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ANALYSIS

Existence value and optimal timber-wildlife management in a flammable multistand forest

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Abstract

The problem of determining the optimal age at which to cut trees on four stands, and optimal fire protection expenditure, is posed. The objective is to maximise the resulting expected returns from timber and the expected value of the continued existence of an endangered possum species that relies on old growth for nesting. Dynamic programming is used to solve the problem. Existence values for the possum are based on the results of a detailed contingent valuation survey. A stochastic metapopulation model is developed for estimating end-stage survival probabilities of the possum dependent on start-of-stage tree ages and occupancies.

The sensitivity of optimal cutting and fire-protection policies to possum existence values, the rate of discount and the cost of reducing fire risk is investigated. The study demonstrates the scope of the combined use of simulation and dynamic optimisation for addressing land management problems involving conservation of species threatened with extinction.

Keywords: Existence value; Stochastic dynamic programming; Forest management; Leadbeater's possum

1. Introduction

1.1. The existence value of a threatened species and its use in bioeconomic modelling

A key feature of multiple-use ecosystem management planning is the conflict between commercial activities and conservation of threatened species. Resolution of this conflict has been hindered by a lack of information on the existence value of threatened species, the value of knowing that a species exists even when there is no intention of using the species. This is reflected in the bioeconomic modelling literature, with wildlife existence values rarely incorporated into models of multiple-use ecosystem management, even though such values may constitute a large proportion of total ecosystem value (Loomis and White, 1996). Instead, the typical modelling approach identifies tradeoffs between the

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commercial value of an ecosystem and the abundance or viability of target wildlife populations, a notable recent example being published in the Journal (Doherty et al., 1999). Instead of identifying a single optimal management regime, tradeoff models provide information on the opportunity cost of meeting alternative conservation targets (Montgomery et al., 1994). Where wildlife existence values have been estimated, it is possible to go beyond tradeoff estimation to identify optimal management regimes that maximise the sum of commercial and ecological values.

Although many studies estimating existence values have been published (see, for example, Jakobsson and Dragun, (1996), Ch. 11, for a survey of contingent valuation studies in Australia and New Zealand), the main interest of the studies is often methodological rather than to use the estimated existence values to find economically efficient strategies for managing ecosystems. Kennedy (1999) has argued that there is great potential for using survey estimates of existence values in management models. Existence values are best elicited in surveys posing simple and comprehensible scenarios. The values can then be used in decision-making models taking account of the complex dynamic and stochastic ecological relationships that must be considered in management models.

In this spirit, we develop a dynamic programming model for identifying optimal forest management strategies that take account of the risk of losing stands to fire, and the risk of the disappearance of an endangered possum species from the stands. The optimal strategies maximise the sum of the expected present values of periodic net returns from timber sales and the continued existence of the threatened species. A notable feature of our approach is the use of a stochastic metapopulation model to estimate the risk of extinction of the threatened species under alternative management choices, and our development of a novel method for linking the metapopulation model to the dynamic programming model. We demonstrate the scope of the combined use of simulation and dynamic optimisation for addressing land management problems involving conservation of species threatened with extinction.

We apply the approach to a case study focusing on the mountain ash forests of south-eastern Australia. These forests contain some of Australia's most highly valued timber and also provide habitat for several threatened species, most notably, Leadbeater's possum (LBP), the faunal emblem of the State of Victoria. The Victorian Department of Sustainability and Environment (DSE), which manages most mountain ash forests, has a legal obligation to conserve LBP and to supply timber to local sawmills and pulpmills. Options to conserve LBP are to reduce the risk of wildfire, and to retain or expand habitat for the species. The latter options can be accomplished by withdrawing younger forest stands from timber production to allow more trees to become old enough to form hollows suitable for nesting by LBP (MacFarlane et al., 1998).

Jakobsson (1994) and Jakobsson and Dragun (1996, 2001) report the results of a mail survey of a random sample of 3900 Victorians of their willingness to pay for conservation of endangered Victorian species in general and for LBP in particular. Valuation questions were based on contingent valuation methodology (CVM). Particular attention was paid to whether survey responses on conservation values of endangered species in general were significantly higher than values for LBP, to identify whether there were any embedding or scoping problems. In the survey, respondents were asked to state their willingness to pay for the full protection and long-term survival of LBP. In our forest management model, the expected existence value of LBP is calculated as the product of the species' survival probability and the mean willingness to pay of Victorians for its guaranteed survival. As in the Jakobsson study, we consider only the existence value of LBP, even though the species may have other values, in particular, values stemming from potential commercial or scientific uses of the species. In the absence of information on the latter values, the total economic value of LBP in our formulation is the species' existence value. The question arises whether existence value is sensitive to LBP population size. Whilst it is possible that people would have a higher willingness to pay (WTP) for a larger population, greater than that necessary for survival, no information on this is available, given that the Jakobsson CVM study asked respondents to consider LBP survival regardless of population size. In this regard, it is worth noting previous studies that have shown respondents' WTP being almost the same for quite different population levels (for example, Boyle et al. (1994) found similar values of waterfowl species in the Central Flyway of the United States even when the abundance of these species varied by orders of magnitude).

1.2. Statement of the forest management problem

We consider a forest comprised of multiple stands, each containing trees of a single age class. Both timber volumes and threatened species extinction risk depend on the age profile of the forest. The consideration of multiple stands and tree ages poses a computational challenge, particularly when the spatial arrangement of stands is considered. For example, if each of S stands can assume one of A ages, the forest can assume A^S different states, implying an intractable problem if there are more than a few stands and age classes to consider. However, as was originally recognised by Bowes and Krutilla (1989), considerable reductions in computational requirements are possible if all that matters for optimal decision making on stands is the combination of stands and not their ordering, nor the location of one stand relative to the location of the other stands. It can be shown that the number of states is reduced from A^S to $((A+S-1)!/S!\ (A-1)!)$ (Kennedy, 1998; Spring, 2002). To exploit this large reduction in dimensionality, we formulate our decision problem so as to capture important features of LBP population dynamics within and between stands, but without accounting for the spatial arrangement of stands. Rather, we consider only the total number of stands containing LBP populations and LBP nesting habitat, as explained in Section 2.1.2. We further reduce state dimensions by considering only the occupancy of stands by LBP populations rather than the species' abundance. Under this formulation, there are $((A+S)!/S!A!)$ possible age-occupancy states when only stands in the oldest age class can be occupied by LBP. This is a much smaller number of states than if spatial layout were considered. For example, if S=6 and A=5, the number of states falls from 46,656 (calculated as $(A+1)^S$) to 462. To demonstrate the approach, we solve a small example problem, comprising 4 stands and 5 tree age classes (S=4 and A=5, with 126 states). In the case of 4 stands actually laid out as a 2 by 2 matrix of stands the assumption of cells' location relative to the others may not be so stringent in matters of possum migration or spread of fire.

