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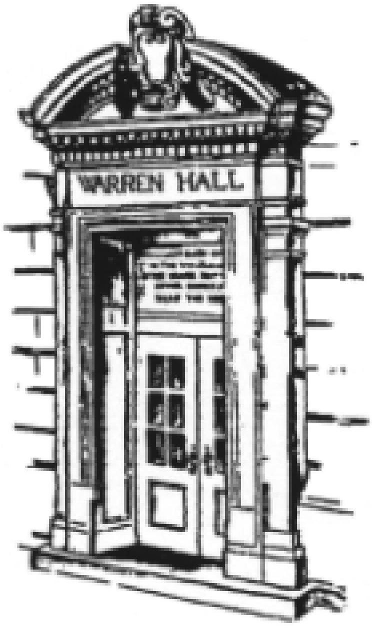

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Timber Harvest Adjacency Economies, Hunting, Species Protection, and Old Growth Value: Seeking the Optimum

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***Abstract*:**

Spatial forest management models recognize that nontimber benefits can be influenced by the status of adjacent land. For instance, contiguous old growth provides habitat, aesthetic value, and environmental services. Conversely, edge areas provide forage and cover habitat for game and non-game wildlife. However, adjacency externalities are not limited to nontimber concerns. Larger harvest areas generate average cost savings as fixed harvesting costs are spread across greater acreage, a problem excluded from most literature on optimal harvesting. Hence, it is typical that economies and diseconomies of adjacency in harvesting occur simultaneously. This complicates the determination of optimal ecosystem management behavior, which recognizes timber, aesthetic, wildlife protection, and hunting values. This paper conceptually portrays economies of adjacency in competing objectives using multiple management strategies.

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I. Introduction

For some time, U.S. public forest management legislation has recognized that forests produce products other than timber (Sundry Civil Appropriations Act, 1897).[1] Nevertheless, in the nineteenth century and much of the twentieth century, public management decisions were dominated by growing timber demand, followed by multiple-use management with a promise of a stable timber supply (the Multiple-Use Sustained Yield Act, 1960 and the National Forest Management Act, 1976). However, environmental legislation, beginning as early as the 1960s (e.g. the Wilderness Act, 1964, the National Environmental Policy Act, 1969, the Clean Air Act, 1970, the Clean Water Act, 1972, and the Endangered Species Act, 1973) and shifting societal priorities have forced a change in management practices on public lands—timber harvests have dwindled for the benefit of nontimber objectives (GAO, 1999a, 1999b). New initiatives with respect to road exclusion and biological preservation are continuing this trend. At the same time, industry has formalized their concern for environmentally sound management (for example, see the 1994 Sustainable Forestry Initiative, SFI, of the American Forest and Paper Association).

As the recognition of social values for nontimber benefits, and the understanding of natural (e.g. biological, ecological, and hydrological) forest processes and their response to disturbances have evolved, so too have forestry management models evolved

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[1] Also known as the Organic Administration Act or the Organic Act. See Gorte (1999) for a brief, but thorough, history of U.S. forest management legislation.

from managing individual stands to the spatial management of entire forests.[2] The importance of forest level modeling is evident in the goods and services that forests provide (Table 1). The provision level of most of the items listed in Table 1 is determined by the spatial pattern of standing tree cover across the forest and over time. "Nontimber benefits" refers to all the benefits in the Table except timber.[3]

Increasing attention has been given to natural systems and the generation, valuation, and optimization of the nontimber benefits. For example, many authors have studied the biological consequences of different forest landscape patterns and their creation of different edge and forest interior habitats.[4] Others have focused on the estimation of nontimber values, such as for old-growth, spotted owls, salmon, recreation, insect damage, and nonuse values.[5] Another literature has sought optimal management solutions for objectives which include nontimber benefits. In general, the models is this last category have not specified the individual nontimber benefits, focusing instead on forest conditions which represent groups of nontimber benefits.[6] Some examples of models that have focused on particular nontimber benefits, such as goshawk, deer, and

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[2] For discussions on the social value of nontimber benefits see, inter alia, Bowes and Krutilla (1989), Niemi et al. (1999), and Chapman, Chapter 14 (2000). For examples of our improved understanding of natural forest processes, see MacArthur and Wilson (1967), Gilles (1978), Thomas (1979), Hoover and Wills (1984), Franklin and Forman (1987), Meehan (1991), and Sturtevant, Bissonette, and Long (1996).

[3] In its popular usage, "nontimber benefits" may imply only the non-market values.

