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OPTIMAL FIRE MANAGEMENT FOR MAINTAINING COMMUNITY DIVERSITY

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Abstract. Disturbance events strongly influence the dynamics of plant and animal populations within nature reserves. Although many models predict the patterns of succession following a disturbance event, it is often unclear how these models can be used to help make management decisions about disturbances. In this paper we consider the problem of managing fire in Ngarkat Conservation Park (CP), South Australia, Australia. We present a mathematical model of community succession following a fire disturbance event. Ngarkat CP is a key habitat for several nationally rare and threatened species of birds, and because these species prefer different successional communities, we assume that the primary management objective is to maintain community diversity within the park. More specifically, the aim of management is to keep at least a certain fraction of the park, (e.g., 20%), in each of three successional stages. We assume that each year a manager may do one of the following: let wildfires burn unhindered, fight wildfires, or perform controlled burns. We apply stochastic dynamic programming to identify which of these three strategies is optimal, i.e., the one most likely to promote community diversity. Model results indicate that the optimal management strategy depends on the current state of the park, the cost associated with each strategy, and the time frame over which the manager has set his/her goal.

Key words: Australia; biodiversity conservation; community succession; decision theory; disturbance events, stochastic; fire; management model; managing wildfire to promote biodiversity; Markov model; modeling disturbance events; stochastic dynamic programming; succession.

INTRODUCTION

The spatial and temporal dynamics of communities are often strongly influenced by one or more types of disturbance event (Sousa 1984, Pickett and White 1985). A disturbance is an event that may, directly or indirectly, disrupt a community and change resource availability (Pickett and White 1985). The event may be abiotic (e.g., fire, frost, flood, severe wave action) or biological (e.g., predation, disease). The pattern of succession following a disturbance is dependent on the disturbance regime. Common descriptors of a disturbance regime include the characteristic size, shape, intensity, season, and frequency of the disturbance (Gill 1981, Sousa 1984, Pickett and White 1985). The pattern of succession is also dependent on other factors, such as the state of the community before the disturbance event, the life-history properties of species at or near the site prior to disturbance, and post-disturbance environmental conditions. Disturbances that occur frequently may favor early-successional species while an absence of disturbance may favor late-successional species. Also, disturbances of larger areal extent may favor early-successional over late-successional species (Miller 1982).

For any area there will be a disturbance regime that minimizes biodiversity losses. Managers of nature reserves have some degree of control or influence over disturbances (e.g., managers may suppress fires or initiate prescribed burns); hence, it is important that management decisions that influence disturbances are well planned (Frankel et al. 1995) and their potential impacts on the population dynamics of threatened species are identified.

If managers of nature reserves are to make effective and efficient management decisions then there must be well-defined management objectives. These objectives may be either short or long term. One objective may be to provide conditions that maximize the chance of long-term persistence of rare or locally threatened species (Good 1981). When different species prefer different successional communities we need to ensure that at any time the reserve is community diverse, i.e., it contains a mosaic of successional states each of sufficient area to support the successional-specific species. Often a manager must choose among a variety of management strategies, each associated with different costs and resource requirements, and each having a different short- and long-term likelihood of success. Ecological theories may identify which strategies may be useful at achieving an objective, but a manager is still faced with the problem of deciding which is the best strategy, given the constraints of time and money. To assist managers we need to merge ecological theory into a de-

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cision-making framework so that managers can make the best strategic decision, given the latest knowledge on the state of the system of interest (Maguire et al. 1987, Possingham and Tuck 1996, Possingham 1997). It is important to note that a single strategy may not always be the best for achieving a management objective; the best strategy may change as the state of the system changes.

In this paper we show how a mathematical model of succession and disturbance can be incorporated into a decision-making framework. To achieve this, the management objective must be explicitly defined and expressed in the context of the model. It is also important to define a list of management strategies available to the manager, along with their effects on the disturbance regime and their relative costs. To illustrate the approach, we consider the problem of managing fire within Ngarkat Conservation Park (CP), South Australia, Australia.

Ngarkat CP is an example of a nature reserve where the fire regime plays an important role in governing community diversity (Specht et al. 1958, Symon 1982, Forward 1996). The park is located 200 km southeast of Adelaide, South Australia, and covers $\sim 270 \times 10^3$ ha. At the broad level, two vegetation associations dominate the park: eucalypt open scrub (mallee), and open heath of sclerophyllous shrubs. The Department of Environment and Natural Resources and the Department of Housing and Urban Development have documented the fire history of Ngarkat CP since the 1940s. Almost every part of the park has been burnt by wildfire in the last 55 yr and some areas have been burnt 5 times during this period (Forward 1996). Many of the wildfires were <20 ha in size but a few were estimated to be $>50 \times 10^3$ ha (20% of the park). The result of these fires has been a continually changing mosaic of vegetation successional states within the park.

In this paper we investigate the problem of deciding when wildfires within Ngarkat CP should be fought and when prescribed burns should be implemented, given that the management objective is to promote community diversity within the park. We assume that habitat can be classified as being in one of three successional states, which we call ''early, middle, and late successional.'' Maintaining a range of successional states in the park is important because Ngarkat CP contains key habitat for several nationally rare and threatened bird species (Garnett 1993). Four species of particular conservation concern are the Slender-billed Thornbill (*Acanthiza iredalei hedleyi*), the Mallee Emu-Wren (*Stipiturus mallee*), the Red-lored Whistler (*Pachycephala rufogularis*), and the Malleefowl (*Leipoa ocellata*). The Slender-billed Thornbill and Mallee Emu-Wren appear to favor vegetation that is recovering from fire; however as the vegetation becomes taller and denser (10–30 yr after fire) their abundance decreases, whereas the abundance of Red-lored Whistlers generally increases (Garnett 1993, Woinarski and Recher 1997). The Malleefowl prefers older vegetation (>30 yr), where mallees are tall and the understory is relatively open (Garnett 1993); hence, any management decision about fire should consider the successional preferences of all four species.

''Wildfires,'' defined as ''fires that are not prescribed,'' may be modeled as a stochastic event. Often, a reserve manager cannot predict with high certainty when or where wildfires will occur, or their subsequent size. However, managers can reduce the chance of wildfires (e.g., placing fire bans), and managers can suppress the spread of wildfires by creating firebreaks and active fire fighting. Fire is an effective management tool to manipulate vegetation (Gill 1977). Low-intensity prescribed burning is often used to reduce fuel buildup in an attempt to reduce the intensity and size of subsequent wildfires. Such burning is controversial (Gill 1977, Good 1981) because it can dramatically alter the community structure of a reserve (Frankel et al. 1995). The purpose of this paper is to show how a mathematical model can be used to help managers determine if the current fire regime is sufficient for promoting community diversity within a reserve, and, if it is not, what management strategies will alter the fire regime so that community diversity is most likely to be achieved. In this paper, the term ''optimal management strategy'' refers to the strategy, from the set of strategies available to a manager, that when implemented will most likely achieve the management objective.