The problem is formulated in the next section, and model parameters given in Section 3. Optimal policies are reported in Section 4. Conclusions and suggestions for further research are presented in the final section.

2. Model formulation

Because decisions are sequential and subject to uncertainty, stochastic dynamic programming (SDP) is used to formulate and solve the problem. The decision-stage interval is set at 50 years, to restrict the number of states to a tractable level whilst capturing the long period required for nest-trees to form (approximately 200 years) in old-growth forest. A decision is made at the beginning of each stage whether to keep or fell stands. Because trees can be lost to fire, with probabilities inversely related to expenditure on fire protection, a decision is also made on the level of fire protection. The objective is to determine, for each possible combination of tree ages and LBP occupancy on the four stands at each decision stage, the decision combination that results in the maximum present value of expected net returns from timber production and LBP survival over infinite stages. By making the simplifying assumption that all stage-return and state-transition functions are the same for all decision stages, the optimal decision for each state (the optimal policy) is the same for all stages. The optimal infinite-stage policy is readily obtained by policy iteration (Kennedy, 1986).

Vectors (4×1) are used to represent age-LBP occupancy states, LBP occupancy and fire events and keep/fell decisions on each stand. As already explained, no significance attaches to the ordering of the stands in the vectors. All bold symbols are (4×1) column vectors, with the ith element denoting the symbol value on the ith stand. The unit row vector is denoted by $1'$. Braces are used for functions. The decision variables are the scalar, a, which denotes forest-wide fire-protection expenditure (one of three possible levels), and the keep/fell column vector, $\boldsymbol{d}$. The i element, d_i, takes the value 0 if the decision is to keep the trees on the ith stand, and 1 if the decision is to fell the trees.

The state variables are x_i, denoting the age of trees and occupancy status of LBP on stand i. These form the (4×1) state vector $\boldsymbol{x}$. Only the oldest tree age class (the Ath age class, referred to hereafter as "old growth forest") contains trees suitable for nesting by LBP, and therefore is the only class that can be occupied by LBP. There are (A+1) possible values for each stand: one value for each of the A age classes, and 1 additional value for the Ath age class being occupied. The age-occupancy state variable on stand i takes a value of 1 if the stand has trees in the first age class (zero years) and a value of A+1 if the stand is occupied and has trees in the Ath age class (200 years). The state vector at the end of a stage t is denoted $\boldsymbol{x}_T$. The sequence and timing of events in the SDP problem, and associated returns and state transitions, are illustrated in Fig. 1.

Allowance is made for the forest state across all four states to change following logging decisions and fire events. The state at the beginning of a decision stage, representing the ages of trees and LBP occupancy, is denoted by x. After the decision to keep or fell trees on each stand is made at the beginning of the stage, tree age and occupancy may change. The state is denoted by $\underline{x}$. Over the following 50 years, migration, reproduction and mortality are simulated, resulting in changed state $\underline{x}_T$. At the end of the stage, fire may burn out some stands. The resulting final state of the system for the decision stage is denoted x_T, which is also the state at the beginning of the following decision stage. The within-stage state transitions are explained in the rest of this section.

Felling and fire protection decisions are made and implemented at the start of the stage. The felling decision immediately transforms the state vector

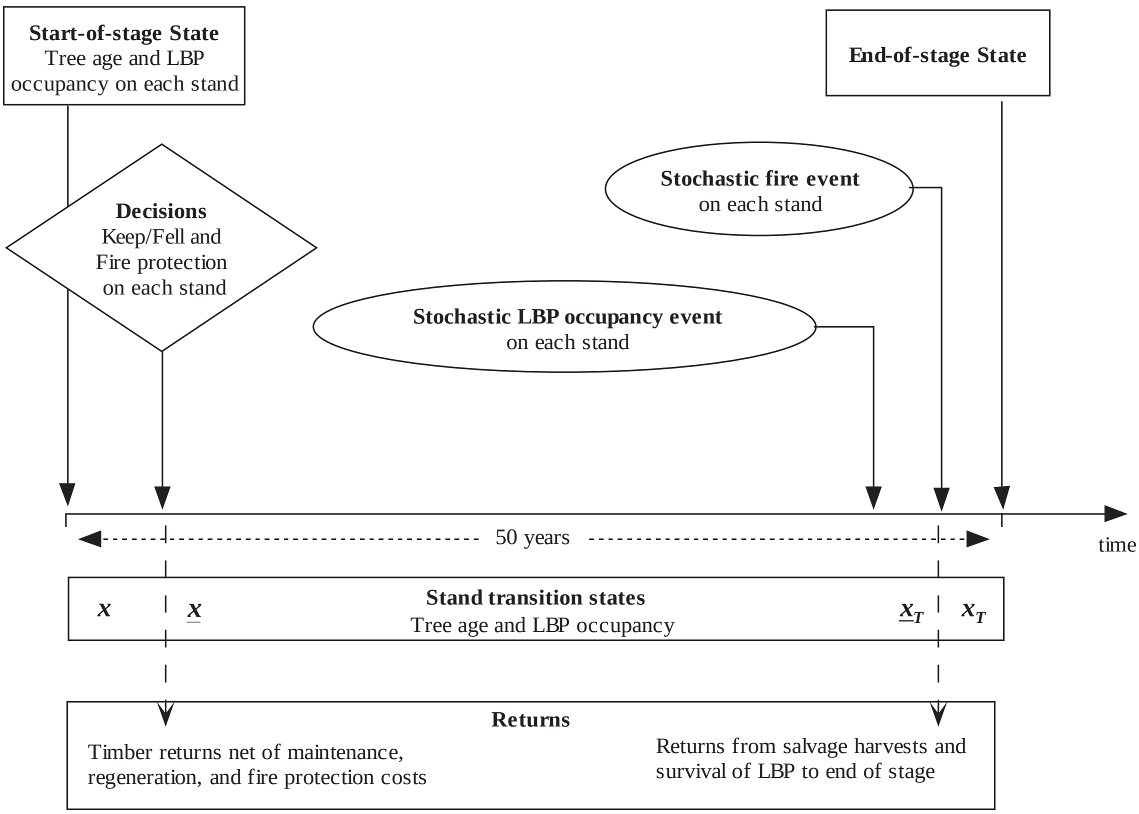

Fig. 1. Forest decision and event time lines for each stage.

