Chapter 8
Bootstrap Simulation, Markov Decision Process Models, and Role of Discounting in the Valuation of Ecological Criteria in Uneven-Aged Forest Management

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1 Introduction

Besides the market value of timber, forests provide substantial nonmarket benefits, especially with continuous-cover silviculture, which have long been acknowledged by forest managers. They include wildlife habitat (e.g. Bevers and Hof 1999), carbon sequestration (e.g. Dewar and Cannell 1992), biodiversity (e.g. Kangas and Kuusipalo 1993; Austin and Meyers 1999), landscape diversity (e.g. Gobster 1999), etc.

Several studies have explored the trade-offs between economic and noneconomic objectives. For example, Liang et al. (2006) find with a response surface approach that annual production is negatively related to tree size diversity. Seely et al. (2004) use a hierarchical decision-support system to combine multiple management objectives such as gross profit, carbon storage, and snag density. Zhou and Buongiorno (2006) and Zhou et al. (2008a, b) explore with Markov decision process (MDP) models how to pursue uneven-aged management under risk with multiple criteria including discounted net returns, landscape diversity, and wildlife habitat. With discounted financial returns in the objective function and undiscounted criteria as constraints, such methods offer a means of computing the shadow price (opportunity cost) of the undiscounted criteria.

Discounting net financial returns has been common practice in forest management, dating back to the ground-breaking Faustmann's formula (Faustmann 1849) which values lands under perpetual even-aged management. Chang (1981) derives the optimal cutting cycle for uneven-aged management from a formulation analog

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to the Faustmann formula. Forest rent and internal rate of return have been proposed as alternative economic criteria (e.g. Bentley and Roger 1966; Bierman 1968), but both are internally faulty or problematic (Newman 1988).

Buongiorno (2001) shows that Faustmann's formula can be viewed as a particular case of a more general MDP model with stochastic stand growth and prices, applicable to both even-aged and uneven-aged forests. Examples of applications of MDP models to forest management include Lembersky and Johnson (1975), Kao (1984), Kaya and Buongiorno (1987, 1989), and Lin and Buongiorno (1998). Real options approaches have also been applied to deal with discounted financial objectives with stochastic timber prices (e.g. Newman and Yin 1995; Plantinga 1998; Insley 2002).

However, disagreements lie in whether or not to discount nonmarket values in the same way as economic returns. Hartman (1976) broadens the general Faustmann formula to include the discounted environmental benefits as a return in the valuation stream (Newman 1988). Howarth (2009) argues that nonmarket values provided by public goods (such as public forests) should be discounted at a risk-free rate, just like financial returns. Still, most of the studies incorporating ecological criteria in forest management do not discount them, especially if they are not expressed in monetary terms (for an exception see Boscolo et al. (1997) which discount tons of carbon stored in forest stands).

However, discounting is just a weighting scheme which gives more importance to the present than to the future. Although it is usually used to discount future benefits and thus encourage resource depletion (Clark 1988), discounting could be used to discount future stock and thus promote conservation. By giving more weight to the present state of a forest (say its biodiversity) than to its future state, discounting "may work in favor of efforts to preserve natural resources in the future" (Gowdy 1996).

The focus of this chapter is to explore the effect of discounting on some characteristics of forests that are deemed valuable by ecologists, without arguing in favor or against discounting per se. We do this with stochastic simulation models of forest stands and MDP models for optimization. MDP models recognize risk in the growth of forest stands and in the price of wood with transition probabilities between stand states and price levels. Expected rewards from decisions include financial incomes from cutting trees and the ecological characteristics of the resulting stand states. Optimal policies from optimization of MDP models tie harvest decisions to stand states and price levels.

The objective is to quantify the effect of maximizing the discounted or undiscounted value of selected ecological criteria on the short and long-term characteristics of forests. We use the Douglas-fir/western hemlock forests in the United States Pacific Northwest as a case study, with the assumption of continuous-cover forestry. These forests provide timbers of superb quality and have the highest productivity in North America. They are also critical habitats to many wildlife species including reptiles, birds, and mammals. The ecological criteria examined in this chapter include the stand basal area, species and size diversity measured with Shannon's index (Shannon 1948), and percentage of the forest in late seral stage (Hummel and Calkin 2005).

2 Methods and Data

2.1 *Markov Decision Process Models and Bootstrap Simulation*

Markov decision process models deal with sequential optimization of discrete-time stochastic processes (Feinberg and Schwartz 2001). The Markovian property states that the conditional probability of any future system state, such as the physical state of a stand of trees, depends only on the present state of the system (Hillier and Lieberman 2005). It is important to note that this does not necessarily imply that the system is "memoryless". Instead, it reflects the truism that the system state at a future point in time $t + 1$ can be predicted only with the information that is available at time t. This information, defining the system state at t can be quite extensive and it could in particular include past behavior of the system. Thus, Markov chain models are general and powerful representations of stochastic processes (Buongiorno and Gilless 2003, p. 352). Markov chains allow the simplification of complex, multi-dimensional stochastic processes and make their optimization easier or at all possible (Holling et al. 1986; Insley and Rollins 2005).

One difficulty of Markov models is the determination of the transition probabilities between stand states. This can be rarely done from direct observation of changes in actual stands because there are usually too few observations in some stand states, even with extensive data set like the one available for this study. However, the transition probabilities can be readily estimated with simulation models of stand growth of a suitable form to capture the complexity of stand growth, mortality and recruitment (Kaya and Buongiorno 1989). In such a simulation, bootstrapping can be used to advantage because it leaves the data as is, without imposing a particular distribution on the shocks, as is the case when multivariate normal distributions of the shocks are used instead (Liang et al. 2006).

The final MDP model being optimized consists of state variables, decisions or actions by state, transition probabilities between states conditional on decisions, and expected rewards by state and decision (Winston 1991, p. 1026). Here we restrict our discussion to MDP models with finite states over an infinite planning horizon. The objective can be either the expected average reward or the total discounted rewards over an infinite period. The optimization of a MDP model can be done with linear programming or dynamic programming.

2.2 *Forest Type Under Examination*

The forest type studied here is Douglas-fir/western hemlock (*Pseudotsuga menziesii/Tsuga heterophylla*) forests in the Pacific Northwest of the United States. This forest type is the source of the highest quality wood in North America, exceeding the biomass and productivity of any temperate or tropical forest (Franklin 1988).

The dominant species are Douglas-fir with a wood of superior mechanical properties (Barbour and Kellogg 1990), and western hemlock which, although less valuable than Douglas fir, is also commercially important (Burns and Honkala 1990; Zhou et al. 2008a).

Douglas-fir/western hemlock forest (Photo: Jingjing Liang)

Even-aged silviculture is most common in this forest type. However, there is growing interest in alternative silvicultural methods (O'Hara 1998; Miller and Emmingham 2001). Intense attention is also being paid to late-seral stands, for their inherent value for wildlife habitat and fonts of biodiversity (Hummel and Calkin 2005). Zhou et al. (2008b) study the long-run effects of implementing diameter caps policy for Douglas-fir/western hemlock forests – keeping all trees equal to or above 41 cm of diameter at breast height, in the context of uneven-aged/continuous cover forestry. Their finding suggests that diameter caps policy, while halving the net present value of timber, would significantly increase the area of late seral forests and of the availability of spotted-owl nesting habitat.

Late-seral Douglas-fir/western hemlock forest (Photo: Jingjing Liang)

2.3 *Simulation and Markov Model of Forest Growth and Management*

To "bring the real world into the laboratory" (Holling et al. 1986), we used a detailed stochastic simulation model of forest growth. This model was compacted into an equivalent Markov model of forest growth by bootstrapping. Decisions and attendant ecological rewards were then introduced to create a MDP model that could be readily optimized by linear programming.

In this MPD model of forest growth and management, the state variables were forest stand states; decisions were harvests given a state; transition probabilities defined changes between states after harvest or without harvest. Expected rewards were ecological criteria arising from stand states and decisions.

The Markov model to predict forest growth was built from 14,794 plots in Oregon and Washington (Zhou et al. 2008b). These plots were all classified in the Douglas-fir/western hemlock forest type. They were mostly in western Washington and Oregon, the Blue Mountains and Columbia Plateau of northeastern Oregon, and the Colville National Forest in northeastern Washington (Fig. 8.1). More than 60% of the plots were located on Federal lands within the range of the Northern Spotted Owl (NWP Regional Ecosystem Office 2005).