The optimal management strategy is obtained using stochastic dynamic programming (SDP) (Intriligator 1971, Mangel and Clark 1988). The objective of SDP is to find a state-dependent strategy that will maximize some well-defined objective. The strategy is called ''state-dependent'' because SDP generates the best strategy for each state of the system. In our example, the state of the system is the proportion of the park in each of the three successional states. This state is assumed to change at discrete time intervals in a stochastic and Markovian fashion. The effect of implementing a management strategy may not be known with certainty, as the vegetation in the park may subsequently move to one of a number of possible states. The optimal management strategy for each state of the park is found by working backwards in time, from some terminal time in the future, assuming that later decisions are always made optimally.

SDP has been applied extensively to problems in behavioral ecology, and it has helped aid our understanding of the following processes: foraging, migration, and reproduction (Mangel and Clark 1988). It has also been applied to the management of fisheries (Clark 1985, Walters 1986). Its potential as a powerful tool for aiding management decision making with regard to nature conservation has been recently recognized by

Possingham (1996), Possingham and Tuck (1996), and Milner-Gulland (1997).

Markovian Model of Community Succession

There are many examples of community-succession Markovian models in the literature, dating back to Horn (1975). To create such a model we first need to define the set of states the reserve may be in at any time. This set of states is referred to as the ''state space.'' Next, we need to calculate the probability the reserve moves from one state to another during a yearly time interval. This will be done first for the case when there are assumed to be no fires in the park. The model will then be modified to allow for fire events.

Suppose the nature reserve is divided into N equal-sized sites. Each site is classified into one of three states that we call early, middle, or late successional, and reflects the successional state of the vegetation within the site. The state of the reserve is described by the number of sites in each of the three successional states. The number of possible states that the reserve may be in is denoted by S and is

$$S = \frac{1}{2}(N + 1)(N + 2). \tag{1}$$

The number of early, middle, and late sites present when the reserve is in state i are denoted e_i, m_i and l_i, respectively, and hence $e_i + m_i + l_i = N$. The ith state of the reserve is denoted (e_i, m_i, l_i).

State transitions in the absence of fire

It is assumed that when the reserve experiences a fire, each site can be considered to be either burnt or unburnt. Burnt sites always revert to an early successional state regardless of their successional state immediately prior to the fire. Assume it takes on average T_e years after a fire disturbance for an early successional site to become a mid-successional site, and on average another T_m years for such a site to become a late-successional site (assuming the site is not burnt by another fire). The model tracks the state of the reserve using yearly time steps. The probability that during the following year a site that was early successional becomes a mid-successional site is denoted by s_e, and the probability a mid-successional site becomes a late-successional site is denoted s_m. These transition probabilities are

$$\begin{aligned} s_e &= 1/T_e \\ s_m &= 1/T_m. \end{aligned} \tag{2}$$

The probability that the reserve has p early sites next year, given that it contained q last year (assuming no fires occur during the year), is the probability that $q - p$ early sites become mid sites:

$$E(p\,|\,q) = \begin{cases} \dbinom{q}{q - p} s_e^{q-p}(1 - s_e)^p & \text{if } p \le q \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

If q of the reserve sites are classified as mid-successional at the start of the year, then the probability that at start of the following year, p of them are still classified as mid-successional (i.e., precisely $(q - p)$ become late successional) is

$$M(p\,|\,q) = \begin{cases} \dbinom{q}{q - p} s_m^{q-p}(1 - s_m)^p & \text{if } p \le q \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

Assuming for the moment that no fires occur, the probability the park moves from state j to state i due to succession during the year, denoted $S_{i,j}$, is the probability that e_i of the e_j early sites stay early, and $(l_i - l_j)$ of the m_j middle sites become late sites, i.e.,

$$S_{i,j} = \begin{cases} E(e_i\,|\,e_j)M(m_j - (l_i - l_j)\,|\,m_j) \\ \quad \text{if } e_j \ge e_i \quad \text{and} \quad l_j \le l_i \le l_j + m_j \\ 0 \quad \text{otherwise.} \end{cases} \tag{5}$$

The elements $S_{i,j}$ form the succession matrix $\mathbf{S}$.

State transitions with fire

When modeling fire events we need to make assumptions about how fires ignite and how they spread. Two models often used in studies of fire frequency are (a) the probability a site burns is constant in time, or (b) the probability a site burns is dependent on the time since the last fire at the site (Johnson and Gutsell 1994). We now describe how these two models may be incorporated into our model of community succession.

First we assume that, given a fire has occurred within the reserve, it is equally likely to be in a site regardless of its successional state. We use the term ''fire hazard'' to refer to the probability a site experiences a wildfire each year (Johnson and Gutsell 1994). Let f_n be the probability that n of the N sites within the reserve experience a wildfire each year. Later, we will estimate the distribution, f_n, from park records of the spatial extent of each wildfire in Ngarkat Conservation Park (Australia). In this model the fire regime is completely described by the distribution, f_n. Note that if all sites are treated as though they burn independently of each other, then f_n will be described by a binomial distribution. An assumption of independence may be unrealistic because fire is a spatially contagious process. Given the assumption of equal fire hazard among sites, it can be shown that the probability of the park moving from state j to state i as a result of wildfire is

$$F_{i,j} = \begin{cases} \displaystyle\sum_{n=m+l}^{e_i} f_n \frac{\binom{e_j}{n-(m+l)}\binom{m_j}{m}\binom{l_j}{l}}{\binom{N}{n}} \\ \quad \text{if } m_j \geq m_i \text{ and } l_j \geq l_i \\ 0 \quad \text{otherwise,} \end{cases} \tag{6}$$

where

$$m = m_j - m_i,$$

$$l = l_j - l_i.$$

Eq. 6 can be interpreted as follows. For the reserve to move from state j to state i we know that precisely m middle sites, precisely l late sites, and between 0 and e_j early sites were hit by fire. The probability of each of these events occurring is reflected by the summation term in Eq. 6. The elements $F_{i,j}$ form the fire matrix $\mathbf{F}$.