from $\boldsymbol{x}$ to $\underline{\boldsymbol{x}}\{\boldsymbol{x},\boldsymbol{d}\}$, defined by individual stand elements:

$$\underline{\boldsymbol{x}}_i\{\boldsymbol{x}_i,\boldsymbol{d}_i\} = \begin{cases} \boldsymbol{x}_i & \text{if} \quad \boldsymbol{d}_i = 0 \\ 1 & \text{if} \quad \boldsymbol{d}_i = 1 \end{cases} \forall i \tag{1}$$

Logged stands are immediately replanted. Possum occupancy of stands and fire on stands are stochastic events occurring at the end of the stage. Burnt stands are salvage-logged immediately after a fire and regenerated. Existence value is obtained at the end of the stage if at least one stand is occupied by LBP. This depends on whether there are any occupied stands at the start of the stage, and if so, whether any are logged, become unoccupied as a result of demographic processes or are burnt. The demographic processes include dispersal mortality and demographic stochasticity, and are collectively referred to hereafter as the "stochastic occupancy event" (Fig. 1).

To limit the number of states, trees that are 200 years old at the start of the stage remain at that age if they are not logged or burnt. Thus, if no logging or fire occurs on stand i, the stand will be 50 years older at the start of the next stage, provided it has trees younger than 200 years old at the start of the current stage. Stands can be occupied at the end of the stage only if they are not logged or burnt, and if their populations do not become extinct as a result of the stochastic occupancy event. Carrying capacity is assumed to change instantaneously, from zero on a 150-year old stand to the maximum capacity of 100 adult females when trees reach 200 years. Thus, stands aged 150 years at the beginning a stage cannot be occupied during the stage as they become suitable for breeding only after all annual dispersal and reproduction events have occurred.

The stochastic occupancy event and fire event are denoted by the vectors $\boldsymbol{z}^j$ and $\boldsymbol{y}^k$, respectively. As occupancy is a binary state, there are 2^4 or 16 possible occupancy vectors. The ith element of the jth occupancy vector, z_i^j, takes the value 0 if the ith stand is not occupied immediately before the fire event and 1 if it is. The occupancy event transforms the state vector from $\underline{\boldsymbol{x}}$ to $\boldsymbol{x}_T\{\underline{\boldsymbol{x}},\boldsymbol{z}^j\}$ defined by individual stand elements:

$$\underline{\boldsymbol{x}}_{T,i}\{\underline{\boldsymbol{x}}_i, z_i^j\} = \begin{cases} \underline{\boldsymbol{x}}_i + 1 & \text{if} \quad \underline{\boldsymbol{x}}_i < 5 \\ 5 & \text{if} \quad \underline{\boldsymbol{x}}_i \geq 5 \quad \text{and} \quad z_i^j = 0 \quad \forall i \\ 6 & \text{if} \quad \underline{\boldsymbol{x}}_i \geq 5 \quad \text{and} \quad z_i^j = 1 \end{cases} \tag{2}$$

There are 16 possible fire vectors, identical in structure to the occupancy vectors. The ith element of the kth fire vector, y_i^k specifies the fire event, taking the value 0 if no fire occurs on the ith stand, and 1 if it does. The fire event transforms the state vector from $\underline{\boldsymbol{x}}_T$ to the end-of-stage vector $\boldsymbol{x}_T\{\underline{\boldsymbol{x}}_T,\boldsymbol{y}^k\}$ defined by individual stand elements:

$$\boldsymbol{x}_{T,i}\{\underline{\boldsymbol{x}}_{T,i},\boldsymbol{y}_i^k\} = \begin{cases} \underline{\boldsymbol{x}}_{T,i} & \text{if} \quad \boldsymbol{y}_i^k = 0 \\ 1 & \text{if} \quad \boldsymbol{y}_i^k = 1 \end{cases} \quad \forall i \tag{3}$$

The probabilities of each pre-fire occupancy vector and fire vector are defined as the probability functions $\Pr\{\boldsymbol{z}^j|\underline{\boldsymbol{x}}\}$ and $\Pr\{\boldsymbol{y}^k|\boldsymbol{a}\}$, respectively. Each is described in the next section.

2.1. Probability distributions for the stochastic events

2.1.1. Probability distributions for the number of stands burnt

For simplicity we assume in our baseline analysis that the probability of fire on a stand is independent of fire on the other stands. The binomial distribution therefore is used to estimate the probability of zero to four stands being burnt. Estimates of fire probabilities $\Pr\{\boldsymbol{y}^k|\boldsymbol{a}\}$ at different levels of protection expenditure are based on unpublished data (Brigham, 1997, discussed briefly in Section 3.2), and are given in Table 1.

Dividing the probabilities of the five possible fire outcomes by the number of ways in which these outcomes can be arranged across the four stands produces the probabilities of each of the 16 fire events, k. This approach is valid if fire on stand i is the same for all i, which implies that fire risks on different stands are not influenced by site specific factors.

Table 1
Probability of fire for different levels of protection expenditure, a[a]

No. of stands burnt	a ($'000/ stage)		Probability		
		1%	0	291	1025
		4%	0	530	1870
0			0.0011	0.2763	0.5262
1			0.0203	0.4192	0.3665
2			0.1351	0.2385	0.0957
3			0.3998	0.0603	0.0111
4			0.4436	0.0057	0.0005

[a] Source: Brigham (1997).

Fire probabilities are influenced by the size of each stand (300 ha) and the duration of the stage interval (50 years). If a significantly larger stand area were modelled, the probability that an entire stand will be burnt during a single stage would be lower. The 300-ha stand area is approximately equal to that of the largest old growth stand in commercially productive forest in the Study Region.

2.1.2. Probability distributions for the number of stands occupied immediately before the fire event

The number of stands occupied by LBP before the fire event depends on demographic stochasticity (random variation in birth and death rates) and environmental stochasticity (random variation in environmental conditions that influences population growth rates). Demographic stochasticity is of particular importance in small populations as it operates independently among individuals (Lande et al., 2003). In addition to demographic stochasticity, dispersal mortality can also strongly influence the survival probability of small populations of LBP. This may reflect not only poor site selection ability of subadult dispersers, but also the high rate of mortality among young female Leadbeater's possums that are excluded from established colonies (Smith, 1984).