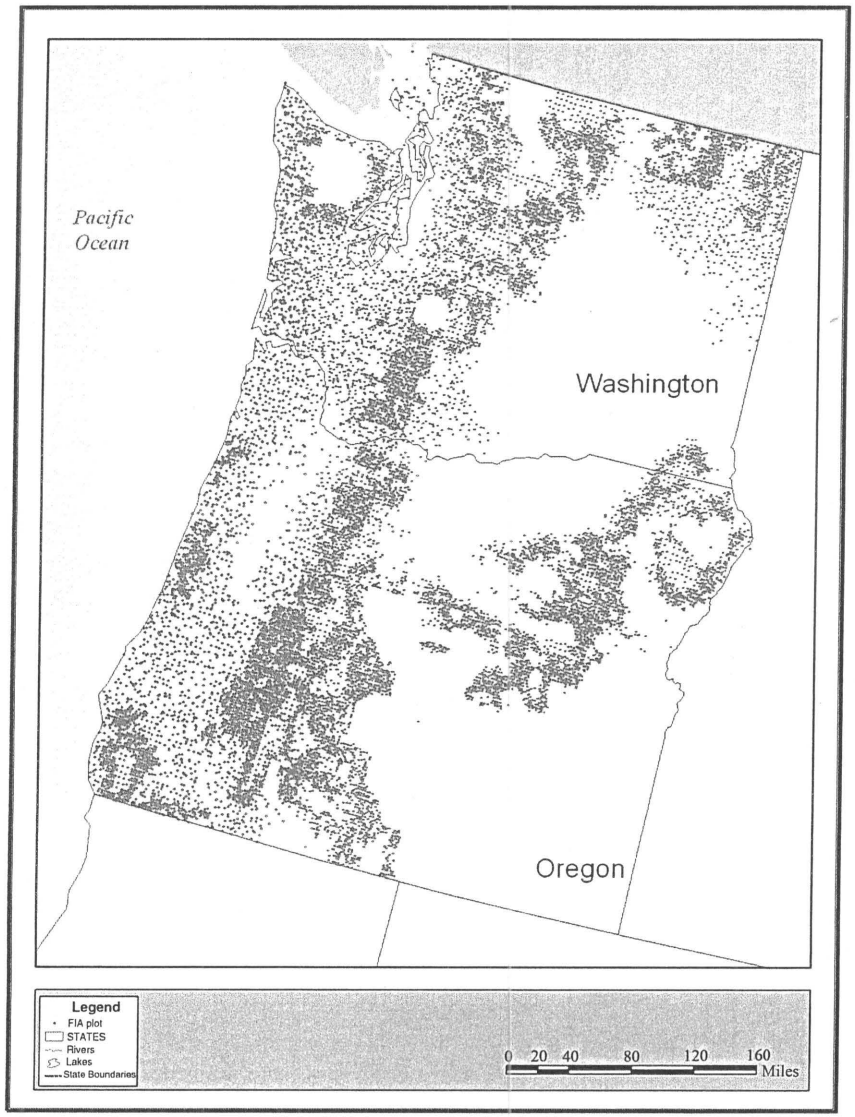

Fig. 8.1 Geographic distribution of the 14,794 FIA plots

The MDP model recognized two species groups. The shade-intolerant species consisted mostly of Douglas-fir (*Pseudotsuga menziesii*, 41% of the number of trees larger than 5.08 cm (2 in.) in diameter according to the Forest Inventory and Analysis (FIA) data), red alder (*Alnus rubra*, 11%), and ponderosa pine (*Pinus ponderosa*, 7%). The shade-tolerant species consisted of western hemlock

Table 8.1 Frequency of tree species in 14,794 FIA plots

Common name	Scientific name[a]	%
Shade-intolerant species		65.34
Douglas-fir	*Pseudotsuga menziesii*	41.27
Red alder	*Alnus rubra*	10.85
Ponderosa pine	*Pinus ponderosa*	7.10
Lodgepole pine	*Pinus contorta*	1.94
Western larch	*Larix occidentalis*	0.92
Black cottonwood	*Populus balsamifera* ssp.*trichocarpa*	0.72
Pacific madrone	*Arbutus menziesii*	0.63
Incense-cedar	*Calocedrus decurrens*	0.44
Oregon white oak	*Quercus garryana*	0.42
Western juniper	*Juniperus occidentalis*	0.26
Oregon ash	*Fraxinus latifolia*	0.25
Noble fir	*Abies procera*	0.18
Quaking aspen	*Populus tremuloides*	0.15
Western white pine	*Pinus monticola*	0.14
Sugar pine	*Pinus lambertiana*	0.05
Jeffrey pine	*Pinus jeffreyi*	0.01
Shade-tolerant Species		34.66
Western hemlock	*Tsuga heterophylla*	18.80
Western redcedar	*Thuja plicata*	5.88
Bigleaf maple	*Acer macrophyllum*	3.09
Grand fir	*Abies grandis*	2.09
Sitka spruce	*Picea sitchensis*	1.44
Pacific silver fir	*Abies amabilis*	1.32
White fir	*Abies concolor*	0.94
Mountain hemlock	*Tsuga mertensiana*	0.42
Engelmann spruce	*Picea engelmannii*	0.34
Subalpine fir	*Abies lasiocarpa*	0.17
Port-Orford-cedar	*Chamaecyparis lawsoniana*	0.12
Pacific yew	*Taxus brevifolia*	0.03
Alaska yellowcedar	*Chamaecyparis nootkatensis*	0.02
Redwood	*Sequoia sempervirens*	0.01
Total		100.00

[a]Nomenclature per Little (1979)

(*Tsuga heterophylla*, 19%), western redcedar (*Thuja plicata*, 6%), and bigleaf maple (*Acer macrophyllum*, 3%). Table 8.1 shows the detailed distribution of trees by species. Shade-tolerant and shade-intolerant trees were further divided into three size categories: small (10 cm $\leq$ dbh < 25 cm), medium (25 cm $\leq$ dbh < 41 cm), and large (dbh $\geq$ 41 cm).

For each species-size class the basal area was low (indicated by 0) if it was less than the threshold – the average basal area over the plots used to build the model, or high (indicated by 1) otherwise. The threshold for shade-intolerant species was 5.85, 5.37, 5.39 m^2/ha for small, medium, and large trees, and 3.25, 2.48, and 2.84 m^2/ha for shade-tolerant small, medium, and large trees.

Thus, each stand state was represented by a string of six digits, such as 100011. The first three digits referred to the basal area of shade-intolerant trees in the small, medium, and large trees, while the last three digits referred to the same for the shade-tolerant trees. With two levels in each of the six species-size categories, there were $2^6 = 64$ possible stand states. Figure 8.2 shows the expected basal area by tree size and species group in each stand state.

Stand growth was described by a matrix giving the probability that a stand would move from one state to another in 1 year (Table 8.2). For example, in 1 year, a stand in state 1 would stay in state 1 with a probability of 0.79, move to state 3 with probability 0.01, move to state 5 with probability 0.06, and so on.

The matrix of transition probabilities between stand states, $\mathbf{T} = [p(s'|s)]$, where $p(s'|s)$ is the annual probability of moving from state s to s', was obtained by stochastic simulation with bootstrapping. The simulation was based on a stochastic nonlinear matrix growth model (Liang et al. 2006):

$$\mathbf{y}_{t+1} = \mathbf{G}\mathbf{y}_t + \mathbf{r} + \mathbf{u}_{t+1} \tag{8.1}$$

where $\mathbf{y}_t = [y_{ijt}]$ is a column vector of the number of trees per *ha* of species group i (Douglas-fir and other shade-intolerant species, or western hemlock and other shade-tolerant species), and diameter class j (nineteen 5.1 cm diameter classes ranging from 7.6 to 99.1 cm and above), at time t. $\mathbf{G}$ is a matrix of transition rates, $\mathbf{r}$ is a column vector representing the recruitment between year t and $t+1$. Both $\mathbf{G}$ and $\mathbf{r}$ depend on $\mathbf{y}_t$, making the model nonlinear.

The elements of $\mathbf{G}$ an $\mathbf{r}$ were obtained with equations that predict individual tree growth, mortality, and stand recruitment as functions of tree and stand characteristics. The stand characteristics include species diversity, size diversity, stand basal area, and tree size (Liang et al. 2005). Diversity was measured with Shannon's index (Shannon 1948). The equations were estimated with individual tree and stand data from permanent plots in western Washington and Oregon. The detailed model structure and the related parameters are in the Appendix. Validation tests comparing the deterministic predictions with observations are reported in Liang et al. (2005).

