Journal of Applied Ecology 2001
38, 000–000

Using stochastic dynamic programming to determine optimal fire management for *Banksia ornata*

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Summary

1. A model of the population dynamics of *Banksia ornata* was developed, using stochastic dynamic programming (a state-dependent decision-making tool), to determine optimal fire management strategies that incorporate trade-offs between biodiversity conservation and fuel reduction.
2. The modelled population of *B. ornata* was described by its age and density, and was exposed to the risk of unplanned fires and stochastic variation in germination success.
3. For a given population in each year, three management strategies were considered: (i) lighting a prescribed fire; (ii) controlling the incidence of unplanned fire; (iii) doing nothing.
4. The optimal management strategy depended on the state of the *B. ornata* population, with the time since the last fire (age of the population) being the most important variable. Lighting a prescribed fire at an age of less than 30 years was only optimal when the density of seedlings after a fire was low (< 100 plants ha^{-1}) or when there were benefits of maintaining a low fuel load by using more frequent fire.
5. Because the cost of management was assumed to be negligible (relative to the value of the persistence of the population), the do-nothing option was never the optimal strategy, although lighting prescribed fires had only marginal benefits when the mean interval between unplanned fires was less than 20–30 years.

Key-words: conservation, decision theory, disturbance, extinction, wildfire.

Journal of Applied Ecology (2001) **38**, 000–000

Introduction

Land managers are often faced with a dilemma when trying to reconcile the trade-off between burning for fuel reduction and the values of biodiversity (Gill & Bradstock 1994). The occurrence of fire at short intervals helps to reduce the fuel load with benefits for fire suppression, but such a fire regime may threaten plant species that experience a period during which they are not reproductively mature and are killed by fire (Gill & Bradstock 1994; Bradstock *et al.* 1996, 1998). Despite considerable information about the response of species to fire regimes (Hoffman 1998; Russell-Smith *et al.* 1998), there are few scientific studies that offer comparative insight into the consequences of differing strategies of prescribed burning.

Prescriptions for the use of fire for conservation management are usually expressed in terms of the time since the last fire, as illustrated by studies of *Banksia* species in Australia. Gill & McMahon (1986) suggested that the minimum interval between fires in populations of the Australian shrub *B. ornata* should be 16 years to allow the population to replace itself, based on seed production, germination and survival of seedlings. Enright, Lamont & Marsula (1996) used a deterministic model to determine a fire management strategy to maximize the finite rate of population increase of *B. hookeriana*. Burgman & Lamont (1992) used a stochastic simulation model to consider management strategies for minimizing the risk of extinction and maximizing the mean population size of a *B. cuneata* population in the presence of unplanned fires. Similarly, Bradstock *et al.* (1996) used a simulation model to examine how different fire regimes influenced the persistence of a hypothetical serotinous *Banksia* species. These different approaches to determining the effect of fire on

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Banksia species indicate that the populations should be burnt at a particular age, but do not suggest whether the optimal strategy should also depend on other aspects of the population, such as abundance. These studies ignore the possibility that the optimal strategy might depend on the abundance of the species concerned, despite rarity being considered a critical factor in extinction events (Burgman, Ferson & Akçakaya 1993). By using a state-dependent decision-making tool, we can determine whether the optimal management strategy also depends on population size.

If conservation biology is to be a useful science for land managers, it is necessary to develop a range of tools that assist decision-making processes (Possingham & Tuck 1996; Possingham 1996, 1997). One such tool that can help to determine optimal management strategies is stochastic dynamic programming (SDP). SDP has been applied usefully to problems in behavioural ecology (Mangel & Clark 1988), the management of fisheries (Clark 1985; Walters 1986) and has the potential to assist ecological management decisions (Possingham & Tuck 1996; Possingham 1996; Milner-Gulland 1997; Richards, Possingham & Tizard 1999; Shea & Possingham 2000). It is a way of optimizing decisions about managing a stochastic system that may exist in multiple different states, such as an ecosystem.