The effects of demographic factors on LBP occupancy probabilities were estimated using a spatially explicit stochastic population simulation model. The model was developed using the software RAMAS Metapop Version 4.0 (RAMAS hereafter) (Akçakaya and Root, 2002). Spatial detail was determined by specifying carrying capacities for each stand and dispersal rates between each pair of stands. Annual dispersal rates (expressed as the proportion of animals in one population that disperse to another population over one year), were estimated using the following dispersal function:

$$p_b(b) = e^{-b/\sigma};\ \sigma>0 \tag{4}$$

where b is dispersal distance and σ is mean dispersal distance (1 km in our case study, based on unpublished data of Harley, in review). Only sub-adult possums disperse (Smith, 1984), therefore our simulation model is age-structured, with three age classes modelled: juveniles (<1 year old); sub-adults (1–2 years old) and adults (>2 years old). We assumed that dispersal is random in direction and occurs once per year. The mean dispersal distance (1 km) is short relative to the distance between centres of stands (1.7 km). To increase the accuracy of the stand-to-stand dispersal estimates, we subdivided each stand into 9 sub-stands arranged on a 3×3 grid. Combining Eq. (4) with the assumption of uniformly distributed dispersal directions produces a bivariate probability distribution, which we numerically integrated to estimate dispersal proportions for a forest comprising 36 square 33.3 ha stands. As all pairs of stands in the SDP formulation are assumed equidistant, we calculated dispersal proportions for the hypothetical case of 4 pairs of adjacent stands (Table 2). Though this leads to some inaccuracy in estimated dispersal proportions, this is small relative to general uncertainty about the dispersal behaviour of LBP (Harley, personal communication). Dispersal beyond the Study Region's perimeter or into stands without nesting habitat was treated as mortality. Other parameters used in the RAMAS simulations are set out in Table 2.

The probability of occupancy at the end of the stage, before any fire event, depends partly on the number of old growth stands at the beginning of the

Table 2
Leadbeater's possum parameters used in the baseline RAMAS simulations

Parameter	Base values
Carrying capacity of sub-stand (adult females/33.3 ha)	10
Initial abundance (no. of sub-stands occupied at capacity per stand)	6[b]
Mean dispersal distance	1 km[d]
Maximum population growth rate/year	1.15[c]
Mortality/year[d]	
Juvenile	0.0
Sub-adult	0.3
Adult	0.3
Fecundity/year	0.4[d]

(a) Based on a capacity of 0.3 animals per hectare, similar to that found by Smith (1984).
(b) This reflects anecdotal evidence that LBP is absent from approximately 40% of its suitable habitat (MacFarlane et al., 1998).
(c) Based on Smith, 1984.
(d) Harley, personal communication.

stage, after planned logging, which is specified by the counting function:

$$\mu\{\underline{\boldsymbol{x}}\} = \sum_{i=1}^{4} \begin{pmatrix} 1 & \text{if } \underline{\boldsymbol{x}}_i \geq 5 \\ 0 & \text{otherwise} \end{pmatrix}_i \tag{5}$$

It also depends on the number of occupied stands at the beginning of the stage after planned logging, specified by the counting function:

$$\Omega\{\underline{\boldsymbol{x}}\} = \sum_{i=1}^{4} \begin{pmatrix} 1 & \text{if } \underline{\boldsymbol{x}}_i = 6 \\ 0 & \text{otherwise} \end{pmatrix}_i \tag{6}$$

The probability of reaching the jth occupancy vector at the end of the decision stage before any fire event, $\Pr\{z^j|\underline{\boldsymbol{x}}\}$, is calculated as follows. For each initial stand age-occupancy state, $\underline{\boldsymbol{x}}$, one thousand 50-year simulations of populations at the sub-stand scale were carried out, in which reproduction and dispersal occur annually. This produced a distribution of end-of-stage occupancy outcomes on the 36 sub-stands, which were aggregated up to the stand scale to estimate the probability of 0/1/2/3/4 stands being occupied. A given stand was defined to be unoccupied at the end of 50 years if none of its sub-stands are occupied. Given that possums on a sub-stand can produce juveniles that colonise other sub-stands, including those in other stands, our formulation allows for the possibility of a small surviving population existing on a single stand to reproduce and provide dispersers to other stands. For each $\underline{x}$, the probability of 0/1/2/3/4 stands being occupied was estimated as the proportion of the 1000 simulations that resulted in each of those possible occupancy outcomes at the end of 50 years. The probabilities of all possible stand-level occupancy outcomes under baseline conditions are illustrated in Table 3.

To assist in interpreting Table 3, consider the probabilities of transition from a state at the start of the stage with 4 old-growth stands, one of which is occupied, to all possible occupancy states at the end of the stage. The three rows starting with '4 1<3 0.000' show there is a zero probability that less than 3 of the stands will be occupied at the end of the stage. The probabilities of 3 and 4 stands being occupied after 50 years, immediately before any final fire event, are 0.004 and 0.996, respectively.

Table 3
Baseline LBP within-stage occupancy transition probabilities

Total no. of old-growth stands	No. of old-growth stands occupied		Probability of no. of old-growth stands occupied
Timing in the decision stage			
Start	Start	End	End
$\mu\{\underline{\boldsymbol{x}}\}$	$\Omega\{\underline{\boldsymbol{x}}\}$	$\Omega\{\underline{\boldsymbol{x}}_T\}$	$\Pr\{\Omega\{\underline{\boldsymbol{x}}_T\}\|\underline{\boldsymbol{x}}\}$
1	1	0	0.060
		1	0.940
2	1	0	0.010
		1	0.060
		2	0.930
2	2	0	0.000
		1	0.010
		2	0.990
3	1	<2	0.000
		2	0.010
		3	0.990
3	2	<3	0.000
		3	1.000
3	3	<3	0.000
		3	1.000
4	1	<3	0.000
		3	0.004
		4	0.996
4	2	<4	0.000
		4	1.000
4	3	<4	0.000
		4	1.000
4	4	<4	0.000
		4	1.000

Inspection of the table indicates that occupancy probabilities are particularly sensitive to the initial number of old growth stands ($\mu\{\underline{\boldsymbol{x}}\}$), and are less sensitive to the initial number of occupied stands ($\Omega\{\underline{\boldsymbol{x}}\}$). The relatively high probability of extinction for states with 1 old growth stand reflects both demographic stochasticity and dispersal mortality. Dividing the probabilities of the five occupancy outcomes (0/1/2/3/4 occupied stands at the end of the stage) by the number of ways in which these outcomes can be arranged over the four stands gives the probabilities of each of the 16 stochastic occupancy events, j.