The stochastic shock vector $\mathbf{u}_{t+1}$ on a particular plot was the difference between the observed and predicted number of trees, $\mathbf{y}_{t+1}$. Bootstrap simulation (Liang et al. 2006; Zhou and Buongiorno 2006) was used to calculate the transition probabilities between stand states. Each replication gave the state at $t+1$ given the state at t. The state at t was a plot taken randomly with replacement from the 14,794 FIA plots. The state at $t+1$ was obtained with model (1) by drawing one shock vector, $\mathbf{u}_{t+1}$, randomly with replacement from the set of all the shock vectors. 150,000 replications gave stable estimates of the complete annual transition matrix between stand states (Table 8.2).

For each predicted stand state we also recorded the stand basal area per ha, the tree species and tree size diversity measured with Shannon's index (Shannon 1948), and whether the state met the definitions of late seral forest (LSF) (Hummel and Calkin 2005). Stand basal area, the cross-sectional area of the stem of all the trees at breast height of a forest stand, is a useful indicator of stand volume and density. The need to keep a rich biological diversity has been an enduring concern

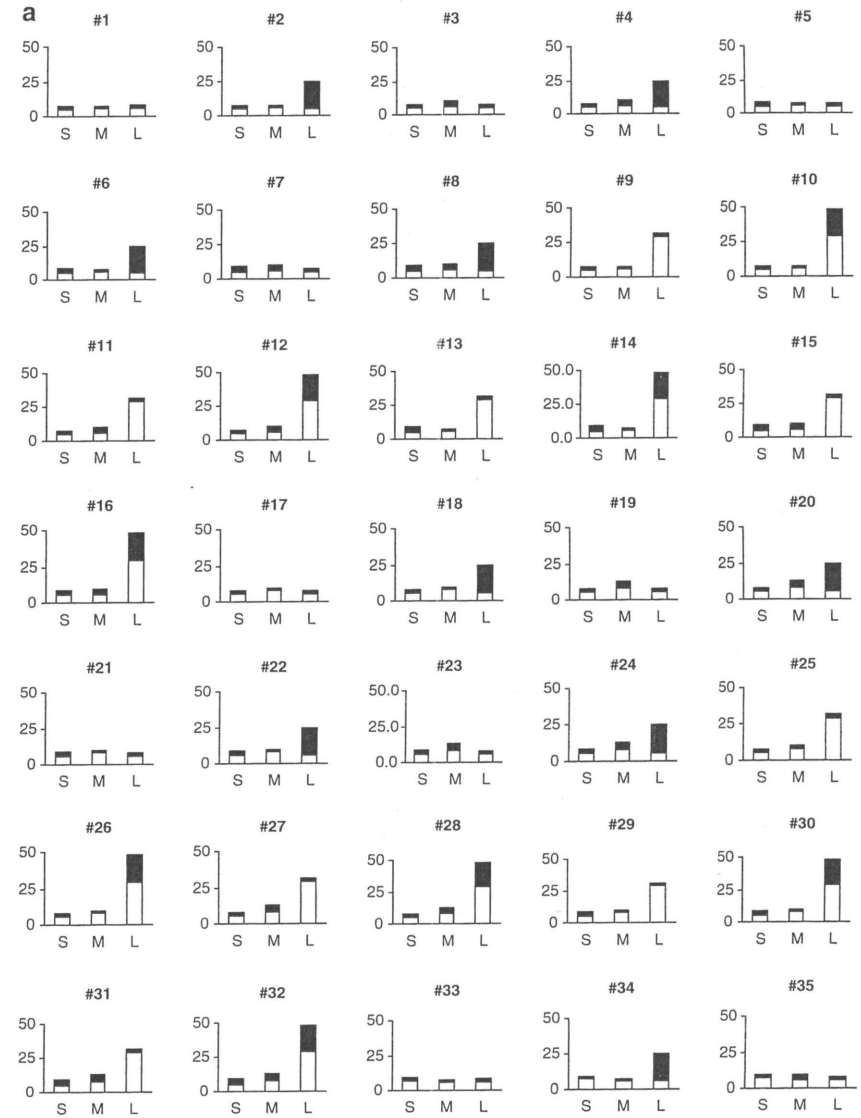

Fig. 8.2 (**a**) Expected basal area (m^2/ha) in small (*S*), medium (*M*), and large (*L*) pine trees (□) and hardwood trees (■), by stand state #. (**b**) Expected basal area (m^2/ha) in small (S), medium (M), and large (L) pine trees (□) and hardwood trees (■), by stand state #

of modern forest management (Hansen et al. 1991). Stands with greater vertical stratification – size diversity and rich in species composition provide critical habitats for many wildlife species (Ambuel and Temple 1983; Liang et al. 2006), and are

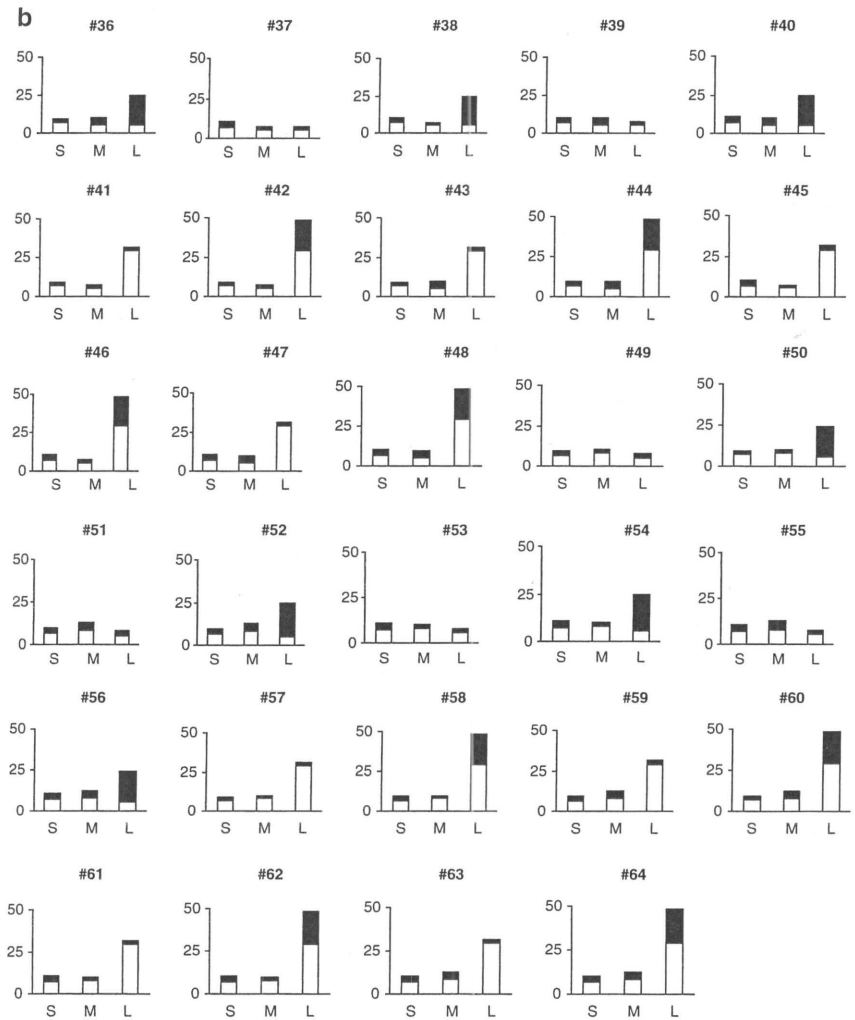

Fig. 8.2 (continued)

more aesthetically desirable (Guldin 1996). Late seral (old and mature) forests are crucial to the conservation of temperate biodiversity in the Pacific Northwest (Jiang et al. 2004).