[4] See MacArthur and Wilson (1967), Diamond (1975), Giles (1978), Thomas (1979), Hoover and Wills, (1984), Franklin and Forman (1987), Gustafson (1996), and Delong and Lamberson (1999).

[5] See Hagen, Vincent, and Welle (1992), Niemi et al. (1999), Loomis and Walsh (1988), Englin and Mendelsohn (1991), Haynes and Horne (1997), Rosenberger and Smith (1997), and Walsh, Bjonback, and Aiken (1990).

[6] For example, early seral-stages (i.e. early steps in a series of steps in the process of ecological succession, Hoover and Wills, 1984) and edge habitat provide hunting and wildlife viewing value by attracting species such as deer, elk, rabbits and grouse. Middle and late-seral stages and interior habitat provide, among other things, water filtration, soil stabilization, water flow control, aesthetic value, habitat for interior species like marten, spotted owls, red-cockaded woodpeckers, squirrels, bears, and turkeys, and recreational opportunities like camping, hiking, biking, off-road vehicle use, and nonuse values like existence, bequest, and option values. See Bowes and Krutilla (1985), Swallow, Talukdar, and Wear (1997), Barrett, Gilless, and Davis (1998), Ohman and Eriksson (1998), Calish, Fight, and Teeguarden (1978), Hochbaum and Pathria (1997), Hof et al. (1994), and Swallow, Parks, and Wear (1990).

Table 1: Economic Benefits of Forest Lands

Extractive Goods and Services

Timber
Plant Products (e.g. landscaping, mushrooms)
Water Supply & Quality (for households, industry, irrigation, aquaculture, hydroelectricity)
Animal Products (e.g. fish, shellfish, furbearers)
Mineral Products (e.g. hardrock minerals, energy minerals, sand, gravel)

Non-extractive Goods and Services

Flood Control
Erosion Control
Soil Fertilization
Wilderness and Biodiversity Protection
Aesthetics (e.g. scenery)
Recreation (e.g. hiking, wildlife viewing, hunting, fishing, swimming, boating, off-road vehicles use)
Pollution Control (e.g. carbon sequestration, runoff filtration)
Existence Values
Bequest Values
Option Values

(Compiled from Niemi et al., 1999, and Chapman, 2000)

marten populations, aquatic habitat, and riparian zones, are Hof and Joyce (1992), Sturtevant, Bissonette, and Long (1996), Bettinger, Sessions, and Johnson (1998), and Yoshimoto and Brodie (1994). For this paper, we employ the optimal management approach and use the forest condition to define the value function for nontimber benefits. Specifically, we represent the variable nontimber benefits of dynamic edge and interior habitats.

In addition, we broaden the management concerns and include timber as well as nontimber costs and benefits in identifying the optimal forest conditions. To this end, we expand the spatial representation beyond nontimber production and include cost economies of scale in harvest tract size. Larger harvest areas generate average cost savings as fixed harvesting, management, and regeneration costs are spread across greater acreage (Cubbage 1983a, 1983b; Capp and Gadt, 1987; Paarsch, 1997; Carter and Newman 1998), a problem excluded from most literature on optimal harvesting.

This paper is interested in delineating the economic trade-offs between net timber and several nontimber values (old growth preservation, hunting, and endangered species protection) associated with harvest management. Section II provides background on spatial forestry modeling. In Section III, our spatial model of economies and diseconomies of adjacency is developed. The model is implemented in the fourth section where simulations are run and discussed. The last section summarizes the key issues analyzed in the simulations and their implications for management.

II. Spatial Models

To account for spatial externalities, a spatial model is required. Limited by their focus on an individual stand, stand level models have not incorporated the state of the surrounding forest in the determination of nontimber benefits (Hartman 1976; Calish, Fight, and Teeguarden 1978; Parks, Barbier, and Burgess 1998). An important exception has been Swallow and Wear (1993). In addition, some multiple stand models have also been non-spatial in the production of benefits (Paredes and Brodie, 1989; Hof and Kent, 1990; Vincent and Binkley, 1993).

Spatial forestry models have been primarily concerned with three aspects of harvesting – rotation length, location, and proximity to other harvests. Location and proximity are the distinguishing features of spatial models. Location is concerned with the decision of where to locate one item with respect to a separate fixed second item. The distance between the items determines a benefit or damage: for example, the distance between a harvest area and a mill (Parks, Barbier, and Burgess, 1998), a harvest area and a stream, or a road and a stream (for an illustration of the importance of the last two, see Bettinger, Sessions, and Johnson, 1998). Distance to the mill impacts the per unit market value of timber. Distance from a stream influences ecological damages and services.