The purpose of this study was to use SDP to identify optimal fire management strategies for plant populations using *B. ornata* F. Muell. as an example. We also illustrated the use of SDP for reconciling the trade-off between fuel reduction burning and species persistence. *Banksia ornata* was chosen because there are good data on its fire ecology. *Banksia ornata* is a shrub that is relatively common in woodlands and mallee scrubs of south-eastern South Australia and western Victoria. It is a serotinous seeder, with individual plants killed by fire and local persistence dependent on successful germination from the canopy-stored seed bank (Specht, Rayson & Jackman 1958). Thus, *B. ornata* occurs predominantly as even-aged stands, and few if any viable seeds occur in the soil. Individuals do not begin to produce seed until approximately 5 years of age, and they survive for up to approximately 50 years (Gill & McMahon 1986). Populations will become locally extinct if fire does not occur prior to the death of all adult plants, but successive fires at short intervals will also lead to extirpation (local extinction) because the number of seeds produced by young plants is insufficient to regenerate the population. Although *B. ornata* is an abundant species, it is ecologically important and is likely to be indicative of fire management issues for numerous other obligate seeding species (Gill & Bradstock 1995). Gill & McMahon (1986) regarded *B. ornata* as a potentially useful indicator species because it is easily identified, dominant, fire-sensitive and its source of regeneration (seeds) is visible on the plant.

A model of the population dynamics of *B. ornata* was developed, and then used in conjunction with SDP to determine optimal fire management strategies that depended on the abundance and age of the population. The results of the SDP model were then compared with results obtained from age-dependent strategies where fire management was applied regardless of the abundance of the population.

Methods

Use of SDP to determine optimal management strategies requires development of a model of the dynamics of the system, identifying options for management and their effects, and defining the management objective. SDP is then used to identify the optimal management strategy for each state of the system, which in this case is defined by the time since last fire and abundance. Details of these steps are provided below.

THE *BANKSIA ORNATA* MODEL

The structure of the model and data on the life history of *B. ornata* were derived from a study by Gill & McMahon (1986). Based on a linear regression (of logarithmic transformed data), the average number of seeds produced per plant was estimated to be:

$$Y(T) = [-1 + \exp(-0{\cdot}777 + 0{\cdot}365T - 0{\cdot}00393T^{2})]$$

where T is the age of the plant (time since the last fire), and the number of seeds per plant reaches a peak at approximately 46 years (Gill & McMahon 1986).

If it is assumed that approximately one-tenth of these seeds germinate after fire (Gill & McMahon 1986), the number of germinants produced per plant (after fire) is:

$$R(T) = Y(T)/10 \qquad \text{eqn 1}$$

$R(T)$ is the multiplicative change in abundance of *B. ornata* following fire.

The density of *B. ornata* declines approximately geometrically with time in the absence of fire (Gill & McMahon 1986). Based on the data presented by Gill & McMahon (1986), the proportion of plants surviving may be approximated by the equation:

$$S(T) = \exp(-0{\cdot}08T) \qquad \text{eqn 2}$$

with the population size declining at the instantaneous rate of 8% per year in the absence of fire.

Equations 1 and 2 provide the basis for the model of *B. ornata*. The state of the system is described by the density of stems ha^{-1} and their age. However, in this form, there are too many possible states of the system for it to be solved by SDP (up to approximately 24 000 stems ha^{-1} and approximately 50 age classes, assuming that equations 1 and 2 are implemented with annual time steps). The number of possible states was reduced by converting abundance into 20 different geometrically sized classes, plus an additional class to represent extirpation. The model was also composed using 5-year

Table 1. The range of parameter values used in the *Banksia ornata* model. The value in parentheses was used in the standard parameter set

Parameter	Range of values
Mean interval between unplanned fires	10–100 (20)
Coefficient of variation in germination (V)	0·1–0·3 (0·2)
Probability of germination failure (F)	0·01–0·05 (0·02)
Proportional reduction in r due to fire control	0·1–0·9 (0·5)
Relative cost of old vs. young stands	1–4 (1)

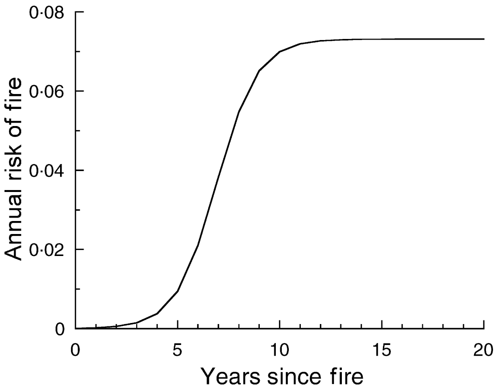

Fig. 1. Age-dependent fire risk model, in which the annual probability of fire is a function of time since fire (T), as defined by the logistic function $r(T) = h/(1 + 1000e^{-T})$. The parameter h is the asymptotic annual probability of fire, which may be modified to change the mean fire interval. In this case, $h = 0{\cdot}0731$, and the mean fire interval is 20 years. In the case of the age-independent fire risk model, $r() = h$, the mean fire 2
interval is equal to $1/h$.