The resulting expected values of the criteria, calculated as the mean over the 150,000 replications are in Table 8.3, together with the frequency of each stand state in the data. The expected basal area by stand state ranged from about 18 m^2/ha for state 1 (000000) with low basal area in all species and size categories, to 67 m^2/ha for state 46 (101101) with high basal area in the smallest and largest tree classes of both species groups. The expected basal area of large trees, 41 cm (16 in.) and

Table 8.2 Transition probabilities between stand states (Zhou et al. 2008a, b)

State #	State at t	State # at $t+1$ year (transition probability)
1	000000	1(.79), 3(.01), 5(.06), 17(.01), 33(.11)
2	000001	2(.78), 4(.03), 6(.07), 10(.02), 14(.01), 18(.04), 34(.04)
3	000010	1(.02), 3(.80), 4(.02), 7(.07), 11(.01), 19(.03), 35(.03)
4	000011	2(.01), 4(.88), 8(.05), 12(.01), 20(.02), 36(.02)
5	000100	1(.04), 5(.82), 7(.07), 21(.02), 37(.04)
6	000101	2(.03), 4(.01), 6(.82), 8(.04), 10(.01), 14(.02), 22(.03), 34(.01), 38(.04)
7	000110	3(.03), 5(.01), 7(.84), 8(.03), 15(.01), 23(.03), 39(.04)
8	000111	4(.02), 8(.91), 16(.01), 24(.02), 40(.03)
9	001000	9(.83), 10(.04), 11(.03), 12(.01), 13(.03), 25(.02), 41(.03)
10	001001	10(.88), 12(.02), 14(.04), 26(.02), 42(.03)
11	001010	9(.04), 11(.76), 12(.07), 15(.02), 27(.05), 43(.03)
12	001011	10(.04), 12(.84), 16(.04), 28(.02), 44(.04)
13	001100	9(.02), 13(.83), 14(.03), 15(.04), 29(.04), 45(.03)
14	001101	10(.03), 14(.88), 16(.03), 30(.02), 46(.04)
15	001110	11(.02), 13(.01), 15(.83), 16(.08), 31(.02), 47(.03)
16	001111	12(.02), 14(.02), 16(.90), 32(.02), 48(.04)
17	010000	1(.02), 17(.81), 19(.03), 21(.03), 25(.04), 49(.06)
18	010001	2(.04), 18(.76), 20(.05), 22(.04), 26(.04), 50(.05)
19	010010	3(.03), 17(.03), 19(.76), 20(.02), 23(.04), 27(.05), 51(.04)
20	010011	4(.04), 18(.02), 20(.81), 24(.04), 28(.03), 52(.05)
21	010100	5(.03), 17(.03), 21(.77), 23(.07), 29(.03), 53(.05), 55(.01)
22	010101	6(.04), 18(.04), 22(.77), 24(.05), 26(.01), 30(.04), 54(.05)
23	010110	7(.04), 19(.03), 21(.01), 23(.78), 24(.03), 31(.05), 55(.05)
24	010111	8(.04), 20(.02), 22(.01), 24(.85), 32(.02), 56(.04)
25	011000	9(.02), 25(.84), 26(.03), 27(.02), 29(.04), 57(.04)
26	011001	10(.05), 26(.84), 28(.02), 30(.04), 58(.04)
27	011010	11(.02), 25(.03), 27(.80), 28(.06), 31(.04), 59(.03)
28	011011	12(.05), 26(.04), 28(.82), 32(.04), 60(.03)
29	011100	13(.03), 25(.03), 29(.82), 30(.03), 31(.03), 61(.04)
30	011101	14(.06), 26(.03), 30(.84), 32(.03), 62(.04)
31	011110	15(.01), 27(.02), 29(.01), 31(.85), 32(.05), 63(.04)
32	011111	16(.05), 28(.03), 30(.02), 32(.85), 64(.04)
33	100000	1(.04), 33(.85), 35(.01), 37(.03), 49(.06)
34	100001	2(.05), 6(.01), 18(.01), 34(.74), 36(.05), 38(.06), 42(.01), 50(.08),
35	100010	3(.02), 19(.01), 33(.03), 35(.75), 36(.02), 39(.04), 51(.10),
36	100011	4(.05), 34(.03), 36(.80), 40(.05), 44(.02), 52(.05)
37	100100	5(.03), 33(.03), 37(.78), 39(.05), 53(.08)
38	100101	6(.07), 8(.01), 34(.01), 36(.01), 38(.75), 40(.06), 46(.03), 48(.01), 54(.05), 56(.01)
39	100110	7(.04), 35(.02), 37(.01), 39(.80), 40(.02), 47(.01), 55(.09)
40	100111	8(.05), 24(.01), 36(.02), 38(.01), 40(.85), 48(.01), 56(.04)
41	101000	9(.04), 41(.73), 42(.07), 43(.02), 45(.03), 57(.08), 59(.01)
42	101001	10(.05), 42(.86), 46(.04), 58(.02)
43	101010	11(.03), 12(.01), 41(.04), 42(.01), 43(.73), 44(.08), 47(.05), 59(.02)
44	101011	12(.06), 42(.04), 44(.81), 46(.01), 48(.04), 60(.02)

(continued)

Table 8.2 (continued)

State #	State at t	State # at $t+1$ year (transition probability)
45	101100	13(.04), 15(.01), 41(.04), 45(.77), 46(.05), 47(.03), 61(.06)
46	101101	14(.05), 42(.03), 46(.88), 48(.02), 62(.02)
47	101110	15(.02), 16(.01), 43(.03), 45(.01), 47(.77), 48(.07), 61(.01), 63(.05)
48	101111	16(.04), 44(.02), 46(.02), 48(.88), 64(.02)
49	110000	17(.03), 33(.01), 49(.87), 51(.02), 53(.04), 57(.02)
50	110001	18(.03), 34(.01), 50(.82), 52(.03), 54(.05), 58(.04)
51	110010	19(.03), 35(.01), 49(.04), 51(.81), 52(.02), 55(.04), 59(.03),
52	110011	20(.04), 36(.02), 50(.02), 52(.86), 56(.04), 60(.02)
53	110100	21(.02), 37(.01), 49(.03), 53(.84), 55(.06), 61(.03)
54	110101	22(.02), 38(.01), 50(.02), 54(.87), 56(.03), 62(.04)
55	110110	23(.03), 39(.01), 51(.02), 53(.01), 55(.85), 56(.03), 63(.04)
56	110111	24(.03), 40(.02), 52(.02), 54(.01), 56(.90), 64(.02)
57	111000	25(.03), 41(.01), 57(.87), 58(.03), 59(.02), 61(.04)
58	111001	26(.03), 42(.02), 58(.88), 60(.02), 62(.04)
59	111010	27(.03), 57(.04), 59(.83), 60(.04), 63(.04)
60	111011	26(.01), 28(.05), 44(.02), 58(.04), 60(.81), 64(.06)
61	111100	29(.03), 57(.04), 61(.85), 62(.02), 63(.04)
62	111101	30(.03), 46(.03), 58(.04), 62(.87), 64(.02)
63	111110	31(.04), 47(.01), 59(.02), 61(.03), 63(.85), 64(.04)
64	111111	32(.04), 48(.03), 60(.02), 62(.02), 64(.88)

A state is defined by the level of basal area by tree species class and size class. For example state #58 (111001) means that basal area is high in the small, medium, and large shade-intolerant trees, low in the small and medium shade-tolerant trees, and high in the large shade-tolerant trees

above, was lowest for state 1 and highest for state 10 (001001) with high basal area in the large trees of the shade-intolerant and shade-tolerant species.

States 12 and 10 had the highest probability of having the structure of a late seral forest. In both states the shade-intolerant species (mostly Douglas-fir) had high basal area in large trees, and low basal area in the small and medium trees. In both states 12 and 10, the shade-tolerant trees (mostly western hemlock) had low basal area in the small trees, and high basal area in the large trees.

A decision means harvesting a stand and thus changing its state. For example, for stand state #4 (000011) – high basal area in medium and large shade-tolerant trees, a decision could be to do nothing, or to thin the large shade-tolerant trees to low basal area and thus move to state #3 (000010) – high basal area only in medium shade-tolerant trees, or to thin the medium shade-tolerant trees and move to state #2 (000001) – high basal area only in large shade-tolerant trees, or to thin the medium and large shade-tolerant trees and thus move to state #1 (000000) – low basal area in all six categories.

Each decision resulted in an immediate return, R_{sd}, the ecological criterion obtained from state s and decision d. After the decision, the residual stand would change state over 1 year according to the transition probabilities in Table 8.2. So, a stand would move from pre-decision state s to state s' after 1 year with probability $p(s'|s,d)$ depending on the decision, d.