Alternatively, we can assume the fire hazard of a site is dependent on the time since the last fire at the site (Johnson and Gutsell 1994). Let the probability that early, middle, and late successional sites experience a wildfire each year be denoted f_e, f_m, and f_l, respectively. Now, the probability that each year the park moves from state j to state i as a result of wildfire is

$$F_{i,j} = \begin{cases} \displaystyle\sum_{n=m+l}^{e_i} \left\{ \binom{e_j}{n-m-l} f_e^{n-m-l}(1-f_e)^{e_j-n+m+l} \right. \\ \quad \left. \times \binom{m_j}{m} f_m^m (1-f_m)^{m_i} \binom{l_j}{l} f_l^l (1-f_l)^{l_i} \right\} \\ \quad \text{if } m_j \geq m_i \quad \text{and} \quad l_j \geq l_i \\ 0 \quad \text{otherwise.} \end{cases} \tag{7}$$

Eq. 7 can be interpreted in a manner similar to Eq. 6. Note, in this model the probability that n of the N sites burn each year is now dependent on the state of the reserve. Eq. 7 still treats sites as though they burn independently of each other in a spatial sense. This implicit assumption is a restriction of this model.

Let the probability the reserve is in state i in year t be denoted $P_{i,t}$. The probabilities associated with each state of the reserve are described by the vector $\mathbf{P}_t$ and yearly transitions of probabilities can be calculated from the succession matrix, $\mathbf{S}$, and the fire matrix, $\mathbf{F}$, using

$$\mathbf{P}_{t+1} = \mathbf{T}\mathbf{P}_t \tag{8}$$

where

$$\mathbf{T} = \mathbf{F}\mathbf{S} \tag{9}$$

is the transition matrix. The elements of this matrix, $T_{i,j}$, represent the probability the reserve will be in state i next year, given it was in state j the previous year. In this example it is assumed that fire events occur at the end of the yearly time steps after succession, i.e., the model calculates the probability of being in each state immediately after the fire season. The model can also be used to calculate probabilities if the fire season is assumed to start at the beginning of the model time step, by swapping the order of the fire and succession matrices in Eq. 9.

Given a distribution of probabilities of the reserve being in any of the S possible states at some initial time, Eq. 8 can be used to predict the probability of the reserve being in any state in the future. As time progresses these probabilities will tend to a fixed distribution (Moore and Noble 1990). At this stage the model could be used to investigate the expected state of the reserve under different fire regimes, i.e. using different fire matrices, $\mathbf{F}$. In the next section we describe how the fire matrix may change when a variety of possible management strategies are implemented. We then describe the technique of stochastic dynamic programming and show how it can be used to determine the management strategy that maximizes the probability of the reserve being in a desirable state in future years.

The Optimal Strategy

In order to use stochastic dynamic programming (SDP) for the management problem presented here, we need to assign a value to each possible reserve state, which indicates how desirable it is to a manager. A reserve is assumed to be in a desirable state if at least N_e, N_m, and N_l of the N reserve sites are in the early, middle and late-successional stage. A reserve in a desirable state has a value of 1, otherwise it has the value 0. The value of a reserve in state i is denoted $\psi(i)$, and hence

$$\psi(i) = \begin{cases} 1 & \text{if } e_i \geq N_e \quad \text{and} \quad m_i \geq N_m \quad \text{and} \quad l_i \geq N_l \\ 0 & \text{otherwise.} \end{cases} \tag{10}$$

If successional diversity is desired then N_e, N_m, and N_l may be set to, say, 20% of N. If late-successional sites are encouraged then one could set N_l to be 50% of N. Here we have assumed that a state is either strictly desirable (value 1) or undesirable (value 0); however, alternative functions for $\psi(i)$ could be considered where desirability is a more complex function of reserve state.

Given a range of management strategies, we want to determine which one to apply, given knowledge of the current state of the reserve, so that the reserve is most likely to be in a desirable state in the following years. Management strategies may include (a) let wildfires burn unhindered, (b) reduce the chance of wildfire (or the spread of wildfire), or (c) perform a controlled burn over part of the reserve. The management strategies are assumed to alter the transition matrix, $\mathbf{T}$. We now present examples of modeling the different management strategies.

Suppress wildfires

One possible management strategy is to try to prevent wildfires from starting and, if some do ignite, to then try and reduce their spread through the reserve. The data we need to model this strategy depend on our assumptions about fire. When sites are assumed to have a common fire hazard, we need data on the fire distribution, f_n, under fire-fighting conditions. Alternatively, if we assume succession-dependent fire hazards, then we need to identify how these fire hazards, i.e., f_e, f_m, and f_l, are reduced when fires are fought.

Prescribed burns

Another possible management strategy is to perform a controlled burn of desired size in either mid- or late-successional sites. Suppose the reserve is in state j and the state of the reserve after either n middle- or n late-stage sites are burnt is denoted by $B_m(j, n)$ and $B_l(j, n)$, respectively. When mid-successional sites are burnt the transition matrix is modified by replacing $T_{i,j}$ with $T_{i,B_m(j,n)}$. The transition matrix is modified when late-successional sites are burnt in a similar way. Note that the controlled burns are implemented at the start of the model year. Controlled burning of n sites is only an option if the reserve is in a state where n sites of the target successional stage are present. As the transition matrix is still a function of the fire matrix the model allows the possibility for wildfires to occur after the controlled burns.

Identifying the optimal management strategy

We assume that the reserve manager wishes to maximize the number of years the reserve is in a desirable state from the current year ($t = 1$) to some terminal year in the future ($t = T_f$), the assumption being that the higher the number of desirable years, the greater the chance that rare species will persist within the reserve. Suppose a manager may choose one of K possible strategies to implement each year (including the strategy to do nothing). We denote the transition matrix associated with the k^{th} management strategy by $\mathbf{T}(k)$. We now adopt notation similar to that presented in Mangel and Clark (1988). The maximum expected number of years the reserve will be in a desirable state from year t to year T_f, given that it is in state i at year t, is

$$V(i, t, T_f) = \max_k \left[\psi(i) + \sum_{j=1}^{S} T_{j,i}(k)V(j, t + 1, T_f)\right] \quad (11)$$

where $i = 1, \ldots, S$ and $k = 1, \ldots, K$. Eq. 11 is often referred to as the "dynamic programming equation." We use the term "expected value of the reserve" to refer to the variable V. To apply Eq. 11 we need to know the value of the reserve at the terminal year, for all possible states the reserve may be in, which is

$$V(i, T_f, T_f) = \psi(i) \quad (12)$$

where $i = 1, \ldots, S$. The expected value of the reserve at year t is dependent on the expected value of the reserve in the successive year, and hence this expectation for any year can be calculated by working backwards in time from the terminal year.