2.2. Timber revenue and cost functions

The combination of $\boldsymbol{x}$, $\boldsymbol{d}$ and y^k determines regeneration costs and harvested timber volumes, T_f, with subscript f referring to the grade of timber, equal to s for sawlog-grade timber and p for pulplog-grade timber. The price of timber is assumed to be independent of the volume sold.

Timber volume of grade f on stand i depends on the stand's age, x_i, and is denoted by $v_{f,i}\{x_i\}$. The volume of timber planned for sale at the start of a decision stage from an individual stand is:

$$q_{f,i}\{x_i, d_i\} = \begin{cases} v_{f,i}\{x_i\} & \text{if} \quad d_i = 1 \text{ (fell)} \\ 0 & \text{otherwise} \end{cases} \quad \forall i \quad (7)$$

Stage returns from timber equal the sum of returns from planned logging at the beginning of the stage and discounted returns from any salvage logging after fire at the end of the stage. The salvage volume is the proportion θ of the volume that would have been available had the stand not been burnt. Thus timber returns are:

$$\boldsymbol{R}_w\{\boldsymbol{x},\boldsymbol{d},\boldsymbol{k}\} = \sum_{f=s,p} p_f[1'\boldsymbol{q}_f\{\boldsymbol{x},\boldsymbol{d}\} + \alpha\theta\boldsymbol{y}^{k\prime}\boldsymbol{v}_f\{\underline{\boldsymbol{x}}_T\}] \quad (8)$$

where $\boldsymbol{q}_f\{\boldsymbol{x},\boldsymbol{d}\}$ is the column vector of planned timber volume on each stand, $1'$ is the unit row vector, $\boldsymbol{y}^{k\prime}$ is the row vector for the kth fire event, p_f is the price of f-grade timber, and α is the discount factor for a 50-year period, equal to $(1+r)^{-50}$, where r is the annual discount rate.

Regeneration costs are incurred on stands aged zero at the beginning of the decision stage, after logging has occurred, and are equal to the product of the unit row vector and the column vector $\boldsymbol{c}\{\boldsymbol{x},\boldsymbol{d}\}$ consisting of stand elements:

$$\boldsymbol{c}_i\{\boldsymbol{x}_i, \boldsymbol{d}_i\} = \begin{cases} \boldsymbol{c} & \text{if} \quad \boldsymbol{d}_i = 1 \quad \text{or} \quad \boldsymbol{x}_i = 1 \\ 0 & \text{otherwise} \end{cases} \quad \forall i \quad (9)$$

where $\boldsymbol{c}$ is the cost of regenerating one stand.

2.3. LBP stage existence value function

Ignoring for the moment the existence of LBP outside the Study Region, the existence value of LBP within the Study Region is obtained only if the species occupies at least one stand at the end of the stage. The existence value function is expressed as the return from survival or extinction of LBP as:

$$R_l\{\Omega\{\boldsymbol{x}_T\}\} = \begin{cases} 0 & \text{if} \quad \Omega\{\boldsymbol{x}_T\} = 0 \\ E & \text{otherwise} \end{cases} \quad (10)$$

where E is the existence value obtained in 50 years time from survival of the species to the end of the stage, and $\Omega\{\boldsymbol{x}_T\}$ is a counting function, similar to Eq. (6), giving the number of stands occupied after any fire event. Thus $\Omega\{\boldsymbol{x}_T\}$=0 indicates the state that no stands are occupied at the end of the stage, and $\Omega\{\boldsymbol{x}_T\}$>0 denotes the state of possum survival. The outcome $\Omega\{\boldsymbol{x}_T\}$ depends on the state vector after the keep/fell decisions x, and on the j occupancy and k fire stochastic events, as given in Eqs. (2) and (3).

However, the region modelled in our case study forms only a part of the total geographic range of LBP. The LBP exists in some forests that are not harvested for timber, and it would be computationally infeasible to determine optimal timber-cutting and fire-protection strategies for all the other harvested forests in which it exists. Thus the probability of survival of LBP depends on the probability of survival outside the Study Region $(1-\delta)$, as well as the survival probability λ within the Study Region. The probability of extinction outside the Study Region, δ, is treated as an exogenous parameter, independent of the occupancy and fire events within the region.

The overall probability of extinction is $\delta(1-\lambda)$, and the corresponding survival probability is:

$$\begin{aligned} SP &= 1 - \delta(1 - \lambda) \\ &= \delta\lambda + (1 - \delta) \end{aligned} \quad (11)$$

Therefore, in the model expected existence value within the Study Region is calculated as the expected value of R_l weighted by δ. The expected existence value for outside the Study Region (equal to $(1-\delta)*E$) is not included.

As for all other parameter values in the model, δ is assumed to apply for all future 50-year decision stages. For lack of estimates of δ, and the uncertainty attached to it, sensitivity analysis was conducted over a large range, with values of 1, 5, 50 and 95% per 50 years.

2.4. Solution method

The objective is to determine the optimal policy vectors for all decision stages resulting in maximum present value of expected stage returns over the planning horizon. Stage returns are the sum of the present values of expected returns from timber and from the public's knowledge of the continued existence of Leadbeater's possum. Each policy vector specifies the optimal decision combination, a and d, across all possible age-occupancy states. Solutions are obtained by dynamic programming.

As there is no obvious finite horizon for this problem, solutions are obtained for an infinite planning horizon. This is readily achieved by making the simplifying stationarity assumption that the return, state transformation and probability functions are the same for all stages. It is found as the policy vector satisfying the following recursive functional equation:

$$\boldsymbol{V}\{\boldsymbol{x}\} = \max_{a,\mathbf{d}} \sum_{k=1}^{16} Pr\{\boldsymbol{y}^k|\boldsymbol{a}\}\left[\boldsymbol{R}_w\{\boldsymbol{x},\boldsymbol{d},\boldsymbol{k}\} - 1'\boldsymbol{c}\{\boldsymbol{x},\boldsymbol{d}\} - \boldsymbol{a} - \boldsymbol{m} + \alpha\left(\sum_{j=1}^{16}\Pr\{\boldsymbol{z}^j|\underline{\boldsymbol{x}}\}(\delta\boldsymbol{R}_l\{\Omega\{\boldsymbol{x}_T\}\} + \boldsymbol{V}\{\mathbf{x}_T\})\right)\right] \tag{12}$$

$\boldsymbol{V}\{\boldsymbol{x}\}$ is the sum of the expected present value of all stage returns to infinity from implementing the optimal policy, $\boldsymbol{a}^*\{x\}$ and $\boldsymbol{d}^*\{x\}$, at the start of each decision stage, for all possible start-of-stage age-occupancy state vectors $\boldsymbol{x}$. It equals the expected value of timber and LBP survival returns for the current stage, plus the expected present value of all the forest states which may be accessed at the end of the decision stage ($\boldsymbol{x}_T$). The optimal value function $\boldsymbol{V}\{\boldsymbol{x}\}$ and associated optimal policy vectors are obtained by solving Eq. (12) numerically for all possible state combinations of tree age and LBP occupancy on the four stands, ($\boldsymbol{x}$). The range of $\boldsymbol{x}$ and $\boldsymbol{x}_T$ is the same.