Table 8.3 Probability of stand states in the study area, with their tree species diversity, tree size diversity, basal area, and probability that a stand state met late-seral forest (LSF) criteria (Hummel and Calkin 2005; Zhou et al. 2008a, b)

Stand state #	Initial prob.	Tree species div.	Tree size div.	Basal area (m^2/ha)	LSF prob.
1	0.066	1.13	2.69	18.2	0.00
2	0.002	1.33	2.81	50.4	0.01
3	0.011	1.25	2.74	28.7	0.00
4	0.011	1.32	2.80	50.2	0.06
5	0.031	1.23	2.69	20.9	0.00
6	0.002	1.34	2.85	54.0	0.01
7	0.025	1.28	2.74	30.3	0.00
8	0.027	1.32	2.83	53.7	0.02
9	0.004	1.07	2.82	49.3	0.00
10	0.024	1.15	2.78	63.6	0.52
11	0.003	1.15	2.83	49.8	0.00
12	0.021	1.19	2.80	63.5	0.83
13	0.004	1.11	2.86	52.2	0.00
14	0.024	1.16	2.80	65.0	0.18
15	0.005	1.17	2.85	52.3	0.00
16	0.043	1.21	2.84	63.9	0.14
17	0.015	1.13	2.75	32.3	0.00
18	0.002	1.33	2.81	50.4	0.00
19	0.007	1.19	2.75	37.9	0.00
20	0.007	1.35	2.79	52.9	0.04
21	0.008	1.17	2.79	35.9	0.00
22	0.002	1.34	2.85	53.8	0.00
23	0.012	1.24	2.76	39.7	0.00
24	0.016	1.34	2.80	53.8	0.04
25	0.013	1.10	2.82	50.9	0.01
26	0.018	1.16	2.82	62.4	0.06
27	0.008	1.15	2.81	51.4	0.12
28	0.018	1.21	2.81	62.0	0.10
29	0.011	1.12	2.85	53.8	0.00
30	0.017	1.19	2.84	64.5	0.05
31	0.016	1.17	2.83	54.8	0.00
32	0.032	1.21	2.84	63.1	0.19
33	0.055	1.08	2.68	21.1	0.00
34	0.001	1.33	2.86	53.5	0.00
35	0.005	1.25	2.73	31.1	0.00
36	0.004	1.34	2.84	53.7	0.01
37	0.016	1.19	2.69	26.3	0.00
38	0.001	1.34	2.85	58.7	0.00
39	0.012	1.26	2.73	34.0	0.00
40	0.011	1.33	2.85	56.4	0.00
41	0.002	1.06	2.86	55.6	0.00
42	0.013	1.15	2.82	66.5	0.02
43	0.001	1.15	2.87	54.3	0.00

(continued)

Table 8.3 (continued)

Stand state #	Initial prob.	Tree species div.	Tree size div.	Basal area (m^2/ha)	LSF prob.
44	0.011	1.19	2.85	65.3	0.02
45	0.002	1.11	2.87	57.7	0.00
46	0.017	1.18	2.84	67.3	0.00
47	0.003	1.16	2.88	54.7	0.00
48	0.028	1.22	2.86	66.8	0.00
49	0.041	1.12	2.74	35.3	0.00
50	0.003	1.31	2.83	57.4	0.00
51	0.013	1.19	2.74	40.7	0.00
52	0.010	1.34	2.80	56.6	0.00
53	0.024	1.16	2.76	38.7	0.00
54	0.004	1.35	2.86	61.9	0.00
55	0.026	1.22	2.74	44.0	0.00
56	0.025	1.34	2.81	58.9	0.00
57	0.022	1.09	2.85	55.1	0.00
58	0.025	1.17	2.85	65.0	0.01
59	0.011	1.14	2.83	56.1	0.05
60	0.015	1.20	2.85	64.3	0.02
61	0.019	1.13	2.86	57.9	0.00
62	0.023	1.19	2.87	66.6	0.00
63	0.022	1.17	2.85	58.5	0.00
64	0.037	1.22	2.87	65.8	0.00

2.4 *Optimizing Discounted Criteria*

The following linear program (d'Epenoux 1963; Hillier and Lieberman 2005, p. 921) was used to find the policy (harvest by stand state) that maximized the discounted value of a specific criterion over an infinite time horizon.

$$\max_{y_{sd}} \sum_s \sum_d R_{sd} \cdot y_{sd}$$

$$s.t.$$

$$\sum_d y_{s'd} - \frac{1}{(1+r)} \sum_s \sum_d y_{sd}\, p\left(s' \,|s, d\right) = \pi_{s'} \quad s' = 1, \ldots, N$$

$$y_{sd} \geq 0, \quad for\ s = 0, 1, \ldots, N. \tag{8.2}$$

where R_{sd} was the immediate ecological criterion resulting from stand state s and decision d. The unknown, y_{sd}, was the discounted expected time in state s and decision d. The constant r was the discount rate, and $\pi_{s'}$ was the initial probability of each of the N initial states, s'.

Given the solution of (8.2), the policy that maximized the discounted criterion was obtained from:

$$p(d\,|s) = \frac{y_{sd}}{\sum_d y_{sd}} \tag{8.3}$$

where y_{sd} was the probability of decision d given state s, under the best policy. The policy was deterministic ($p(d|s) = 0$, or 1). Furthermore, the best policy was independent of the initial condition $\{\pi_{s'}\}$ (Hillier and Lieberman 2005, p. 921).

The steady-state probability of state s and decision d, needed to determine the long-term expected effect of the best policy, was obtained as follows. The transition probability matrix with the best policy was:

$$\mathbf{T}^* = \mathbf{DT} \tag{8.4}$$

where **D** was the decision matrix of the best policy and **T** the transition probability matrix without decision.

The steady-state probabilities of stand states under the best policy, $\mathbf{P} = [p_s]$, were then obtained by solving the system of simultaneous equations:

$$\mathbf{P} = \mathbf{PT}^* \tag{8.5}$$

Then, the probability of state s and decision d for the best policy was:

$$p_{sd} = p_s\, p(d\,|s) \tag{8.6}$$

2.5 *Optimizing Undiscounted Criteria*

Without discounting, the objective function was the expected value of the ecological criterion, over an infinite horizon. The following linear program was used to obtain the best undiscounted policy (Winston 1991, p. 1034):

$$\max_{z_{sd}} \sum_s \sum_d R_{sd} \cdot p_{sd}$$

$$s.t.$$

$$\sum_d p_{s'd} - \sum_s \sum_d p_{sd}\, p\left(s' \,|s, d\right) = 0 \quad j = 1, \ldots, N$$

$$p_{sd} \geq 0,$$

$$\sum_s \sum_d p_{sd} = 1 \tag{8.7}$$

where the unknown, p_{sd}, was the steady-state probability of state s and decision d.

The best policy was given by:

$$p(d|s) = \frac{p_{sd}}{\sum_d p_{sd}} \tag{8.8}$$

where $p(d|s)$ was the probability of decision d given state s under the best policy. As in the discounted case, the best decision was deterministic ($p(d|s)$ =0, or 1).

The steady-state probability of stand state s under the best policy was:

$$p_s = \sum_d p_{sd} \tag{8.9}$$

2.6 *Effects of Policies*

The immediate impact of a policy on a particular stand was R_{sd}, the ecological criterion resulting from stand state s and decision d. The steady state probability of a stand state, p_s, derived above could also be interpreted as the expected fraction of a large forest area that would be in a particular state in the long-run, under the chosen policy.

The long-term or steady-state effects of a policy on the ecological criteria (tree species diversity, tree size diversity, stand basal area, and late-seral forest probability) were computed as the expected value of the undiscounted criteria:

$$E(R) = \sum_s \sum_d p_{sd} R_{sd} \tag{8.10}$$

To assess the interim effect of a policy, the probability of stand state s after n years of applying a policy was calculated from:

$$\pi_n = \pi \mathbf{T}^n \tag{8.11}$$

where $\boldsymbol{\pi} = [\pi_s]$ was the row vector of probability of the initial state. As n increased, $\boldsymbol{\pi}_n$ converged to $\mathbf{P} = [p_s]$, the steady-state probability of stand states.

For a particular policy, the expected cutting cycle, $E(c)$, was the expected interval between states that called for harvest. As p_s was the steady state probability of state s under that policy, the probability of being in a state that called for harvest, p_c, was:

$$p_c = \sum_{s \in S} p_s \tag{8.12}$$

where S was the set of all states that called for harvest under the policy. Then,

$$E(c) = \frac{1}{p_c} \tag{8.13}$$

was the expected cutting cycle (Kaya and Buongiorno 1989).

3 Results

3.1 *Best Policies With and Without Discounting*

The same discount rate of 3.8%, used previously by Zhou et al. (2008a, 2008b) to discount economic returns, was also used to discount the ecological criteria. With discounting, the maximum value of the criteria over an infinite time horizon (but not the corresponding best decisions) depends on the initial condition. For the stand states, the initial condition was defined by the frequency of stand states in the forests under study (Table 8.3).