Incorporating management-strategy costs

If the effort or cost of implementing a strategy is large yet it only slightly reduces the chance of the reserve being in a desirable state in the future, then it may be better to do nothing with regard to wildfire. Suppose a cost can be associated with each management strategy k, denoted $c(k)$. The dynamic programming equation, Eq. 11, becomes

$$V(i, t, T_f) = \max_k \left[\psi(i) - c(k) + \sum_{j=1}^{S} T_{j,i}(k)V(j, t + 1, T_f)\right]. \quad (13)$$

The cost needs to be in units comparable to those used to describe the value of a desirable reserve. Hence a cost of one unit is high in this model, as it negates the value of being in a desirable state for a year. When we include a management cost into the dynamic programming equation the expected value of the reserve is not the maximum expected number of years the reserve is in a desirable state. However this expectation can still be calculated by noting the temporal sequence of optimal management decisions produced by Eq. 13. Suppose the management strategy that maximizes Eq. 13 is $k = \kappa(i, t, T_f)$. If we define $R(i, t, T_f)$ to be the maximum expected number of years, from year t to year T_f, when the reserve is in a desirable state, then

$$R(i, t, T_f) = \psi(i) + \sum_{j=1}^{S} T_{j,i}(\kappa(i, t, T_f))R(j, t + 1, T_f) \quad (14)$$

with

$$R(i, T_f, T_f) = \psi(i). \quad (15)$$

Note that Eq. 14 is the same as Eq. 11 if there is no cost associated with implementing any of the management strategies. The total expected cost of implementing the optimal management strategy from year t to year T_f, which we will denote $C(i, t, T_f)$, can be calculated using

$$C(i, t, T_f) = R(i, t, T_f) - V(i, t, T_f). \quad (16)$$

Model parameters, with Ngarkat Conservation Park as an example

Using our knowledge of the successional stages preferred by the four rare and threatened bird species, we assume that on average it takes 10 yr after fire for a site to change from early successional to middle successional, and then on average a further 20 yr to become late successional. We also assume that the long-term management objective is to maintain a relatively even mix of these three successional stages within the park.

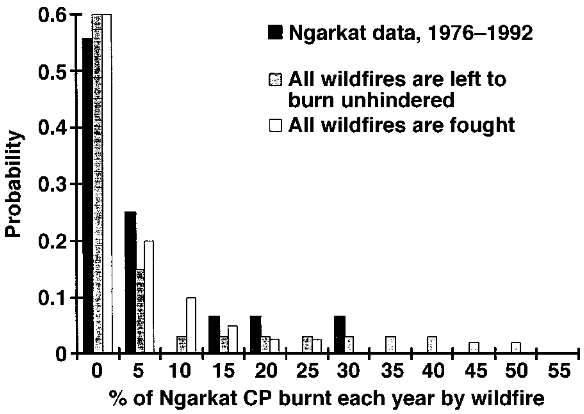


FIG. 1. The size–frequency distribution (represented as a probability distribution) of wildfire within Ngarkat Conservation Park (Australia) each year from 1976 through 1992. Also shown are the probability distributions assumed in the model simulations when wildfires are left to burn unhindered and when wildfires are always suppressed.

Here, the park is desirable if each successional stage is represented by at least 20% of the park. The park is sectioned into 20 sites so $N_e = N_m = N_l = 4$ sites (i.e., 20% of 20); applying Eq. 1 with $N = 20$ yields $S = 231$ states.

Fire records of Australia's Ngarkat Conservation Park (CP) show a site can sustain a fire within 5 yr of a previous fire. We first assume that each year all sites have a common fire hazard; then, we will investigate the case when the fire hazard of a site increases with successional age. Fig. 1 shows estimates of the percentage area of Ngarkat CP burnt by wildfires each year from 1976 through 1992 (frequencies are represented as probabilities). For the years when at least one wildfire did occur within the park, up to 30% of the park was burnt. It is difficult to determine from these data a probability distribution of fire sizes when wildfires are left to burn or when attempts are made to suppress them. This is partly because the ability to fight fires is likely to have changed over the last 20 yr. Large sections of Ngarkat CP are difficult to access for fire fighting, and so there is always going to be a chance that a significant part of the park will be burnt. We first model the size and frequency of fires within Ngarkat CP, under different management strategies, by the probability distributions presented in Fig. 1. It is assumed there is a 40% chance each year that at least one wildfire occurs within the park. If wildfires are left to burn then smaller fires (<5% of the park) are assumed to be most likely but larger fires (up to 50% of the park) are possible. If efforts are made to suppress wildfires then on average fires are assumed to be smaller with a maximum fire size being 25% of the park.

The probability a site will experience a wildfire each year can be calculated from the fire regime, using

$$\Pr\{\text{fire}\} = \sum_{n=0}^{N} \frac{nf_n}{N}. \tag{17}$$

The mean time between fires at a site is the inverse of this probability. Assuming the proposed fire regimes presented in Fig. 1, when wildfires are left to burn, on average a site will burn approximately once every 13 yr, and when wildfires are suppressed a site will burn on average approximately once every 26 yr. Hence, it is assumed that fire fighting approximately halves the chance a site will burn each year, i.e., fire fighting halves the fire hazard of a site.

When we model succession-dependent fire hazards, we propose the parameter values presented in Table 1. These parameters represent a system where the fire hazard of a site increases with successional age. We chose parameter values where the fire hazard of an early successional site is approximately half the fire hazard of a late-successional site. Like the previous fire model, when wildfires are left to burn, sites burn on average once every 13 yr; when wildfires are fought, sites burn on average once every 26 yr.

RESULTS

Before looking at the optimal management strategy we first explore the impact of fire on the state of the park. Initially, we consider the case when all sites have an equal fire hazard. If wildfires are always left to burn and their distribution is that presented in Fig. 1, then the probability of the park being in a particular state is represented by the probability distribution presented in Fig. 2a. The park is most likely to be in either state (50, 35, 15) or state (55, 30, 15). The values in the parentheses indicate the percentage of the park represented by early-, mid-, and late-successional stages. Note that neither of these likely states is desirable as only 15% of the park is in a late-successional stage. On average though, 43.3% of the time the park is likely to be in 1 of the 45 desirable states. Fig. 2b shows the probabilities when wildfires are always fought. In this case, the most likely state is (30, 30, 40), which is a desirable state, and the park is on average in a desirable state 70.7% of the time. This suggests that the management objective is more likely to be achieved if wildfires are always fought, compared with when they are always left alone.

Suppose the manager is interested in knowing the expected number of years, in the next 30 yr, that Ngarkat CP will be in a desirable state, given knowledge about the current state of the park. These expectations

TABLE 1. Parameter values when the fire hazard of a site is assumed to be associated with its successional stage.

Fire hazard†	Wildfires are left to burn	Wildfires are fought
f_e	0.065	0.028
f_m	0.09	0.037
f_l	0.12	0.055

† For fire hazard, f_e, f_m, and f_l denote the probabilities that early-, middle-, and late-successional sites, respectively, experience a wildfire each year.