Eq. (12) is recursive because $\boldsymbol{V}\{\boldsymbol{x}\}$ for any stage on the LHS depends on $\boldsymbol{V}\{\boldsymbol{x}\}$ on the RHS. The same function appears on both sides of the equation because the planning horizon is infinite (the passing of one stage still leaves infinite stages in the planning horizon, and the same optimal value for each possible start-of-stage state), and because stationarity is assumed.

3. Case study parameter values

Some of the parameter values used in the baseline analysis were set out in the above tables. Remaining parameter values are set out in Tables 4 and 5 and are described briefly below.

3.1. Timber yields and prices

Timber volume yields at different stand ages were estimated using the mountain ash stand simulation model STANDSIM (Coleman, 1989), which indicated that no change in timber volumes takes place after a stand reaches 150 years of age (Table 4).

Sawlog and pulplog prices were obtained from recent unpublished records (Source: M. Woodman, Senior Forester, DSE, personal communication) of the royalties received from the most recent timber sales in the Study Region, which are: $64/m^3$ for grade B sawlogs, $50/m^3$ for grade C sawlogs and $27/m^3$ for grade D sawlogs. Approximately 40% of the sawlogs harvested are grade B, 40% are grade C, and the remaining 20% are grade D. The weighted average sawlog price is therefore calculated as follows:

$$p_s = 64\times0.40 + 50\times0.40 + 27\times0.20 = \$51/m^3.$$

The price of pulpwood is approximately $\$12.60/\mathrm{m}^3$.

3.2. Fire protection expenditures

The following protection strategies (drawing on Department of Conservation and Natural Resources,

Table 4
Timber volume yields by age (m^3/ha)[a]

Tree age	Tree age index x	Sawlog volume $v_s\{x\}$	Pulplogs volume $v_p\{x\}$
0	1	0	0
50	2	84	509
100	3	516	379
150	4	628	371
≥200	5	628	371

[a] Source: Simulations conducted using STANDSIM.

Table 5
Other model parameters

Parameter	Symbol	Values for rate of discount p.a.		Value
		r=1%	r=4%	
Area of each stand (ha)				300
Rate of discount (%) per stage		65	611	
Probability of extinction of LBP outside the Study Region within each 50-year stage (%)	δ			1, 5, 50, 95
Salvage rate of burnt timber	θ			0.67[c]
Sawlog price ($/m^3)	p_s			51
Pulplog price ($/m^3)	p_p			12
Future value of certain LBP survival over 50 years ($m/stage)	E			
Lower bound (at $58.31 m/year)		1253[a]	2285[b]	
Upper bound (at $320.17 m/year)		6878[a]	12,550[b]	
Costs				
Present value of maintenance costs (at $68 m/year)[c]	m	2692	1519	
Regeneration ($/ha)	c			1622[c]

The rate used by the Victorian Government (Victorian Government 1986).
[a] At a discount rate of 4%.
[b] At discount rate of 1%.
[c] Source: Galapitage (1992). Prices are in real terms expressed in Australian dollars.

1995) were considered: fire detection using lookout towers; fire response using alternative levels of manpower in readiness for fighting an outbreak; fire protection by burning off strategic corridors every three years; and education to reduce fires initiated by people. Annualised costs were calculated for each strategy from estimated capital and annual costs. Rough estimates of the impact of the strategies alone and in combination were obtained from staff at the Alexandra office of the DSE.

Three points on the efficient frontier of the set of 12 fire-probability/protection-expenditure points based on the study of Brigham (1997) were selected as the basis of three fire protection programs in the study (Table 1). The first program is the null program of no protection, chosen because there has been a longer period of observation of fires under this program than any under any other. Brigham (1997, p. 35) gives a probability of a destructive fire spreading through a particular hectare of mountain ash forest, without any detection or suppression activity, to be 1 year out of 30. This estimate was made in consultation with staff of Alexandra Office of the DSE on the basis of historical data prior to 1940 when no State-owned fire agency was employed to prevent or suppress an outbreak of fire.

The second program is the combination of towers and home standby. The third program is the combination of towers, depot standby, education and burnoff. Changes have been made to the original estimates in Brigham (1997) by adding the cost of fire access roads to the cost of lookout towers in reducing the probability of destructive fire due to basic infrastructure. The original cost of the burnoff strategy related to a mix of forest types in the Alexandra fire protection region. After consultation the cost has been increased to reflect the higher costs for an all-mountain-ash stand which is relatively more dense and inaccessible (Greg McCarthy, Senior Researcher, Forest Science Centre, DSE, personal communication).

3.3. Leadbeater's possum existence value

The annual existence value of LBP estimated by Jakobsson and Dragun (1996) for a sample of registered voters in the State of Victoria, on the basis of a contingent valuation survey was between $58 and $320 per year per head. These figures were adjusted for inflation between 1989 (the year in which the survey was conducted) and 2002 using the Australian consumer price index (ABS, 2002). Multiplying the willingness-to-pay to ensure the long term survival of

LBP per respondent by the number of registered voters in Victoria (3.266 million in November 2002) gives upper and lower bounds on the range of possible existence values in Victoria for LBP. We consider both the lower and upper bound values in our analysis.

These and other parameter values used in the case study are set out in Table 5.

Optimal policies for different discount rates and δ, E combinations are presented in Section 4 for selected states. Conclusions and suggestions for further research are presented in the final section.

4. Optimal policies

Optimal policy vectors were found numerically by solving Eq. (12) using the general purpose dynamic programming software developed by Kennedy (1986, 2003). The vectors show the optimal keep/fell decision on each stand, and the optimal fire protection expenditure, for all 126 state combinations of age and occupancy on the four stands that can be reached at any stage. The optimal policy is implemented at all future stages by applying the optimal decision set for the state reached, which in turn depends on the initial state and stochastic events of the previous stage.