Models (8.2) and (8.7) were used to maximize the discounted and undiscounted ecological criteria, respectively. The best policies were defined by the stand state that would be left after harvest, given the stand state at decision time (Table 8.4).

With or without discounting the policies are stationary (independent of the time of the decision), deterministic (the probability of making a decision in a particular state is 0 or 1), independent of the initial state, and dependent only on the stand state at decision time (Hillier and Lieberman 2005, p. 911 and 921).

For example, if the objective was to maximize discounted species diversity and the stand was in state 21 (010100) – high basal area in medium shade-tolerant and small shade-intolerant trees, the best decision was to cut the stand to state 5 (000100) – high basal area only in small shade-tolerant trees, by reducing the basal area of medium shade-intolerant trees (Table 8.4). If instead species diversity were not discounted, the best decision was to cut the same stand to state 17 (010000) – high basal only in medium shade-intolerant trees, reducing the basal area in small shade-tolerant trees.

When maximizing tree species diversity, 18 of the 64 stand states called for different decisions depending on whether discounting was or was not done. In maximizing tree size diversity, the decisions with and without discounting were different for five states only. When basal area was maximized, all but two stand states called for the same decisions with or without discounting. To maximize discounted LSF, 13 stand states required different decisions depending on whether LSF was discounted or not.

3.2 *Immediate Impact of Discounting*

Table 8.5 shows how discounting changed the ecological criteria of the stand that remained immediately after a harvest. For 20 stand states there was a difference in at least one of the criteria.

For example, when maximizing tree species diversity, for a stand in state #45 (101100) – high basal area in small and large shade-intolerant trees and small shade-tolerant trees, the policy with discounting called for cutting the stand to state #5 (000100) – high basal area only in small shade-tolerant trees, with an expected

Table 8.4 Decisions that maximized discounted (D) or undiscounted (U) ecological criteria

	Species diversity		Size diversity		Basal area (m^2/ha)		Late seral forest (%)	
Stand state	D	U	D	U	D	U	D	U
1	–	–	–	–	–	–	–	–
2	–	–	–	–	–	–	–	–
3	–	–	–	–	–	–	–	–
4	2	2	2	2	**2**	**3**	2	2
5	–	–	–	–	–	–	–	–
6	–	–	–	–	–	–	2	2
7	–	–	–	–	–	–	–	–
8	6	6	6	6	6	6	2	2
9	–	–	–	–	–	–	–	–
10	2	2	9	9	–	–	–	–
11	**3**	–	–	–	–	–	–	–
12	2	2	11	11	–	–	–	–
13	**5**	–	–	–	–	–	9	9
14	6	6	13	13	–	–	10	10
15	**7**	–	13	13	–	–	–	–
16	6	6	13	13	14	14	12	12
17	–	–	–	–	–	–	–	–
18	–	–	–	–	–	–	–	–
19	3	3	–	–	–	–	–	–
20	–	–	**18**	–	18	18	–	**18**
21	**5**	**17**	–	–	–	–	–	**17**
22	–	–	–	–	–	–	18	18
23	7	7	–	–	–	–	–	**19**
24	20	20	22	22	22	22	**20**	–
25	**9**	**17**	–	–	9	9	9	9
26	18	18	–	**25**	10	10	10	10
27	**3**	–	11	11	–	–	–	–
28	20	20	11	11	12	12	12	12
29	**5**	–	13	13	–	–	9	9
30	22	22	13	13	14	14	10	10
31	**7**	**15**	13	13	–	**15**	15	15
32	20	20	13	13	14	14	12	12
33	1	1	–	–	–	–	–	–
34	–	–	–	–	–	–	2	2
35	3	3	–	–	–	–	–	–
36	–	–	34	34	–	–	**2**	–
37	**5**	–	–	–	–	–	–	–
38	–	–	–	–	–	–	–	–
39	7	7	–	–	–	–	–	–
40	38	38	38	38	38	38	38	38
41	–	–	–	–	–	–	–	–
42	34	34	41	41	–	–	10	10
43	–	–	–	–	–	–	–	–
44	36	36	43	43	42	42	12	12

(continued)

Table 8.4 (continued)

	Species diversity		Size diversity		Basal area (m^2/ha)		Late seral forest (%)	
Stand state	D	U	D	U	D	U	D	U
45	**5**	**41**	–	–	–	–	41	41
46	38	38	45	45	–	–	10	10
47	**7**	**15**	–	–	–	–	43	43
48	38	38	47	47	46	46	12	12
49	**17**	–	17	17	–	–	**17**	–
50	18	18	34	34	–	–	–	–
51	3	3	19	19	–	–	**19**	–
52	**20**	–	34	34	50	50	**20**	**50**
53	**5**	**49**	21	21	–	–	**21**	–
54	–	–	–	–	–	–	50	50
55	7	7	**23**	–	–	–	**23**	–
56	54	54	54	54	54	54	**20**	**50**
57	**41**	**49**	41	41	41	41	41	41
58	18	18	**41**	–	42	42	10	10
59	43	43	43	43	43	43	43	43
60	**20**	**52**	43	43	42	42	12	12
61	**5**	**49**	45	45	45	45	**41**	–
62	54	54	–	**45**	46	46	10	10
63	**7**	**15**	47	47	47	47	43	43
64	54	54	47	47	46	46	**12**	–

Numbers refer to stand states resulting from a decision (harvest). Those in bold indicate decisions that differed if the criterion was discounted. Hyphens mean no harvest

species diversity of 1.23 (Table 8.3). Meanwhile, maximizing undiscounted species diversity called for cutting the stand to state 41 (101000) – high basal area in small and large shade-intolerant trees, with an expected species diversity of 1.06. Thus discounting led to a 16% immediate gain in expected species diversity. For most stand states, discounting led to higher expected tree species diversity immediately after harvest, but for stand states #25 (011000) – high basal area in medium and large shade-intolerant trees, and #57 (111000) – high basal area in all three sizes of shade-intolerant trees, it led to 5% lower expected tree diversity, which presumably was compensated by higher expected tree species diversity from subsequent decisions, leading to a higher discounted tree species diversity over an infinite time horizon.

When maximizing tree size diversity only for states #20 (01001) – high basal area in medium shade-intolerant trees and large shade-tolerant trees, and #55 (110110) – high basal area except for large shade-intolerant and shade-tolerant trees, did the policy with discounting lead to a slightly higher index of expected tree size diversity immediately after harvest.

Maximizing discounted stand basal area led to decisions that increased the expected post-harvest basal area only in pre harvest states #4 (00011) – high basal area in medium and large shade-tolerant trees, and #31 (011110) – high basal area except for small shade-intolerant and large shade-tolerant trees. State #4 called for

Table 8.5 Immediate impact of policies that maximized discounted criteria relative to those that did not discount

		Max			
State		Tree species diversity	Tree size diversity	Basal area	Late seral forest[a]
4	000011	0.00	0.00	0.76	0.00
11	001010	0.09	0.00	0.00	0.00
13	001100	0.11	0.00	0.00	0.00
15	001110	0.09	0.00	0.00	0.00
20	010011	0.00	0.01	0.00	0.04
21	010100	0.09	0.00	0.00	0.00
25	011000	−0.05	0.00	0.00	0.00
27	011010	0.09	0.00	0.00	0.00
29	011100	0.10	0.00	0.00	0.00
31	011110	0.09	0.00	0.05	0.00
37	100100	0.03	0.00	0.00	0.00
45	101100	0.16	0.00	0.00	0.00
47	101110	0.09	0.00	0.00	0.00
49	110000	0.01	0.00	0.00	0.00
52	110011	0.01	0.00	0.00	0.04
53	110100	0.10	0.00	0.00	0.00
55	110110	0.00	0.01	0.00	0.00
56	110111	0.00	0.00	0.00	0.04
57	111000	−0.05	0.00	0.00	0.00
58	111001	0.00	0.00	0.00	0.00
60	111011	0.01	0.00	0.00	0.00
61	111100	0.10	0.00	0.00	0.00
63	111110	0.09	0.00	0.00	0.00
64	111111	0.00	0.00	0.00	0.83

[a] Increase in probability that a stand meets late seral forest criteria

harvest to state #2 (00001) – high basal area only in large shade-tolerant trees, with discounting, compared to state #3 (00010) – high basal area only in medium shade-tolerant trees, without discounting, for an immediate 76% gain of expected post-harvest basal area. State #31 called for no harvest with discounting, and harvest to state #15 (001110) – high basal area in large shade-intolerant and small and medium shade-tolerant trees, without discounting, for a 5% gain in expected basal area immediately after harvest.

