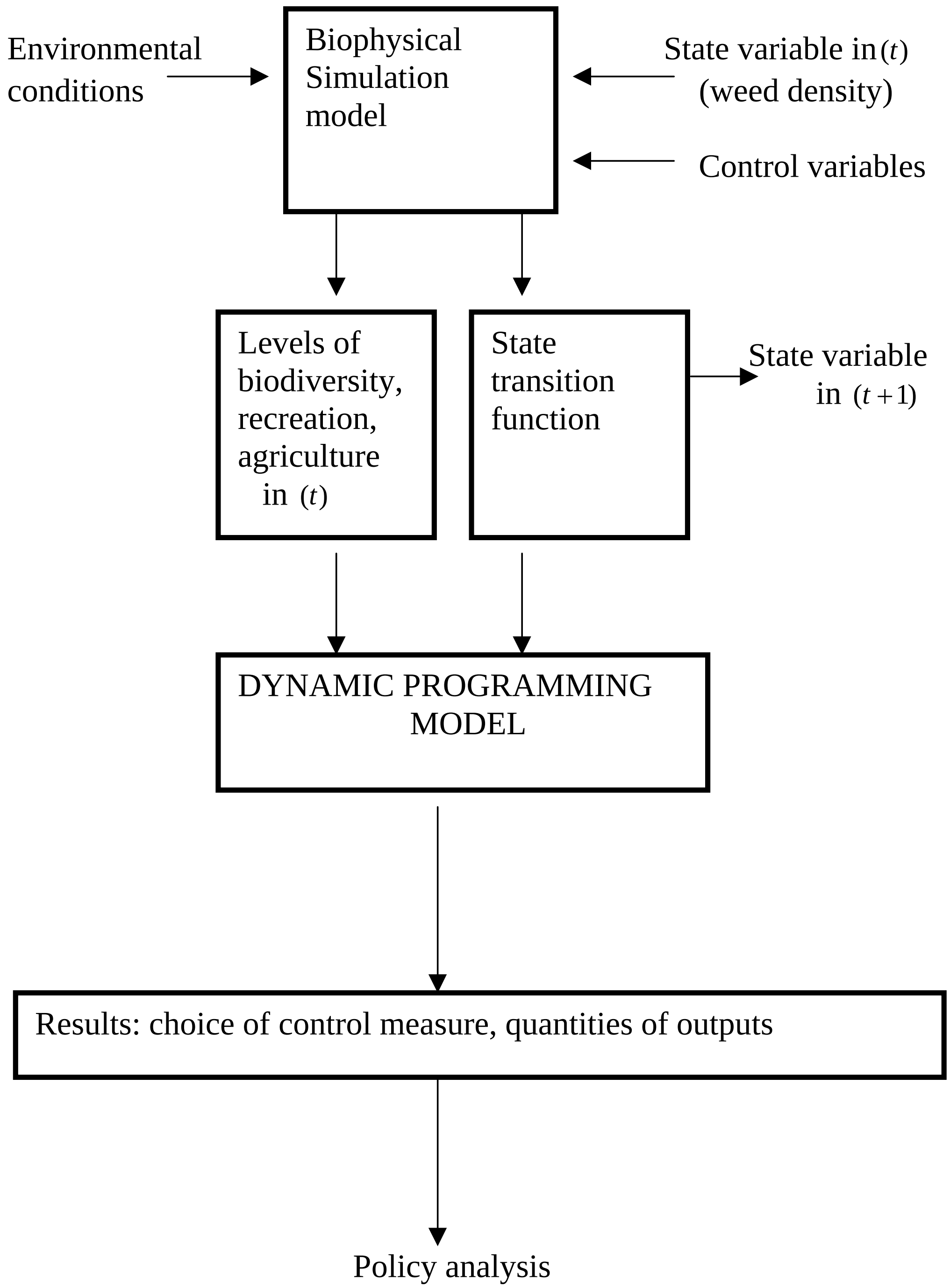


Figure 2. The state transition equation.