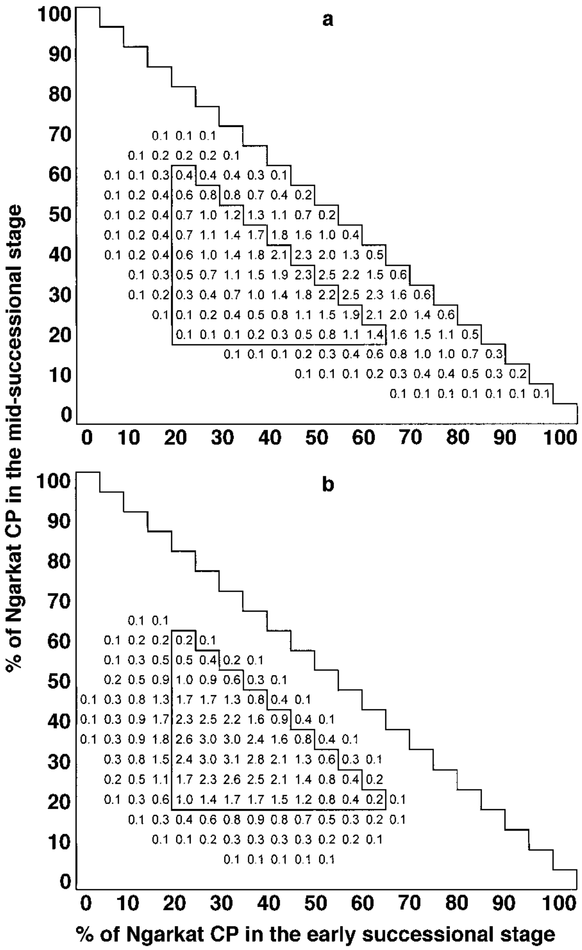


FIG. 2. Long-term expected percentage of time that the reserve is in each potential state, when (a) wildfires are always left to burn, and (b) wildfires are always fought. Blanks indicate that the percentage is <0.1. The inner ''triangle'' shows the set of desirable states. All sites have equal fire hazard.

are presented in Fig. 3 when (a) wildfires are always left to burn out, and (b) when wildfires are always fought. Note that the expectations presented in Fig. 3a are less than those in Fig. 3b, except near the origin. These results show that it is only better to always let wildfires burn out if the park is currently in a state where nearly all of it is composed of late-successional sites, although from Fig. 2 the park is unlikely to ever be in such a state.

Thus far, the model has been used to identify the expected outcome when management employs a state-independent approach, i.e., when wildfires are either always left to burn or always fought. Now, we investigate the case when, in any year, management may adopt one of the 6 strategies presented in Table 2. The manager is assumed to have the resources available, which makes it possible to control burn either 10% or 20% of the park in any year.

First, we consider the case when the cost of implementing each management strategy does not influence decision making, i.e., the cost of implementing each strategy is negligible or all are relatively equal. The optimal management strategy obtained using stochastic dynamic programming (SDP) for each possible current state that the park may be in, assuming community diversity is the management objective over the next 30 yr, is presented in Fig. 4a. Increasing the time horizon beyond 30 yr results in virtually no change in the optimal decision. Hence, if community diversity is a long-term objective, then Fig. 4a could be used at any time to aid decision making. The model never suggests letting wildfires burn themselves out. For some states the optimal strategy is to perform a controlled burn. The expected number of times, in the next 30 yr, the park will be in a desirable state, provided the optimal strategy is always chosen, is presented in Fig. 4b. The gain by possibly varying the strategy each year can be seen by comparing Fig. 4b with Fig. 3. Ngarkat CP is expected to be in a desirable state between 7 and 14 yr

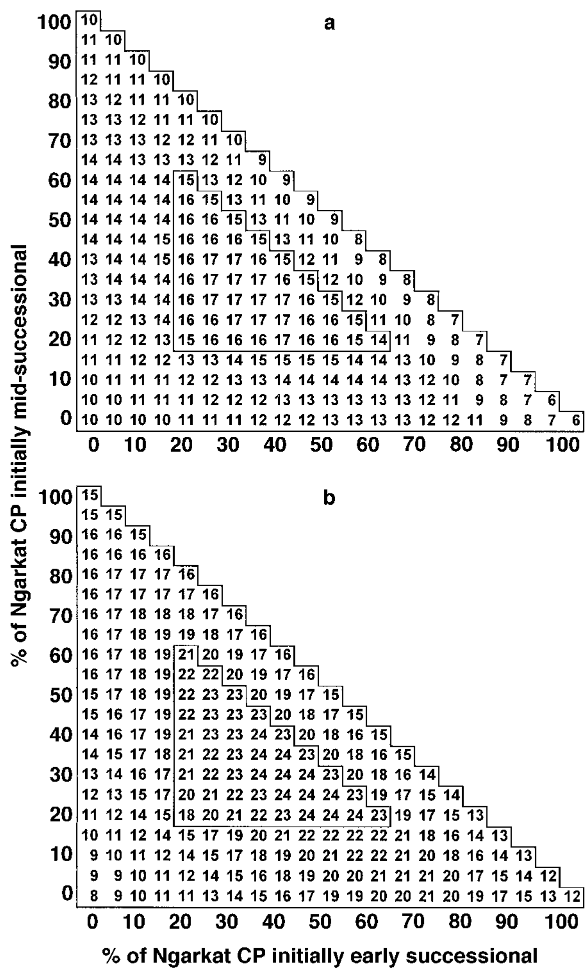


FIG. 3. Expected number of years, in the following 30 yr, that the reserve will be in a desirable state, for all possible initial states, if (a) wildfires are always left to burn, and (b) wildfires are always fought. Expectations are shown to the nearest integer. All sites have equal fire hazard.

TABLE 2. List of strategies available to a park manager each year, and their associated cost.

Management strategy for the year	Cost (dimensionless)
Let all wildfires burn	0
Fight all wildfires	0.25
Burn 2 mid-successional sites (i.e., 10% of the park)	0.25
Burn 4 mid-successional sites (i.e., 20% of the park)	0.5
Burn 2 late-successional sites (i.e., 10% of the park)	0.25
Burn 4 late-successional sites (i.e., 20% of the park)	0.5

more often, within the next 30 yr, if the optimal strategy is chosen compared with when wildfires are always left to burn. The expected gain is between 1 and 13 yr compared with when wildfires are always fought. The biggest gains in making the optimal state-dependent decision is when much of the park is in a late-successional stage because controlled burns can quickly bring the park back into a mix of successional stages, after which the optimal decision is to fight wildfires. The lowest gains are when the park is mainly early successional because then the best strategy is to constantly fight fires in the hope that some sites remain fire free for time sufficient to eventually become late successional. There is no quick way to recover from too many recent fires.