time steps so, at each step in the model, abundance would reduce to exp(−0·4) (= 67%) of its previous density. The greatest abundance was set at 24 000 stems ha^{-1}, and to ensure that abundance changed by one class in the absence of fire, class boundaries were staggered at geometric intervals, 24 000, 16 088, 10 784, etc., down to 8. Thus, the smallest age class was a density of less than 8 plants ha^{-1}, which, for the sake of this model, was assumed equivalent to extirpation (quasi-extinction at the local scale). Therefore, changes in abundance in the absence of fire simply involved moving to the next lower abundance class in each 5-year time step. However, to reflect higher mortality of older stems (Gill & McMahon 1986), abundance declined by two classes in each time step when plants were more than 30 years old, and by three classes when plants were more than 40 years old. It was assumed that all remaining plants died when they exceeded 55 years of age, because this appears to be the maximum age (Gill & McMahon 1986).

The mean number of plants germinating after fire was obtained by multiplying equation 1 by the number of plants present. It was assumed that the age of the plants in each age class was equal to the mid-point of each class (2 for 0–4 years, 7 for 5–9 years, etc.). Similarly, it was assumed that the abundance of the plants in each class was equal to the geometric mid-point of each class (e.g. 19 650 ha^{-1} for the 16 088–24 000 abundance class). To reflect stochasticity in germination success (Specht 1981), abundance after fire was drawn from a normal distribution with a specified coefficient of variation, V (Table 1), and ascribed to the appropriate abundance class. Additionally, the occurrence of frost or drought may kill all germinants (Bradstock &
1 Bedward 1992; Burgman & Lamont 1992), and the probability of such an event is F.

MANAGEMENT OPTIONS AND THE SDP FORMULATION

Three different management strategies were considered: (i) prevention and suppression of unplanned fires; (ii) lighting a prescribed fire; and (iii) doing nothing. One of these options was optimal in each time step, depending on the state of the system. It was assumed that the *B. ornata* population was exposed to a constant annual risk of fire (r), which was reduced by protection and suppression of unplanned fires. This assumption is unlikely to be true because reduced fuel loads immediately after a fire will limit the chance of fire spread. In areas where *B. ornata* occurs, fires will rarely if ever spread 1 year after a fire, but have been observed 4 years after a fire, and are likely to spread readily 10 years after fire (P. Billing, Department of Natural Resources and Environment, personal communication). To reflect this, we also conducted analyses in which the annual probability of fire was defined by a logistic function of time since the last fire (Fig. 1; McCarthy, Gill & Bradstock,
in press). It was assumed that, for a given abundance 3
and age, all fires had the same effect on the number of germinating *B. ornata* regardless of the fire's cause, and that the risk of fire was not influenced by population density.

The biodiversity benefit of *B. ornata* stands remaining extant was reflected in the SDP solution by assigning one point for each year of persistence over the next 100 years. Persistence was chosen instead of abundance because the actual population size is highly variable over time. In Australia, prescribed fire is used predominantly to help control the occurrence of unplanned fires, rather than for biodiversity benefits. To reflect a management preference for lower fuel loads, a cost was incorporated into the SDP solution that depended on stand age. It was assumed that this cost was proportional to the annual probability of fire (Fig. 1; Moore 1990), with a maximum cost of four points per period for the oldest stand. This choice was arbitrary, and is used only for illustrative purposes. The true cost will depend on local circumstances, such as distance to human assets, ease of access and other factors relevant to fire management. It would also be possible to specify a separate cost for each management strategy, but for simplicity we used a single universal value. Thus, the actual benefit ($B[i,j]$ in equation A1) depended on the persistence, and in some cases age, of the *B. ornata* stand.

SDP was used to determine the optimal management strategy for each state of the system (Intriligator 1971; Mangel & Clark 1988). The objective was to find the state-dependent strategy that maximized the number of years that *B. ornata* persisted in the next century while accounting for the increased value of younger stands for fire management purposes. The strategy is called state-dependent because SDP finds the best strategy for each state (abundance and age combination) of the *B. ornata* population. The optimal management strategy for each state of the population is found by working backwards in time, from some terminal time in the future, assuming that later decisions are always optimal. Details of the construction and solution of the *B. ornata* SDP are provided in the Appendix.