Proximity, on the other hand, refers to the distance between tracts, harvested or unharvested. The influence of proximity has, until this paper, been restricted to the production of nontimber goods and services (Roise, 1990; Hof and Joyce, 1992; Swallow, Talukdar, and Wear, 1997; Hochbaum and Pathria, 1997; Murray, 1999). Bowes and Krutilla (1985) allude to the importance of the proximity of harvests. They find the optimal acreage of stand age classes to maximize timber and old growth benefits.

However, their analysis does not include information about the location of the age classes within the forest and with respect to each other. Subsequent locational representations of proximity in the production of nontimber benefits can be divided into two categories: adjacency and fragmentation.

Adjacency has traditionally referred to the nontimber damages of harvesting adjacent stands, which produce larger contiguous harvested areas, and the benefits of creating edge habitat. Adjacent harvest damages have been portrayed as penalties or as constraints on harvest size, location, and timing (Roise, 1990; Yoshimoto and Brodie, 1994; Barrett, Gilless, and Davis, 1998; Murray, 1999). Alternatively, old-growth acreage and spacing constraints have been imposed (Öhman and Eriksson, 1998). Edge effects have been portrayed as exogenous fixed benefits (Hochbaum and Pathria, 1997) or computed by endogenous species growth functions (Hof and Joyce, 1992; Swallow, Talukdar, and Wear, 1997). Fragmentation analysis, derived from island biogeography (MacArthur and Wilson 1967; Diamond, 1975), refers to the benefits and damages of fragmenting habitat through harvesting, where species populations are capable of repopulating forested patches of minimum size and maximum distance from populated patches (Hof and Joyce, 1992).

The concept of adjacency should be broadened to encompass the fixed costs of managing adjacent stands. Costs for moving and setting-up equipment and crew, renting equipment, building roads, administration, replanting, and surveying are broadly speaking the fixed costs associated with harvesting, management, and regeneration.

These costs have historically been treated as constant stand specific fixed costs.[7] Hence, harvesting cost economies of adjacency have not been acknowledged. Despite the statistical evidence of economies of scale in tract size and harvest volumes (Cubbage 1983b; Paarsch, 1997), few models have explored the effect of spatial harvesting configurations on average costs and the actions of loggers.[8] Spatial management models, which simultaneously determine the harvesting decisions of multiple stands, permit the exploitation of cost economies of scale in the harvesting of adjacent stands. Hence, by geographically consolidating harvests, harvesters can benefit from cost economies of adjacency.

This paper is not concerned with location and fragmentation. In addition, while building logging road networks is clearly a spatial problem that produces nontimber damages and substantial financial cost, this paper does not address network decisions. We are interested in portraying the timber and nontimber trade-offs associated with managing adjacent stands.

III. Model

Three conflicting classes of economies or diseconomies of adjacency are represented. First, adjacent harvests yield cost savings through fixed harvesting cost economies. Second, adjacent older and younger trees provide cover and forage respectively, creating appealing habitat for game and other edge species. Lastly, contiguous mature growth provides a variety of nontimber benefits, such as recreation,

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[7] As a result, these models regard fixed cost increases as they do per unit timber price decreases (Clark, 1990, pp. 268-74). The result of either is to increase the optimal rotation length. This treatment of fixed costs remains unchanged to date. See Lewis and Schmalensee (1977) for a general discussion of non-spatial fixed costs in renewable resource extraction.

aesthetic value, endangered species habitat, wildlife habitat, and watershed management, which increase with both the acreage and the age of the tract of mature forest.

The model employs a recursive formulation. In each period, stand ages and harvest histories define the condition of the forest. Given the forest condition, management makes stand level clearcutting decisions.[9] The result is a dynamic forest, a mosaic of different aged patches, which produces an intertemporal stream of net timber and nontimber benefits in perpetuity or until a terminal period is reached. The objective in any decision period *t* is to maximize the net present value of this stream. The general problem can be stated as follows (see Appendix A for a complete index of the notation used in this paper):

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[8] An exception is Rose (1999).