Most of the commercially productive forest in the Study Region is regenerating from a large wildfire that occurred in 1939, with smaller areas of younger and older forest. In our case study applications, we give particular attention to states with a single occupied old-growth stand surrounded by 50- or 100-year-old regrowth stands. We also consider a state with more old-growth stands. For brevity, results for the state 50/50/50/200–0/0/0/1 are not included in Table 6, but are described in the text.

Optimal policies for two states are presented in Table 6. Decisions and expected values from implementing the optimal policy across infinite stages are reported for two discount rates (r), two existence values (E_l) and four values of δ. The existence values are at the lower and upper bounds of the range estimated by Jakobsson and Dragun (1996).

We begin by discussing the results at a 4% discount rate, the rate currently used by DSE for forest policy evaluation. To place the impact of LBP existence value in perspective, if the existence value

Table 6
Optimal decisions for selected age-occupancy states at different discount rates, stage existence values, and LBP survival probability outside the Study Region

Tree ages	Occupancy	Optimal protection expenditure (***a***) and keep/fell (K/F) decisions								
		δ	δE	r=4%			δE	r=1%		
Stands 1/2/3/4	Stands 1/2/3/4		$m	***a*** $	Keep/fell 1/2/3/4	EPV* $m	$m	***a*** $m	Keep/fell 1/2/3/4	EPV* $m
100/100/100/200	0/0/0/1	0.01	13	3	F.F.F.K.	36.3	23	3	F.F.F.K.	68.3
			69	3	F.F.F.K.	86.9	126	3	F.F.K.K.	231.4
		0.05	63	3	F.F.F.K.	81.3	114	3	F.F.K.K.	212.8
			344	3	F.F.F.K.	335.1	628	3	K.K.K.K.	1099.6
		0.50	626	3	F.F.F.K.	589.8	1143	3	K.K.K.K.	1994.0
			3439	3	F.F.F.K.	3127.5	6275	3	K.K.K.K.	10,962.8
		0.95	1190	3	F.F.F.K.	1098.3	2171	3	K.K.K.K.	3791.3
			6534	3	F.F.K.K.	5923.7	11,922	3	K.K.K.K.	20,832.0
100/200/200/200	0/0/0/1	0.01	13	3	F.F.F.K.	39.7	23	3	F.F.K.K.	71.7
			69	3	F.F.K.K.	93.9	126	3	F.K.K.K.	305.4
		0.05	63	3	F.F.K.K.	87.1	114	3	F.K.K.K.	278.9
			344	3	F.K.K.K.	403.8	628	3	K.K.K.K.	1518.5
		0.50	626	3	F.K.K.K.	730	1143	3	K.K.K.K.	2761.9
			3439	3	F.K.K.K.	3,979.6	6275	3	K.K.K.K.	15,215.2
		0.95	1190	3	F.K.K.K.	1381.2	2171	3	K.K.K.K.	5257.5
			6534	3	F.K.K.K.	7555.4	11,922	3	K.K.K.K.	28,918.7

**TV refers to the threshold value of retaining a stipulated number of old growth stands (see text).
* EPV refers to expected present value.

is zero, it is optimal to fell all trees at 50 years of age and older.

For those states in which there is one old-growth stand, it is optimal to retain the stand and fell the other stands. This result applies over the entire range of existence values estimated by Jakobsson and Dragun (1996) ($58 to $320 m/year in 2002 prices) for the lowest value of δ=1%. In order for it to be optimal to retain at least one 100-year-old stand, δE would need to be at least $5.15 billion (not illustrated), which is within the range of values estimated by Jakobsson and Dragun if δ is set at the highest trial value of 95%. Table 6 shows that for δE set at $6.534 b (with annual willingness to pay for LBP survival set at its upper limit of $320 m and δ set at 95%), it would be optimal to retain one 100-year-old stand for the state 100/100/100/200–0/0/0/1. In order for it to be optimal to retain at least one 50-year old stand, δE would need to be at least $14.8 b/stage. The much larger threshold conservation value for 50-year-old stands than 100-year-old stands reflects the longer time required for the younger stand to reach an age of 200 years. The longer is the time required for new habitat to form, the lower is its expected value in terms of the monetary value of increased future survival probability. This is due not only to discounting, but also the risk that the stand will be destroyed by fire before new habitat forms, and the risk of extinction on the sole existing old growth stand. If extinction occurs before any new habitat forms, the new habitat would have zero conservation value, given our assumption that there is no immigration of possums into the Study Region. In sum, whether it is optimal to expand old growth habitat in the future will depend on the current age profile of the forest and the value of δE.

Though decisions optimal for a 4% discount rate are of interest because it is the rate used by DSE for forest policy evaluation, it can be argued that lower rates should be used on grounds of intergenerational equity. Future generations may prefer to inherit a world with more old-growth-dependent wildlife species than would result from the current generation applying a 4% discount rate to choices between such species and timber production. Weitzman (2001) has argued on different grounds that the discount rate for appraising a project should depend on the term of the project—e.g., 4% for projects of 1–5 years, 1% for 76–200 years, and 0% for over 200 years. For illustrative purposes, we conducted the analysis at discount rates of 4, 1, and 0.1%. Results for discount rates of 4 and 1% are presented in Table 6. Results for 0.1% are discussed briefly in the text.

Table 6 shows that discounting has a strong influence on the optimal habitat retention and expansion decision. At the lower discount rate of 1%, lower values of δE are required for it to be optimal to expand old growth habitat than under the higher discount rate. For example, if the initial state is 100/100/100/200–0/0/0/1 and δE is set at $114.3 m, it is optimal to retain one of the 100 year-old stands, while it is optimal to retain none of the 100-year old stands at the equivalent δE value under a discount rate of 4% ($62.65 m). Initial occupancy has much less influence on the keep/fell decision than the age profile of the forest (not illustrated). This reflects the fact that initial occupancy has only a small influence on the 50-year extinction probability (Table 3) and this applies only to relatively few states, namely, those in which there are two old growth stands.