In maximizing LSF probability, although the best decisions with discounting differed from those without discounting for 13 stand states (Table 8.4), discounting led to a stand with higher probability of LSF characteristics only for four stand states. The largest difference was for state #64 (111111) – high basal area in all six species-size categories, for which discounting led to stand state 12 (001011) – high basal area in large shade-intolerant and medium and large shade-tolerant trees with a 0.83 probability of LSF characteristics, while not discounting maintained state 64, with a 0.00 LSF probability.

Table 8.6 Long-term effects of maximizing discounted or undiscounted ecological criteria on expected forest characteristics

Expected forest characteristics	With discounting	Without discounting
	Max tree species diversity	
Tree species diversity	1.33	1.34
Tree size diversity	2.82	2.83
Basal area (m^2/ha)	54.16	54.85
Late seral forest (%)	1.01	0.76
Cutting cycle (year)	9.40	10.35
	Max tree size diversity	
Tree species diversity	1.11	1.11
Tree size diversity	2.85	2.85
Basal area (m^2/ha)	53.19	53.12
Late seral forest (%)	0.00	0.04
Cutting cycle (year)	7.90	7.87
	Max basal area (m^2/ha)	
Tree species diversity	1.16	1.17
Tree size diversity	2.80	2.81
Basal area (m^2/ha)	65.13	65.32
Late seral forest (%)	21.58	21.47
Cutting cycle (year)	22.33	22.32
	Max late seral forest area (%)	
Tree species diversity	1.16	1.17
Tree size diversity	2.78	2.79
Basal area (m^2/ha)	63.26	63.33
Late seral forest (%)	61.56	61.60
Cutting cycle (year)	9.87	9.87

3.3 Long-Term Effects of Discounting

Regardless of the immediate impact of a policy, the long-term effect would be different due to the cumulative effect of successive decisions over a long period of time. We present first the effects of discounting over an infinite time horizon, and then the transient effects during the first five decades.

To determine the forest characteristics that would result in the long term from discounted or undiscounted policies we computed the undiscounted expected value of the criteria, over an infinite time horizon with Eq. 8.10. Being undiscounted, this expected value was independent of the initial condition. Equation 8.13 gave the expected cutting cycle.

Discounting tree species diversity, tree size diversity, basal area, and LSF probability had a negligible effect on their long-term expected value (Table 8.6). Discounting changed the expected cutting cycle only when maximizing tree species diversity, shortening it by about 1 year.

Table 8.7 shows the expected long-term composition of the forest, defined by the distribution of stand states that would result from maximizing each ecological

Table 8.7 Long-term frequency (%) of stand states in the forest landscape, resulting from the maximization of discounted ecological criteria

	Max:			
Stand state	Tree species diversity	Tree size diversity	Basal area (m^2/ha)	Late seral forest (%)
1	0.0	0.0	0.0	0.0
2	12.1(10.6)	0.0	0.1	0.5
3	0.0	0.0	0.0	0.0
4	1.3	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	16.4(15.1)	0.1	0.1	0.0
7	0.0	0.1	0.0	0.0
8	0.9	0.0	0.0	0.0
9	0.0	12.6	0.1	0.2
10	0.4	0.6	21.9	58.1
11	0.0	6.3	0.0	0.1
12	0.0	0.7	4.8	30.3
13	0.0	28.3	0.1	0.0
14	0.5	1.0	29.0	2.6
15	0.0	1.8	0.1	0.1
16	0.0	0.2	1.1	1.6
17	0.0	0.0	0.0	0.0
18	13.0	0.0	0.0	0.2
19	0.0	0.0	0.0	0.0
20	14.5(10.3)	0.0	0.0	0.1
21	0.0	0.0	0.0	0.0
22	7.1	0.0	0.0	0.0
23	0.0	0.1	0.0	0.0
24	1.2	0.0	0.0	0.0
25	0.0	2.2(2.7)	0.0	0.0
26	0.8	0.5	0.5	1.1
27	0.0	0.5	0.0	0.0
28	0.5	0.0	0.1	0.8
29	0.0	1.6	0.0	0.0
30	0.3	0.1	0.6	0.1
31	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0
34	3.5	0.0	0.0	0.0
35	0.0	0.0	0.0	0.0
36	1.4	0.0	0.0	0.0
37	0.0	0.0	0.0	0.0
38	6.8	0.0	0.0	0.0
39	0.0	0.1	0.0	0.0
40	0.6	0.0	0.0	0.0
41	0.0	11.6	0.1	0.1
42	0.0	1.1	15.7	2.0

(continued)

Table 8.7 (continued)

	Max:			
Stand state	Tree species diversity	Tree size diversity	Basal area (m^2/ha)	Late seral forest (%)
43	0.0	5.5	0.1	0.1
44	0.0	0.5	0.6	1.5
45	0.0	12.3	0.1	0.0
46	0.2	0.7	23.0	0.1
47	0.0	7.4	0.0	0.0
48	0.0	0.6	0.6	0.1
49	0.0	0.0	0.0	0.0
50	1.5	0.0	0.0	0.1
51	0.0	0.0	0.0	0.0
52	0.9	0.0	0.0	0.0
53	0.0	0.0	0.0	0.0
54	14.5(17.5)	0.0	0.1	0.0
55	0.0	0.0	0.0	0.0
56	0.6	0.0	0.0	0.0
57	0.0	1.2	0.0	0.0
58	0.1	0.0	0.4	0.0
59	0.0	0.3	0.0	0.0
60	0.0	0.0	0.0	0.0
61	0.0	1.0	0.0	0.0
62	0.6	0.0	0.5	0.0
63	0.0	0.5	0.0	0.0
64	0.0	0.0	0.0	0.0
Total	100.0	100.0	100.0	100.0

In parentheses are the frequencies with undiscounted criteria that were significantly different

objective, with discounting and without discounting (in parentheses) over an infinite time horizon. Alternatively, this can be interpreted as the long-term probability that a particular stand would be in any given state, independently of its initial condition.

In maximizing tree species diversity, discounting raised the frequency of stand states #2 (000001) – high basal area only in large shade-tolerant trees, #6 (000101) – high basal area in small and large shade-tolerant trees, and #20 (010011) – high basal area in medium shade-intolerant and medium and large shade-tolerant trees. It lowered the frequency of state 54 (110101) – high basal area except for large shade-intolerant and medium shade-tolerant tree, by 3%, the largest change.

In maximizing tree size diversity, only stand state #25 (011000) – high basal area in medium and large shade-intolerant tree, would be less frequent with discounting, but by less than 1%. When maximizing basal area or LSF probability, discounting had no effect on the frequency distribution of stand states.

Table 8.8 Effects of maximizing discounted or undiscounted ecological criteria on expected forest characteristics after 10, 20, or 50 years, for a forest with the initial distribution of stands in Table 8.2

	With discounting			Without discounting		
Forest characteristics	10 years	20 years	50 years	10 years	20 years	50 years
	Max. species diversity					
Species diversity	1.29	1.31	1.33	1.28	1.31	1.33
Size diversity	2.79	2.81	2.82	2.80	2.81	2.82
Basal area (m^2/ha)	44.81	49.17	52.43	46.36	50.08	53.10
Late seral forest (%)	0.99	1.20	1.38	0.52	1.05	1.15
	Max. size diversity					
Species diversity	1.15	1.13	1.11	1.15	1.13	1.11
Size diversity	2.83	2.85	2.85	2.83	2.85	2.85
Basal area (m^2/ha)	49.46	52.33	53.14	49.47	52.26	53.07
Late seral forest (%)	0.11	0.09	0.06	0.09	0.06	0.04
	Max. basal area					
Species diversity	1.18	1.18	1.17	1.18	1.18	1.17
Size diversity	2.80	2.80	2.81	2.79	2.80	2.81
Basal area (m^2/ha)	53.86	57.26	62.65	53.26	56.48	61.94
Late seral forest (%)	9.97	12.54	17.73	10.15	12.41	17.46
	Max. late seral forest					
Species diversity	1.18	1.17	1.17	1.18	1.17	1.17
Size diversity	2.79	2.79	2.79	2.78	2.79	2.79
Basal area (m^2/ha)	55.31	60.73	63.01	55.42	60.64	62.89
Late seral forest (%)	40.35	53.67	60.45	39.28	52.95	60.21

3.4 Transient Effects of Discounting

Table 8.8 shows the effects of discounting ecological criteria on the expected characteristics of the forest after 10, 20, and 50 years, given the initial forest condition defined by the distribution of stand states in Table 8.3.