We now investigate how associating a strategy with a cost can influence the decision on when to use it. As an example, consider the costing presented in Table 2. It is assumed that it costs nothing to let wildfires burn but costs are associated with fighting wildfires and lighting fires. These costs are relative and indicate both the expense and risk involved when implementing the strategy. The optimal strategy is presented in Fig. 5a when the management objective is to maintain community diversity over the next 30 yr. As before, the optimal strategy remains virtually the same when the time horizon is increased beyond 30 yr and so Fig. 5a can also be considered to be the optimal long-term strategy. Now, the model suggests that in some cases it may be better to let wildfires burn, as trying to fight them is not likely to be worth the effort. Little is likely to be gained by fighting wildfires when there are virtually no late-successional sites; however if there are a few late-successional sites present then it does become worthwhile to fight fires. This result indicates the importance of protecting late-successional sites from fire if they are rare. Although lighting fires has been associated with a high cost, the model still suggests that controlled burns be implemented for park states similar to when burning was associated with no cost (compare with Fig. 4). The reason for this is that it would generally take only a few successive years, at most, of lighting fires to bring the park into a desirable state, after which the need to control burn again would be unlikely.

The expected number of years that Ngarkat CP will be in a desirable state when costing is considered is presented in Fig. 5b. Comparing with Fig. 4b, it can be seen that the strategy that takes into account costs will, on average over the next 30 yr, result in Ngarkat CP being in a desirable state 2 yr less often than the strategy that ignores costs. The expected cost of implementing the optimal strategy is presented in Fig. 5c and ranges from 2.8 to 5.6 units, depending on the current state of the park. If the strategy is to always fight fires over the next 30 yr, then the expected cost would be 7.5 units. This value is about 2 units greater

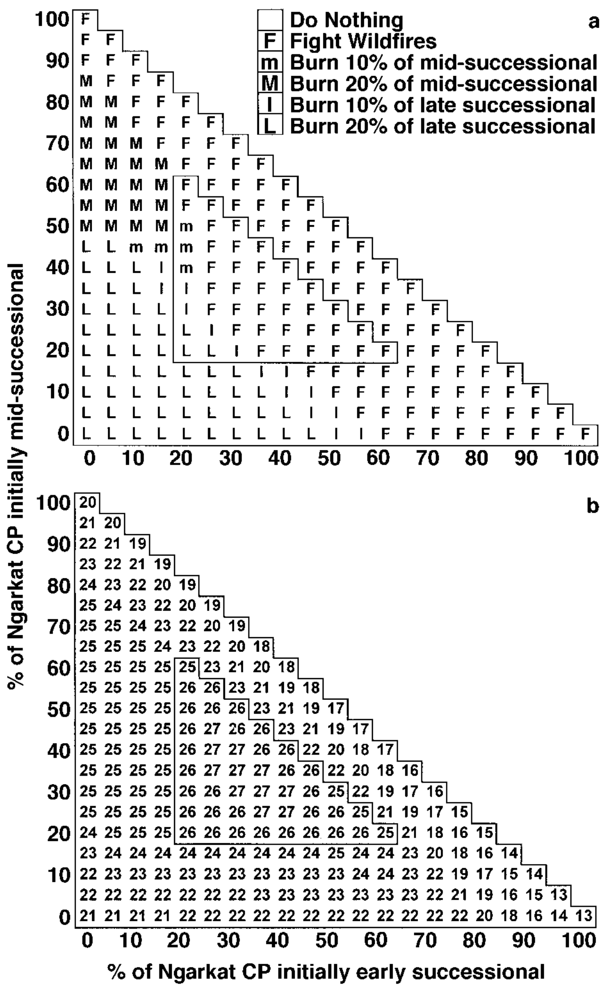
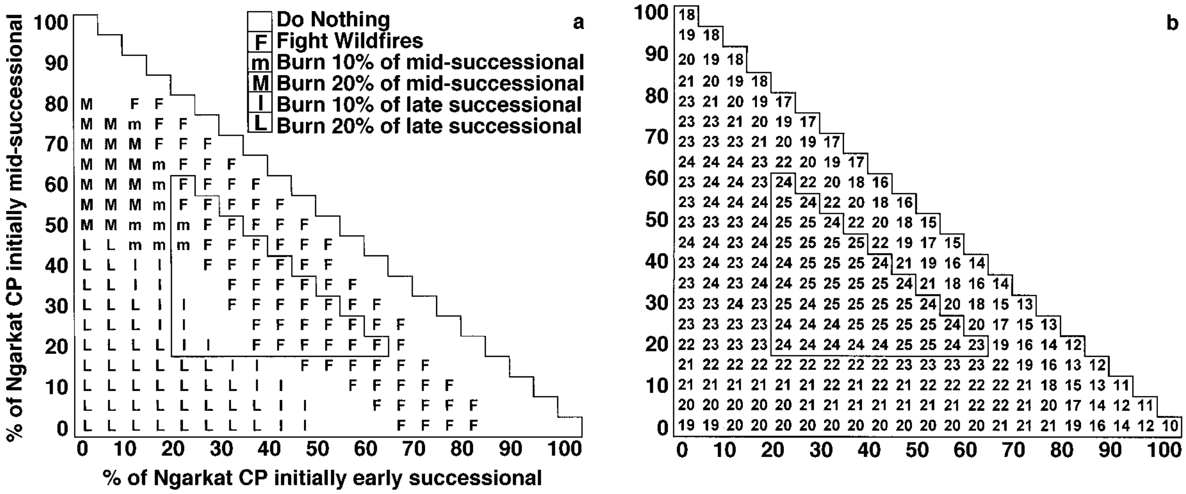


FIG. 4. Optimal reserve-management strategy to maximize community diversity for some terminal year in the future, T_f, assuming (1) three successional states (early, e; middle, m; and late, l), (2) a choice of six annual strategies, and (3) the cost of each strategy is ignored. (a) The optimal management strategy in year 1 with T_f = 30 yr, T_e (the time) it takes after a fire disturbance, on average, for an early successional site to become a mid-successional site) = 10 yr, and T_m (the additional time for such a site to become a late-successional site [assuming the site is not burnt by another fire]) = 20 yr. (b) The expected number of years the reserve is in a desirable state, in the next 30 yr, for all possible initial states, assuming the optimal strategy is always chosen.