The optimal management strategy was determined for a range of parameter values for the mean interval between unplanned fires, probability of outright germination failure (F), coefficient of variation in germination success (V), effects of fire control, and relative values of stands of different ages (Table 1). This was done to test the robustness of the result by determining if the optimal strategy was sensitive to variations in the parameter values.

AGE-DEPENDENT STRATEGIES

To examine the importance of considering state-dependent strategies, we compared the persistence of the population managed under the state-dependent SDP solution, with that managed under three strategies that depended only on the age of the population. Results were obtained when we assumed that the annual probability of fire increased with time since fire (Fig. 1), and also when we assumed that the probability was constant. The first age-dependent strategy was the one that maximized the population growth rate of a deterministic model (following Enright, Lamont & Marsula 1996). The population growth rate for *B. ornata* may be obtained by multiplying equations 1 and 2, and taking the Tth root (where T is the age of the plants):

$$\lambda = [S(T) \times R(T)]^{1/T}$$

This equation is maximized when T is 28 years, implying the optimal strategy is to burn when the population is 28 years old. Two other age-dependent strategies were considered: (i) burning the population with a prescribed fire at 16 years of age (Gill & McMahon 1986); and (ii) not using prescribed burning.

Results

THE OPTIMAL STRATEGY

In the face of unplanned fires and the risk of germination failure, the optimal strategy for *B. ornata* persistence requires that prescribed burns be delayed beyond 30 years, unless the population density is low (Fig. 2). In general, prescribed fires are optimal when the population is small and destined for extirpation in the next time step, or it is old (> 40–45 years) and recruitment rates are about to decline (Fig. 2). The strategy was relatively insensitive to the probability of unplanned fires, the risk of germination failure, the coefficient of variation in germination or changes in the efficacy of fire control. When the annual probability of fire increased with time since fire (Fig. 1), there was only a small change in the optimal management strategy. With the assumption that costs of management are negligible relative to the costs of extirpation of *B. ornata*, the SDP model predicted the do-nothing management strategy was never optimal, with either fire suppression or lighting fires being the preferred strategy. When benefits of maintaining *B. ornata* stands in a younger state were included, the optimal strategy was to use prescribed fires more frequently, provided that the density of plants was high (Fig. 2), although this would reduce the probability of persistence.

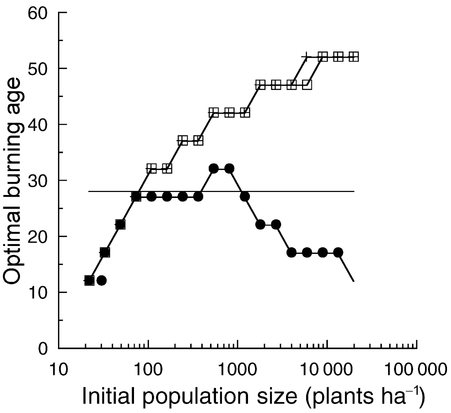

Fig. 2. Optimal age of burning to maximize the persistence of the modelled *Banksia ornata* population as a function of population density following the last fire for different assumptions: +, constant probability of fire; ?, probability of fire increases with stand age (Fig. 1); ?, fuel reduction benefits of young stands are preferred to older stands. The horizontal line represents the strategy of maximizing the population growth rate.

POPULATION PERSISTENCE

When using prescribed fire, the probability of persistence over the next 100 years was maximized when the mean fire interval between unplanned fires was long (Fig. 3). The probability of persistence when the population was burnt at 28 years of age was only slightly less than that under the optimal strategy. Burning at a younger age of 16 years caused a further small reduction in the probability of persistence (Fig. 3). Equivalent results were obtained when the annual probability of fire depended on stand age, although the probability of persistence was greater due to the reduced chance of fires occurring when the abundance of seeds was