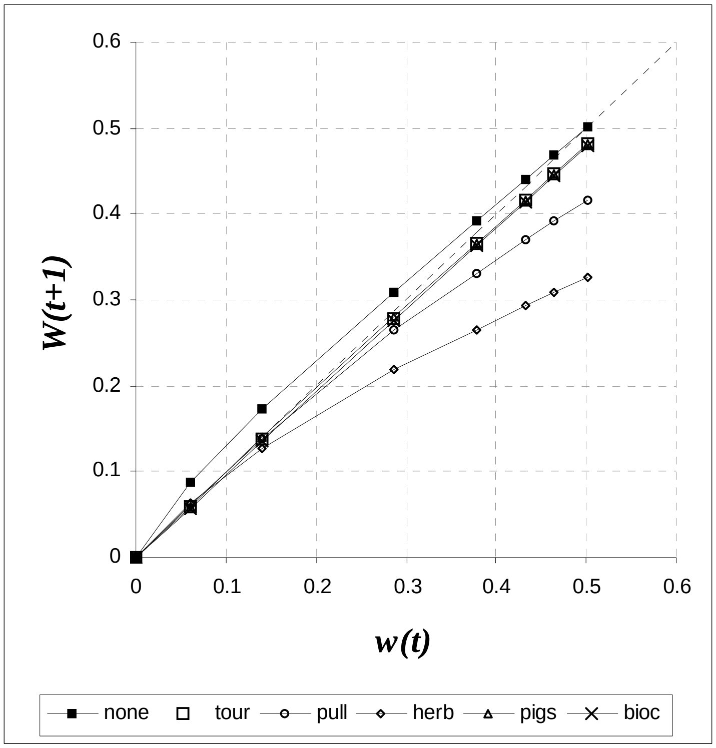
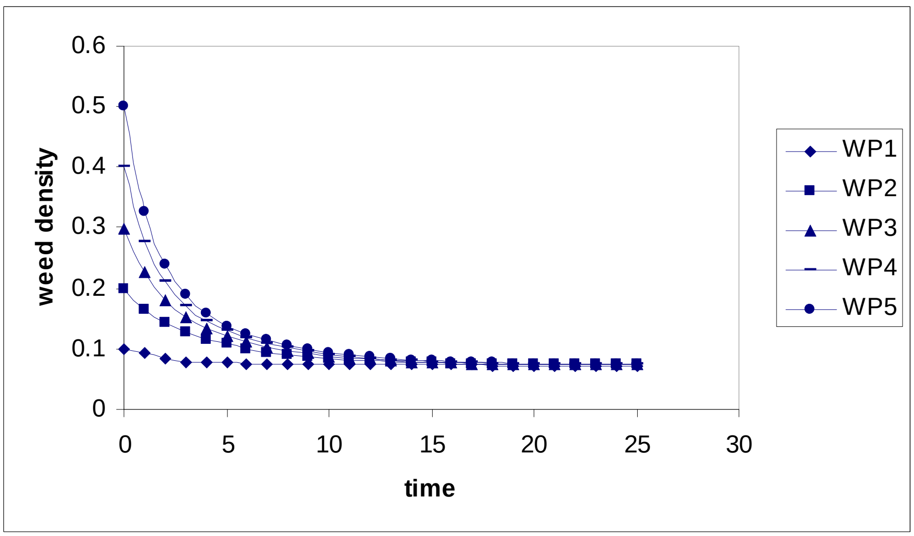


Figure 3. The Long - run Equilibrium



WP = weed density path

Table 1. Biological parameters and their values

Parameter	Value	Description
p_{dist}	0.05	probability that a site is disturbed
p_g	0.03	probability that a seed becomes a seedling
p_s	0.5	probability that a seedling survives the first year
P_d	0.5	probability that a seed is lost from the seedbank (decay)
A_{min}	2	minimum age for reproduction of broom
A_{max}	20	maximum plant age
F	5600	seed production per site (numbers per square metres)
f_h	0.6	probability that seed is retained in the parental site
p_{so}	0.05	probability that site becomes suitable for colonisation after senescence
f_r	0.6	fraction of broom plants that are reproductive

Table 2. Initial conditions of the area

Variable	Fraction
Area occupied by broom	0.125
Sites that are unsuitable for broom	0.4
Sites that are suitable for broom	0.6
Areas open for colonisation*	0.475

*Areas suitable for broom but not yet colonised

Table 3. Economic parameters, to define the relationship between weed density and output

Parameter	Biodiversity	Recreation	Agriculture
υ_j	130	15000	1.2
κ_j	0.18	0.3	-2
η_j	0.6	0.6	0.9
P_j	100,000	138	1,680,000 *

* Agricultural output is measured as percentage of potential yield, the price of this output is estimated by multiplying the gross margin per hectare times the number of hectares in pasture.

Table 4. Economic parameters, control costs

Method	Cost ($/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

Table 5. The base results: Long-term weed densities, Control measures and Outputs

Initial weed density	Long-term weed density	Optimal control*	Outputs**
0.1	0.0729	herbicide	Bio. 96% Rec. 9,375 Agric. 96%
0.2	0.0734	herbicide	Bio. 90% Rec. 8,571 Agric. 90%
0.3	0.0736	herbicide	Bio. 81% Rec. 7,500 Agric. 84%
0.4	0.0738	herbicide	Bio. 68% Rec. 6,000 Agric. 76%
0.5	0.0739	herbicide	Bio. 46% Rec. 3,750 Agric. 66%

* In each year, in each initial weed density, the optimal control was herbicide.

** Bio : Biodiversity, Rec : Recreation, Agric: Agriculture

Table 6. Sensitivity analysis

Sensitivity analysis	Long-term weed density	Optimal control	Outputs [bio, rec, agric]
Base results	0.0736	Herbicide	81%, 7500, 84%
Low value biodiversity	0.0615	Manual pull	97%, 9633, 98%
High value biodiversity	0.0736	Herbicide	97%, 9555, 97%
Low agric. price	0.0736	Herbicide	97%, 9555, 97%
High agric price	0.0736	Herbicide	97%, 9555, 97%
Low herbicide effectiveness	0.1175	Manual pull	95%, 9249, 95%
High herbicide effectiveness	0.0002	Exclude tourist	99%, 9999, 99%
Lower price of herbicide	0.0736	Herbicide	97%, 9555, 97%
Higher price of herbicide	0.0994	Manual pull	96%, 9379, 96%
Lower cost of bio-control	0.0715	Herbicide	97%, 9569, 97%
Higher cost of bio-control	0.0736	Herbicide	97%, 9555, 97%

- The level of output changes with a change in the level of weed density
- where the level of weed density did not change, the same applied to the level of outputs

Appendix 1. The shape of the function and the influence of the parameters