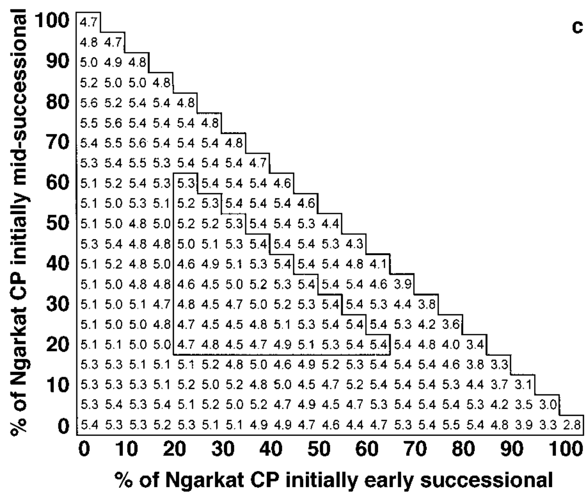


FIG. 5. Optimal reserve-management strategy to maximize community diversity, with cost as a factor (see Fig. 4 legend for other assumptions and definitions). (a) The optimal management strategy in year 1 when $T_f = 30$ yr, $T_e = 10$ yr, $T_m = 20$ yr, and strategies are associated with the costs presented in Table 2. (b) The expected number of years the reserve is in a desirable state, in the next 30 yr, assuming the optimal strategy is always chosen, $R(i, 1, 30)$. Results are displayed to the nearest integer. (c) The expected total cost, over the next 30 yr, of implementing the optimal strategy, $C(i, 1, 30)$. All sites have equal fire hazard.

than the expected costs of Fig. 5c. As fire fighting, which is generally the optimal decision, has a cost of 0.25 units, a reduction of 2 units indicates that when strategy costs are considered, we should expect that, for ~8 yr of the 30 yr, wildfires will be allowed to burn.

Now, we investigate the model with the assumption that the fire hazard of a site increases with successional age. It can be shown that when wildfires are always left to burn, Ngarkat CP is expected to be in a desirable state 22.7% of the time. When wildfires are always fought this expectation is 80.8%. Fig. 6a shows the optimal management strategies when management costs are ignored. In general, the optimal strategy is the same when compared with the results of the previous model, presented in Fig. 4a. One notable difference is that the strategy to ignore wildfires is now optimal for two of the desirable reserve states. It can be shown that the number of years the reserve is expected to be in a desirable state, over the next 30 yr, is similar to the distribution presented in Fig. 4b. When the management costs presented in Table 2 are considered, the set of optimal strategies is as shown in Fig. 6b. Again, the optimal strategy is generally the same when compared with the previous model results, presented in Fig. 5a. In this example, though, the strategy to fight fires is more dominant, and the strategy to control burn is less dominant. The expected values of the reserve are also found to be similar to those presented in Fig. 5b.

At the start of the 1997–1998 fire season, Ngarkat Conservation Park was in a state where it contained approximately 30% early successional, 40% mid-successional and 30% late-successional sites, when successional age is defined by the parameters $T_e = 10$ yr and $T_m = 20$ yr. This state is desirable as at least 20% of the park is classified as being in each of the three successional states. All of the results presented in Figs. 4, 5, and 6 suggest that management should fight wildfires if they occur during the 1997-1998 fire season, if the management objective is to promote community diversity within the park. Fighting wildfires is considered optimal even when the costing presented in Table

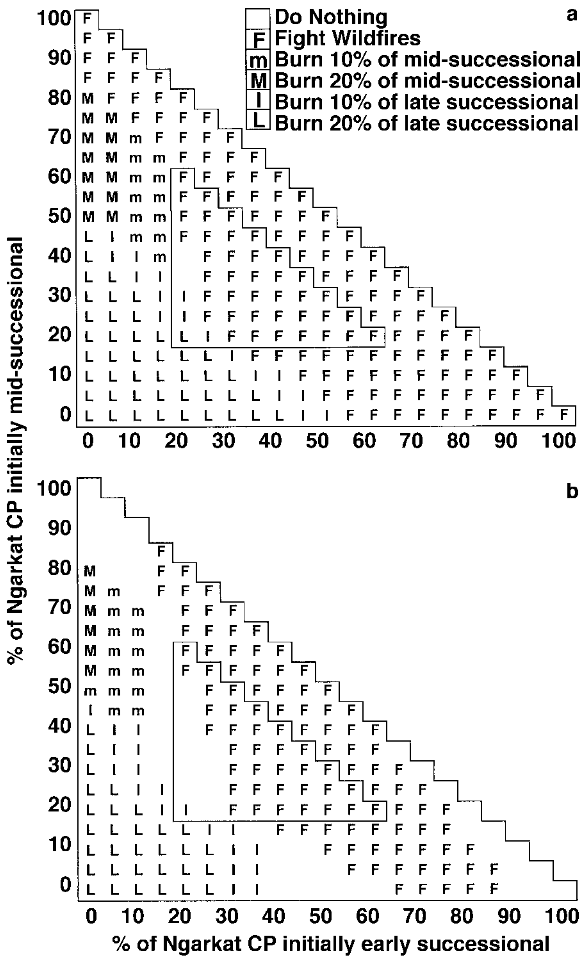


FIG. 6. Optimal reserve-management strategies in year 1 when the fire hazard of a site is dependent on its successional stage (see Table 1). Again, T_f = 30 yr, T_e = 10 yr, and T_m = 20 yr (see Fig. 4 legend for other assumptions and definitions). Part (a) assumes no strategy costs, and part (b) assumes the strategy costs presented in Table 2.

2 is assumed. This suggests that the objective of management is much more likely to be achieved if management attempts to reduce the spread of fire. It should be noted that although the optimal management strategy at this point in time is to fight wildfires, if the park were to remain relatively fire free in the years to come, then the state of the park may change sufficiently so that very few early successional sites remain and controlled burning may then be the optimal management strategy.

DISCUSSION

The modeling approach presented in this paper produces a simple tool that we can use to help us manage disturbances with the aim of maintaining community diversity. Given an explicitly defined management objective the model identifies the management strategy, from a set of available strategies, that is most likely to achieve the management objective. Making management decisions with regards to fire is particularly difficult because of the uncertainties involved with predicting its occurrence and effect. Stochastic dynamic programming enables us to make decisions in an uncertain environment. Our model shows that the optimal management decision depends to varying degrees on a number of factors and modeling assumptions. We now discuss these dependencies.

The model has shown that the optimal management strategy may change as the state of the reserve changes. The likelihood of attaining the management objective can be greatly enhanced if the decision to adopt a management strategy is based on the current state of the reserve. This work emphasizes the importance of implementing regular monitoring programs. Without such information, management runs the risk of choosing an inappropriate strategy.

A less intuitive result from the model is that when the reserve is currently in a desirable state it may be optimal to perform a controlled burn. This can occur when the reserve is on the borderline of switching from a desirable to an undesirable state. Performing a controlled burn in such a situation can potentially move the reserve to an alternative desirable state where it is more likely to remain desirable for a number of successive years. The model shows that the strategy to do nothing when the reserve is in a desirable state may not be optimal and management should always perform actions that try to move the reserve into the safest desirable state possible—the safest state being the one where the reserve is most likely to remain desirable when the associated optimal management strategy is implemented.