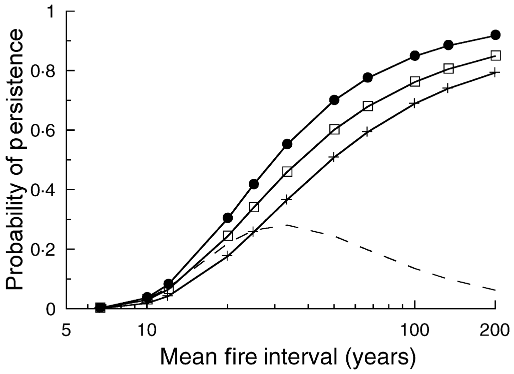

Fig. 3. The probability of persistence of a *Banksia ornata* population for the next 100 years under different management strategies vs. the mean interval between unplanned fires, assuming the annual probability of unplanned fire is constant. The management strategies are: the SDP solution (?); burning at 28 years of age (?); burning at 16 years of age (+); not lighting prescribed fires (dashed line).

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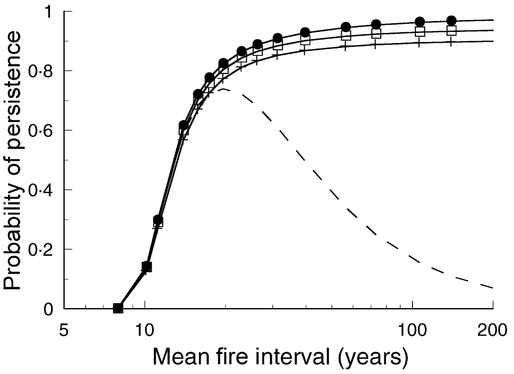

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Fig. 4. The probability of persistence of a *Banksia ornata* population for the next 100 years under different management strategies vs. the mean interval between unplanned fires, assuming the annual probability of unplanned fire increases with stand age (Fig. 1). The management strategies are: the SDP solution (?); burning at 28 years of age (?); burning at 16 years of age (+); not lighting prescribed fires (dashed line).

low (Fig. 4). In the absence of management, the probability of persistence was maximized when the mean fire interval was approximately 20–30 years (Figs 3 and 4).

Discussion

The method used in this paper determined the optimal fire management strategy for *B. ornata* by maximizing the expected number of years during which the species would persist in the next century. Other authors have attempted to determine optimal fire regimes of *Banksia* species using different methods and with different objectives. Enright, Lamont & Marsula (1996) estimated the optimal fire frequency for *B. hookeriana*, a serotinous fire-killed shrub of western Australia, by determining the fire interval that maximized the finite rate of population increase. Focusing on the finite rate of population increase ignores risks associated with prescribed fires, such as the chance of germination failure after a fire or the chance of a subsequent fire killing immature plants. When risks are appreciable, the optimal management strategy is to attempt to burn the population as infrequently as possible but before the plants senesce and density becomes low (Fig. 2). The optimal age of burning varied between 12 and 52 years depending on abundance (Fig. 2). However, the influence of considering population size was small compared with the influence of considering population age (Figs 3 and 4), suggesting that the age of the population rather than abundance was the most important management variable for *B. ornata*. Nevertheless, changing from an age-dependent strategy to one based on age and abundance (the SDP solution in Figs 3 and 4) could lead to an approximate halving of the 100-year extinction risk (Figs 3 and 4).

Burgman & Lamont (1992) considered the efficacy of a number of different management strategies with a stochastic simulation model of *B. cuneata*. They determined that burning the population increased the risk of extinction, but it was not clear whether this recommendation may change depending on the population size. The size of the state space meant that an optimal state-dependent strategy could not be determined from their simulations. The results of our SDP model of *B. ornata* suggested that population size was less important than time since fire, although this may not be true for less abundant species such as *B. cuneata*, which may be exposed to greater stochasticity associated with small population size. SDP has the advantage over these other methods by incorporating stochasticity in the model while at the same time considering the state of the system. SDP also finds the true optimum with numerical methods, while simulation models require exhaustive analysis of all possible management regimes. However, current limitations of most computers mean that only a few thousand different states can be considered within an SDP model, often requiring somewhat simplified descriptions of population dynamics like those presented here.

The optimal strategy for the persistence of *B. ornata* is to burn the population at moderately regular intervals. However, to better mimic natural disturbance regimes and to promote ecosystem heterogeneity and diversity, several authors have argued that prescribed disturbances should have a random component (Keith & Bradstock 1994; McCarthy & Burgman 1995; Morrison *et al.* 1995). Richards, Possingham & Tizard (1999) used SDP to determine the optimal fire management strategy to retain a diversity of different successional states across a mosaic of patches. In such cases, although the mean interval is the same for all parts of the landscape, a diversity of fire intervals was required, with the prescription depending on the proportion of the area in early, mid- and late successional states.