The probability of each stand state after 10, 20, and 50 years, following the policies that maximized the discounted or undiscounted criteria, was derived with Eq. 8.9.

Other things being equal, discounting had little influence on the expected forest characteristics. The main difference was that, with the initial conditions used here, maximizing discounted LSF probability led after 10 years to an expected LSF frequency that was 3% higher than maximizing undiscounted basal area. After 50 years the expected value of the forest characteristics was practically the same as with an infinite time horizon, shown in Table 8.6.

4 Summary and Conclusion

This chapter has presented general methods to develop management strategies that optimize ecological or economic criteria in continuous cover forestry. They rely on Markov decision process models, with transition probability matrices generated by bootstrap simulation of forest stand growth.

As an application, we dealt with the question of whether ecological costs and benefits should be discounted in the same way that financial costs and benefits are discounted in standard financial analysis. Without taking any position in this debate, this chapter investigated some of the purely ecological consequences of discounting ecological criteria.

To this end, Markov decision process models were developed, with infinite time horizons and discounted or undiscounted objective functions. The data were from Douglas-fir/western hemlock forests in the U.S. Pacific Northwest, with the assumption of continuous-cover forestry. The Markov probabilities of transition between stand states were obtained by bootstrap simulation.

The ecological criteria examined were: tree species diversity, tree size diversity, stand basal area, and probability of LSF characteristics. As the present value of the discounted criteria (but not the optimum policies) depend on the initial condition, the current distribution of stand states in the study area was used as initial condition. The discount rate for the ecological criteria was comparable to typical discount rates for financial returns.

In this context, we found that in maximizing expected tree species diversity over an infinite time horizon, 18 out of 64 stand states would call for different decisions with discounting. For tree size diversity, the decisions differed for five stand states. For basal area all but two states called for the same decision. For LSF frequency, discounting led to different decisions in 13 stand states.

However, when decisions differed with discounting, for only a few stand states were the criteria substantially different immediately after the decision. Thus, discounting would matter only for a few stand states, which in the study area had a low frequency within the overall forest landscape.

Given this initial forest landscape, the only criterion that differed substantially after a decade of applying a policy with discounting, compared to not discounting, was the expected frequency of LSF. But the difference disappeared in less than 50 years.

In the long-run (infinite time horizon), the initial conditions do not matter, and it was found that discounting or not discounting led to very similar values of expected tree species diversity, tree size diversity, stand basal area, and late seral forest.

In this as in many previous applications, the Markov decision process model has been found to be a very powerful means of investigating decision making under risk in forest management. It is a very appealing metaphor of the decision making process. At any point in time, the best decisions should, and can only be, based on the information available at that moment. The outcomes of various decisions, including doing nothing, are not known exactly and can only be thought of in terms

of probabilities. High system complexity, such as the growth of a multi-species, uneven-aged forest which may be first modeled with simulation models, can then be reduced to Markov transition probability matrices for easy optimization leading to simplified decision-making rules.

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Appendix

The matrix **G** and the vector **r** in the deterministic part of the growth model (8.2) have the following form (Liang et al. 2005):

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & \\ & \mathbf{G}_2 & & \\ & & \mathbf{G}_3 & \\ & & & \mathbf{G}_4 \end{bmatrix}, \quad \mathbf{G}_i = \begin{bmatrix} a_{i1} & & & & \\ b_{i1} & a_{i2} & & & \\ & \ddots & \ddots & & \\ & & b_{i,17} & a_{i,18} & \\ & & & b_{i,18} & a_{i,19} \end{bmatrix}$$

$$\mathbf{r} = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \mathbf{r}_3 \\ \mathbf{r}_4 \end{bmatrix}, \quad \mathbf{r}_i = \begin{bmatrix} r_i \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

where a_{ij} is the probability that a tree of species i and diameter class j stays alive and in the same diameter class between t and $t+1$. $i=1$ for Douglas fir, 2 for other shade tolerant species, 3 for western hemlock, and 4 for other shade-tolerant species. b_{ij} is the probability that a tree of species i and diameter class j stays alive and grows into diameter class $j+1$, and r_i is the number of trees of species group i recruited in the smallest diameter class between t and $t+1$, with a time period of 1 year. Recruitment is zero in the higher diameter classes. The b_{ij} probability is equal to the annual tree diameter growth, g_{ij}, divided by the width of the diameter class. Diameter growth is a function of tree diameter D_j (cm), stand basal area B (m^2/ha), site productivity Q (m^3/ha/year), tree species diversity H_s, and tree size diversity H_d.

$$g_{1j} = 0.7860 + 0.0124D_j - 0.0001D_j^2 - 0.0107B + 0.0267Q + 0.0658H_s - 0.2426H_d$$

$$g_{2j} = 0.6104 - 0.0038D_j + 0.0001D_j^2 - 0.0080B + 0.0170Q + 0.0707H_s - 0.0693H_d$$

$$g_{3j} = 0.9026 + 0.0148D_j - 0.0001D_j^2 - 0.0107B + 0.0061Q - 0.0250H_s - 0.1750H_d$$

$$g_{4j} = 0.5851 + 0.0081D_j - 0.00003D_j^2 - 0.008B + 0.0178Q + 0.1285H_s - 0.1441H_d$$

The expected recruitment of species i is represented by a Tobit model:

$$r_i = \Phi(\boldsymbol{\beta}_i\mathbf{x}_i/\sigma_i)\boldsymbol{\beta}_i\mathbf{x}_i + \sigma_i\phi(\boldsymbol{\beta}_i\mathbf{x}_i/\sigma_i)$$

with:

$$\boldsymbol{\beta}_1\mathbf{x}_1 = -21.9317 - 1.2996B + 0.0971N_1 + 0.8007Q + 11.119H_s - 6.8020H_d$$

$$\boldsymbol{\beta}_2\mathbf{x}_2 = -23.6333 - 0.8293B + 0.0975N_2 + 0.2032Q + 8.4122H_s - 5.9733H_d$$

$$\boldsymbol{\beta}_3\mathbf{x}_3 = -30.8842 - 0.9359B + 0.0926N_3 + 0.6699Q + 14.693H_s - 9.8919H_d$$

$$\boldsymbol{\beta}_4\mathbf{x}_4 = -34.5350 - 0.7512B + 0.0924N_4 + 0.7375Q + 8.0361H_s - 2.2701H_d$$

where N_i is the number of trees per hectare in species group i; Φ and ϕ are respectively the standard normal cumulative and density functions, and the standard deviations of the residuals are, $\sigma_1 = 23.5417$, $\sigma_2 = 22.4354$, $\sigma_3 = 27.3244$, $\sigma_4 = 23.0297$.

The probability of tree mortality per year, m_{ij}, is a species-dependent probit function of tree size and stand state:

$$m_1 = \frac{1}{10.5}\Phi(-2.1103 - 0.0356D_j + 0.0002D_j^2 + 0.0081B - 0.0200C + 0.0059H_s + 0.5110H_d)$$

$$m_2 = \frac{1}{10.5}\Phi(-1.4063 - 0.0204D_j + 0.0002D_j^2 + 0.0053B - 0.0147C + 0.0022H_s + 0.1411H_d)$$

$$m_3 = \frac{1}{10.5}\Phi(-3.1746 - 0.0416D_j + 0.0003D_j^2 + 0.0156B - 0.0230C + 0.3252H_s + 0.4192H_d)$$

$$m_4 = \frac{1}{10.5}\Phi(-1.5188 - 0.0093D_j - 0.0000D_j^2 - 0.0042B - 0.0303C - 0.2721H_s + 0.3528H_d)$$

The probability that a tree stays alive and in the same size class from t to $t+1$ is, then:

$$a_{ij} = 1 - b_{ij} - m_{ij}$$

The expected single tree volume v_{ij} (m^3) is a species-dependent function of tree and stand characteristics:

$$v_{1j} = -0.6116 - 0.0119D_j + 0.0012D_j^2 + 0.0132B + 0.0293Q - 0.1249H_s - 0.0330H_d$$

$$v_{2j} = -0.5487 + 0.0038D_j + 0.0009D_j^2 + 0.0044B + 0.0173Q + 0.0136H_s + 0.0358H_d$$

$$v_{3j} = -0.4621 - 0.0141D_j + 0.0013D_j^2 + 0.0072B + 0.0104Q - 0.0659H_s + 0.0516H_d$$

$$v_{4j} = -0.1401 - 0.0170D_j + 0.0011D_j^2 + 0.0087B + 0.0146Q - 0.2471H_s + 0.0125H_d$$

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