When strategy costs are considered, the optimal strategy for a particular state may change from performing some action to doing nothing. An examination of how the optimal strategy changes as costs are altered, can tell us how effective the strategy is at achieving the management objective. For example, when costs were considered, the fire-fighting strategy was not optimal when the reserve had low numbers of late-successional sites and high numbers of early successional sites (see the bottom right corner of Fig. 5a). Although fire fighting is the best strategy (see Fig. 4a), if a wildfire were to occur, then the most likely event would be for early successional sites to be burnt and the final state of the reserve would often be similar to that when wildfires were fought. However, there are a number of reserve states where the strategy to fight fires does not change when a cost is introduced. For these states the model strongly supports the fighting of wildfires. The value of having the option to perform a management strategy may be evaluated by recalculating the likelihood of achieving the management objective when the strategy is removed from the set of available strategies.

It can also be shown that the optimal strategy for a particular reserve state may change as the management objective is changed from being short term to long term, i.e., as the horizon time, T_f, is increased. For some reserve states the optimal decision changes from controlled burning in the short term ($T_f < 5$ yr), to fighting wildfires in the long term. Burning is a risky strategy, but it is a way of drastically and quickly changing the state of a reserve. Burning may be an effective way to achieve a short-term management objective, but when the objective is longer term, the safer approach of fighting wildfires may then be optimal.

When the management objective is short term the model tends to evaluate the cheaper strategies as being optimal. However, as the time horizon is increased the more costly strategies may then become optimal, provided they perturb the state of the reserve sufficiently towards, or into, the set of desirable states. Some initial years of performing costly strategies may place the reserve in a state where it is subsequently cheap to maintain the reserve in a desirable state. For example, when the reserve is in a state where late-successional states dominate, the optimal decision may be to burn, even if it is associated with a high cost, as otherwise it could potentially take a number of years before wildfires occur that may move the reserve closer to a desirable state.

As the treatment of succession is simple, the model requires relatively little data to parameterize. The first step when using this model is to explicitly describe the potential states of the reserve that are desirable to the manager. Ideally, one needs some information about the successional state of the vegetation where each desired species is most commonly found within the reserve.

It is worth noting that the greater the proportion of the reserve occupied by mid- and late-successional sites, the greater the number of management strategies that may be implemented. Mid- and late-successional sites can quickly be returned to early successional sites by prescribed burning; however, early successional sites cannot be as easily manipulated (Good 1981). If data on species abundance following a disturbance are few, then a manager may choose to set high values for the mean time a site takes before it moves from an early successional state to a mid-successional state (T_e), and the mean time a site takes to move from a mid-successional state to a late-successional state (T_m). These model parameters may then be changed when new data are acquired.

To parameterize the fire regime, one needs to have some idea on the frequency and spatial scale of wildfires when they are left to burn, and when attempts are made to suppress them. Simulations, though, tend to show that the optimal strategy is relatively robust to small changes in the fire regime. For example, the results presented in Figs. 4 and 5, when each site had an equal fire hazard, are not greatly altered when it is assumed that sites burn independently of each other, i.e., when f_n is described by a binomial distribution. Comparing the results presented in Figs. 4 and 5 with those presented in Fig. 6, we can see that the model is relatively robust to the assumption about how a site's fire hazard varies with successional age.

The model is also robust with regard to the number of reserve partitions or sites, N. Similar qualitative results to those presented here are produced when only 10 reserve sites are considered. Increasing the parameter N will increase the resolution of the reserve state space, i.e., increase S, however the value of considering a larger state space will depend on how much detailed information we have on the state of the park.

In this work we have assumed that the successional state of a site can be considered to be in one of three categories. A more precise way of classifying the successional state could be considered; however, when the possible number of categories is increased beyond three, the size of the state space of the reserve can become very large. The time taken to then evaluate the optimal strategies may be high, making the model unattractive to management who would want to use it to quickly investigate a number of scenarios. The size of the state space also increases dramatically when the reserve is sectioned into a greater number of sites, i.e., as N is increased. We found that when 20 sites were considered each scenario took only a few minutes to simulate on a typical personal computer.

In this model the management objective is to maximize the number of years the reserve is in a desirable state during some future period. This model may not maximize the temporal correlation of the desired years, which may also be important if we wish to promote the persistence of rare species in the reserve. Which management objective is likely to be better may depend on a number of factors, such as the dispersal ability of the desired species, and the location and size of neighboring habitats that are favorable to the species. The model could also be modified to allow for discounting, so a high priority is placed on having the reserve in a desirable state in the immediate future.

The model of community succession presented here is simplistic when it assumes the successional state of a site is only related to the time since last disturbance. However, when the underlying mechanisms governing succession are not well known, which is often the case, then a simple treatment of succession is a valid first approach to modeling the system. Here, we have treated both mallee and heath as a single habitat type, but the model could be extended to allow for multiple habitat types within the reserve. If life-history attributes of species and competition effects between species have been documented, then more sophisticated models of succession can be constructed (Noble and Slatyer 1980, Green 1989, Moore and Noble 1990). We have assumed that fires always revert late-successional sites to early successional sites. An alternative management option that may be modeled is a light burn, which changes the successional stage from late to middle. A fire of this type alters the vegetative structure within a site but it does not necessarily kill the stand.

In order to greatly simplify the model, we have ignored the spatial arrangement of the sites—hence the model does not explicitly consider how the three successional stages are distributed within the reserve. As a result, when the model suggests controlled burning of a particular successional stage, it does not indicate which sites of the target stage should be burnt. Care needs to be taken when deciding on the number of reserve partitions and the minimum areas of successional stages because some threatened species may not persist in a reserve where its desired sites are small and patchily distributed. The interspersion of successional stages may also be important for persistence (e.g., a species may need late-successional sites for denning and nearby early successional sites for foraging). Models that explicitly identify the spatial arrangement and fire hazard of each site have been constructed, usually using a cellular-automata approach (Green 1989, Bradstock et al. 1996). The importance of adding spatial dimension to models of community dynamics is often unclear and continues to be a key topic in theoretical ecology (Tilman and Kareiva 1997).

Future work is required to investigate how detailed models can be incorporated into an efficient decision-making framework. The state space of the reserve typically increases as the complexity of the succession model increases, which can lead to problems with the optimal strategy being too computationally expensive to evaluate. In this paper we have calculated the optimal available management strategy for a particular set of parameter values; however, when we considered management costs it was shown that sub-optimal strategies may also be effective at achieving the objective of management. Thus it may be worthwhile to investigate efficient heuristic methods for finding the optimal or near-optimal strategies, as they could make the more complex models of succession computationally feasible.

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