Reducing the annual discount rate to 0.1% has a marked effect on the optimal policy. For a wide range of values of δE, it is optimal to keep all stands for any state containing at least one occupied stand. A much less marked habitat expansion policy is evident at higher discount rates, including a rate of 1% p.a. This can be illustrated for an δE value of $114 m/stage: at this value, it is optimal to fell up to two stands for a range of states in which LBP exists, whereas it is optimal to retain all stands in those states at a 0.1% discount rate. An implication is that the debate on the appropriate discount rate to apply to projects that have environmental impacts extending into the far-distant future has significant implications for forest management choices involving old-growth-dependent wildlife species.

Because of the difficulty of obtaining estimates of the probability of fire destroying a stand of a given area over a given time period, protection expenditures double and half the rates shown in Table 1 for the three levels of protection were tested. The effect of doubling protection expenditures was found to depend on the discount rate and the value of δE. This can be seen in the results for the two states in Table 6. Consider the first state, 100/100/100/200–0/0/0/1, with δE set at $13 m under the 4% discount rate and $23 m under the 1% discount rate. After doubling forest protection costs at 4%, it is no longer optimal to retain the old growth stand. In contrast, it remains optimal to retain the stand at 1%. Similarly, for the state 100/200/200/200–0/0/0/1 and the same values of δE, doubling the protection cost only causes a fall in the number of retained old growth stands at the 4% discount rate; not at the lower discount rate (for which the optimal number of retained old growth stands remains at two). Qualitatively different responses to higher fire risk at the two discount rates were observed not only for the lowest values of δE, but also higher values. This is illustrated for the case where equivalent δE values at the higher and lower discount rates are \$62.65 m and \$114.3 m, respectively, and the initial state is 100/200/200/200–0/0/0/1. In this case, doubling the protection cost increases the optimal number of retained stands, from two to three, at the lower discount rate, but has no effect on the habitat retention decision at the higher discount rate. Halving the protection costs has no effect on the optimal decisions for the states in Table 6.

5. Conclusions

We obtained solutions to a timber-wildlife management problem using existence values for the threatened wildlife based on the results of a contingent valuation survey. Expected stage existence value was calculated as the product of the species' probability of surviving to the end of the stage and the willingness of the public to pay for guaranteed survival of the species. We considered environmental and demographic threats to the species' survival, and two management options that reduce those threats: reducing the risk of wildfire and retaining or expanding old growth habitat. Choice amongst these options entails weighing up the public's value of believing the species will survive in the future against foregone timber value. Our dynamic optimisation approach is well suited to considering this tradeoff, as it accounts for the possibility of extinction. Applying our approach to a case study indicated that the decisions on whether to retain or expand habitat and how much to spend on reducing fire risk can be highly sensitive to the discount rate, the cost of reducing fire risk, the threatened species' existence value and its risk of extinction outside the Study Region.

An important untested assumption in our analysis is that of a linear relationship between expected existence value and probability of survival. It has been argued elsewhere that the marginal utility of increases in survival probability of a threatened species declines with increases in survival probability (Maguire, 1986). If this were proven correct, it could reduce the optimal number of stands to retain as habitat, as increments in survival probability would be worth less, the greater is the number of stands already retained.

Another factor affecting relative timber and possum values that we did not consider is the difference in reinvestment opportunities between timber returns and existence value. Assuming existence value can be reinvested, as we have done, when in fact it cannot be reinvested, is likely to lead to an underestimate of wildlife existence value relative to timber value, as one should apply the lower consumption rate of discount to existence value, increasing present values of conservation relative to timber present values. A method of working with two rates of discount for this situation in dynamic programming models is discussed in Kennedy (1986, Ch. 8).

Another methodological issue is whether to consider only the occupancy of stands by the target species, as we have done, or whether to consider the species' abundance on each stand. The latter would enhance the biological realism of the model by accounting for possible changes in LBP abundances on stands between one decision stage and the next. This would be particularly useful if changes in abundance influence future occupancy probabilities. However, additional state values would be required to account for the different abundance classes, resulting in a large increase in the number of states. Thus, the occupancy approach used here entails some loss of information on occupancy probabilities, at the gain of a considerable reduction in problem size. The occupancy approach is a reasonable simplification in cases where local population sizes can change rapidly on the time scale of the extinction/colonization processes that determine the dynamics of the metapopulation (Hanski and Thomas, 1994). Possingham (1996) used a similar occupancy model to determine optimal policies for a metapopulation. As noted above, such a formulation allows for the three main influences on LBP extinction risk to be considered:

demographic processes operating at the landscape and local scales, including the ability of a small surviving population existing on a single stand to reproduce and provide dispersers to other stands; environmental risk, including fire risk, and the removal of habitat as part of timber harvesting.

Our use of binary keep/fell decision variables on each stand is somewhat unrealistic because, in practice, it may be possible to remove a proportion of trees on a stand, for example, in a thinning operation or in post-fire salvage harvesting. Furthermore, if thinning occurs on a stand containing hollow-bearing trees (HBTs), partial tree removal may not significantly reduce the carrying capacity of the stand for LBP. For example, LBP abundance in old growth forest is limited by food availability rather than HBT availability (MacFarlane et al.), implying that some trees could be removed without reducing carrying capacity. Accordingly, a useful extension of our formulation would be to allow for partial harvests of stands, although this would increase the size of the problem, requiring increases in the number of decision variables. It also would require additional state variables, if thinning results in changed timber volume and/or tree age structure on the stand. The latter outcome is likely in old growth stands, where natural thinning processes have ended; in contrast, thinning a young stand can replicate natural processes and thereby have no impact on the stand's tree age structure. It also would require additional state variables, for at least two other reasons. First, thinning results in a change to a stand's tree density, which may persist over subsequent successional stages reached by the stand. Second, thinning of an old growth stand can result in a changed tree age structure on the stand, from one with a uniform age to one with a mix of old and young trees.

The multi-stand approach suggested by Bowes and Krutilla (1989) proved a useful way of incorporating the results from a simulation model of possum dispersal between stands in a dynamic programming model without greatly increasing the dimensionality of the problem. Many previous optimization analyses of multiple-stand management for timber production and wildlife conservation portray logging-induced damages to wildlife indirectly, using adjacency relationships (Murray, 1999). With this structure it is simple to allow for other interdependencies if these do not significantly depend on the relative positions of stands. For example, the model could be extended to allow for interdependent fire risk among stands (that is, the risk of fire spreading among stands). This might have the effect of reducing the number of stands to retain as habitat at high discount rates and low existence values, a similar effect to that described in our sensitivity analysis for the case of increased fire risk.

Our analyses demonstrate how dynamic optimisation combined with stochastic population simulation offer a useful framework for gaining a deeper understanding of habitat management issues.

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