In the solutions where younger stands of *B. ornata* were preferred to older stands (Fig. 2), the benefit of having young *B. ornata* was five times that of having old *B. ornata.* This suggests a very strong preference for younger stands at the expense of a higher risk of local extinction. The values we used were for illustrative purposes, and the exact values would depend on management priorities. In areas close to human assets, the relative benefit of young stands may be quite large. In more remote areas, the benefit may be negligible. Nevertheless, the *B. ornata* example illustrates how to consider the trade-offs between fuel reduction burning, control of unplanned fires and biodiversity conservation. It emphasizes that, as we do not have perfect control of fires, it is important to consider the effects of such unplanned events when making management decisions. In our example, costs of lighting and fighting fires were greatly simplified, but extra detail could be readily incorporated if the costs could be expressed in terms of the local persistence of the species. In the case of an endangered species, these relative costs are likely to be small and may have little influence on the results. However, for a common species like *B. ornata*, including management costs may mean that the do-nothing option is optimal for certain states of the population, especially in cases where the relative benefits of the two active management strategies (light a prescribed fire or control fires) are small.

Our model of *B. ornata* considered only a single population, ignoring dispersal of seeds between areas. The model predicts that a single population is destined for extinction in the presence of unplanned fire because a fire will eventually occur during its juvenile period. In reality, such local extinction events are usually balanced by dispersal of seeds into unoccupied areas. Such colonization events will buffer the species from global extinction. Including this feature would improve the realism of the model and might be included by using a metapopulation model or some other representation of space (Husband & Barret 1996; Bradstock *et al.* 1996, 1998; McCarthy, Gill & Lindenmayer 1999). Such spatial considerations may influence the optimal management strategy because the risk of unplanned fires may be greatly reduced by burning only a portion of the area.

We caution against the use of the present results as a recipe for management. Our results should be considered to be indicative and illustrative only at this stage. In particular, the strategy of burning relatively young (but reproductively mature) populations when densities are low depends on the exact density at which local extinction is deemed to occur, and the rate of decline in abundance of the plants. Slower rates of decline to local extinction, perhaps due to density-dependent effects on mortality, would result in an older optimal age of burning for these stands.

SDP is a new technique in a growing toolkit of methods that includes expert systems (Walker, Davies & Gill 1985), demographic prediction based on fire interval (Bradstock & O'Connell 1988), decision support systems based on monitoring of plant communities (Gill & Nicholls 1989), and methods based on stochastic interval distributions of fires considered concurrently with life-history characteristics of species (Gill & McCarthy 1998). The SDP model developed here explicitly considers population size and disturbance probability while implicitly considering the stochastic effects on other life-history processes. It differs from all other methods in optimizing management outcomes by being able to choose between projected pathways of the population in order to maximize the persistence of the species.

The SDP solution of the *B. ornata* model indicated that the optimal management strategy is state-dependent, with the most important state variable being the age of the population. Thus, optimal management requires that the state of the system be monitored if appropriate fire regimes are to be prescribed.

Acknowledgements

This work was conducted as part of the Managing Uncertainty Working Group supported by the National Center for Ecological Analysis and Synthesis and while H.P. Possingham was a Sabbatical Fellow at the Center, which is funded by the NSF (grant number DEB-94-21535), The University of California-Santa Barbara, the California Resources Agency, and the California Environmental Protection Agency. We thank the other members of the Working Group (Tim Coulson, E.J. Milner-Gulland, Katriona Shea and Chris Wilcox), Shane Richards and Andrew Moore for comments that improved the manuscript. We thank Peter Billing for information on the flammability of *Banksia ornata* populations of different ages.

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Received 1 March 2000; revision received 8 January 2001

Appendix

This appendix provides details of the *Banksia ornata* model and the stochastic dynamic programming (SDP) solution of the optimal management strategy.

THE BANKSIA ORNATA MODEL

For each of the management strategies, the probability of moving between different states of the system was determined. Let $p_m[i, j][k, l]$ be the probability of moving from a population of age class i and abundance class j, to age class k and abundance class l, under management strategy m. The number of age classes was equal to 11 and the number of abundance classes was equal to 20.

If a prescribed burn is used, the probability of moving to the zero abundance class (extinction) and 16 the zero age class is:

$$p_p[i, j][0, 0] = F + (1 - F) \times N(-(E_0, R(i \times 5 + 2) \times A_j(V)$$

where F is the probability of germination failure, and $N(a, b, c, V)$ is the cumulative probability between the limits a and b of a normal distribution with mean c and coefficient of variation V. E_l is the upper limit of abundance class l, A_j is the geometric mid-point of abundance class j, and $R(T)$ is as defined in equation 1. The other transition probabilities are equal to:

$$p_p[i,j][0, l] = (1 - F) \times N(E_{l-1}, E_l, R(i \times 5 + 2) \times A_j(V), \quad 0 < l < 20$$

$$p_p[i, j][0, 20] = (1 - F) \times N(E_{19} (R(i \times 5 + 2) \times A_j(V)$$

with all other values of p_p being zero.

Under the do-nothing management strategy, fires occur annually with probability r_a, which may be a function of the age of the population (a). In a 5-year period, the probability of fire is equal to:

$$1 - \prod_{k=5i} (1 - r_k).$$

Thus, the transitions considered above occur with probability:

$$[1 - (1 - r_k)], \text{ so } p_n[i, j][0, 0] = [1 - (1 - r_k)] \times [F + (1 - F) \times N(-(E_0, R(i \times 5 + 2) \times A_j(V)]$$

$$p_n[i, j][0, l] = [1 - (1 - r_k)] \times (1 - F) \times N(E_{l-1}, E_l, R(i \text{‘} \times 5 + 2) \times A_j(V), \quad 0 < l < 20$$

$$p_n[i, j][0, 20] = [1 - ((1 - r_k)] \times (1 - F) \times N(E_{19} (R(i \times 5 + 2) \times A_j(V)$$

If fires do not occur, then the age class increases by 1 and the abundance class declines. Thus:

$$p_n[i, j][i + 1, j - 1] = (1 - r_k), \quad 0 < i < 6$$

$$p_n[i, j][i + 1, j - 2] = (1 - r_k), \quad 5 < i < 8$$

$$p_n[i, j][i + 1, j - 3] = (1 - r_k), \quad 7 < i < 10$$

$$p_n[i, j][i, 0] = (1 - r_k), \quad i = 10$$

with limits imposed to ensure that the smallest abundance class reached is 0. Other transition probabilities are equal to zero. Thus, extinction occurs when populations are 60 years old.

The transition probabilities in the presence of fire control (prevention and suppression) p_c are identical to the do-nothing probabilities p_n except that the probability of fire in each 5-year period is equal to $[1 - (1 - sr_k)]$, where s represents the effect of fire prevention and suppression on the annual probability of fire.

THE SDP SOLUTION

The above transition probabilities for the three different management strategies fully define the probability of movement from one state of the system to another under a given management regime. SDP was used to determine the optimal strategy for each state of the system. Details of SDP are provided by Intriligator (1971) 17 and Mangel & Clark (1988). Below is a description of the SDP algorithm used in this study. Let $B[k, l]$ be the value of the system being in age class k and abundance class l, the benefit of remaining extant minus the cost associated with stand age. In this paper, $B[k, l]$ was equal to 5 for non-extinct stands, minus any age-dependent costs that were proportional to the risk of fire (Fig. 1). It was assumed that extinct stands had a value of zero, $B[k, 0] = 0$. To obtain the SDP solution, a terminal time in the future, representing the time frame of management concern, must be established, which in this example was 100 years or $T = 20$ time steps. The time-dependent value of the system was defined as $J[k, l, t]$. At the terminal time, $J[k, l, T] = B[k, l]$. For each of the management strategies, we determine the value of J_m, the value of the system when implementing management strategy m in the preceding time step, accounting for the transition probabilities:

$$J_m[i, j, t - 1] = B[i, j] + (_{k,l} (p_m[i, j][k, l] J[k, l, t]) \qquad \text{eqn Al}$$

where the summation is over all values of k and l. The optimal management strategy at time $t - 1$ when in age class i and abundance class j is the one that maximizes $J_m[i, j, t - 1]$. For each i and j, the maximum $J_m[i, j, t - 1]$ is set to $J[i, j, t - 1]$. This process (equation Al) is repeated for each time step from the terminal time until the present, and the optimal strategy for each state of the system (i, j) is determined until time t = 0.

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