[9] Clearcutting will be the only harvesting practice considered. Here clearcutting is defined as a silvicultural practice which maintains soil fertility by leaving logging slash and is not practiced where soil stability, snow stability, or snow melt are an issue. In addition, it is assumed that road building, log removal, and post-harvest site treatment practices are carried out with minimal environmental and timber regeneration damage. See Kimmins (1992) Chapter 6 for an excellent introduction to the issues surrounding clearcutting.

$$\underset{h_t}{\text{Max}}\,\Theta_t = PQ_t h_t - C(h_t) + V(h_t) + e^{-\delta}\Theta^{*}_{t+1}(h_t) \tag{1}$$

t	Current decision period (year).
Θ_t	Net present value ($) of this period's harvest decisions h_t given the current state of the forest (a_t, l_t, m_t) and the present value of future optimal harvest decisions $\Theta^{*}_{t+1}(h_t)$: $\Theta_t = \Theta_t(h_t; a_t, l_t, m_t)$.
S	Number of stands (scalar).
$a_t = (a_{1t}, a_{2t}, \ldots, a_{St})$	Vector of timber ages on all stands in period t (years), where a_{st} is the age of stand s in period t.
$l_t = (l_{1t}, l_{2t}, \ldots, l_{St})$	Matrix record of the lengths of all rotations on each stand through period t (years), where the rotation record on stand s in period t is a vector that includes only the m_{st} rotations that have occurred prior to year t, i.e. $l_{st} = (l_{s1t}, l_{s2t}, \ldots, l_{smt})$ and $l_{smt} = a_{st}h_{st}$ is the length of rotation m on stand s (years).
$m_t = (m_{1t}, m_{2t}, , m_{St})$	Vector of the number of rotations performed on each stand to date (scalar), where m_{st} is the number of rotations that have occurred on stand s before period t.
$h_t = (h_{1t}, h_{2t}, \ldots, h_{St})$	Vector of harvest decisions in period t, where h_{st} is the harvest decision on stand s in period t; if harvesting is undertaken it is at the beginning of the period.

$$h_{st} = \begin{cases} 1 & \textit{clearcut} \\ 0 & \textit{no}\ \text{harvest} \end{cases}$$

P	Unit price of timber ($\$/\mathrm{f}^3$).
$Q_t = Q(a_t,l_t,m_t) = (Q_1(a_{1t},l_{1t},m_{1t}),\ldots, Q_S(a_{St},l_{St},m_{St}))$	Vector of merchantable timber volumes on each stand in period t (f^3), where $Q_s = Q_s(a_{st},l_{st},m_{st})$ is the merchantable timber volume on stand s in period t.
$C(h_t)$	Total fixed cost in period t over all stands for harvest configuration h_t ($\$$).
$V(h_t) = V(h_t;a_t,l_t,m_t)$	Nontimber benefit value of the forest condition between harvest decisions ($\$$).
δ	Interest rate (%/100).
$\Theta^*_{t+1}(h_t)$	Net present value ($\$$) of the optimal harvest decisions in the future given the resulting state of the forest from this period's decisions: $\Theta^*_{t+1}(h_t) = \Theta^*_{t+1}(a_{t+1}(h_t),l_{t+1}(h_t),m_{t+1}(h_t))$.
$a_{st+1} = a_{st}(1\text{-}h_{st}) + 1$	Age of stand s next period (years).
$m_{st+1} = m_{st} + h_{st}$	Number of rotations performed on stand s after the current period (scalar). Note, $m_{st+1} = \sum_{i=1}^{t} h_{si}$.

Given stand ages (a_t), rotation length records (l_t), and the number of rotations to date (m_t), the manager chooses whether or not to harvest each stand in year t (h_t), to maximize the current timber value $PQ(a_t,l_t,m_t)h_t = P[Q_1h_1 + \ldots + Q_Sh_S]$, less harvesting costs $C(h_t)$, plus this period's non-timber benefits $V(a_t,l_t,m_t,h_t)$, plus the discounted value of the optimal harvesting sequence and configuration that follow from this period's harvesting decisions $\Theta^*_{t+1}(a_{t+1}(h_t), l_{t+1}(h_t), m_{t+1}(h_t))$.[10] The current period's non-timber benefits are determined by the stand ages which follow from the beginning of the period harvesting decisions, i.e. $a_{1t}(1\text{-}h_{1t})$, …, $a_{St}(1\text{-}h_{St})$.[11]

For this analysis, we simplified the structure above, ignoring rotation records and rotation counts,[12] and specified functions for merchantable timber, fixed harvesting costs, and three nontimber amenities—the hunting value of game species, the use and nonuse value of contiguous mature stands, and the nonuse value of endangered interior forest species. The result is the following model:

$$\underset{h_t}{\mathrm{Max}}\, \Theta_t = PQ_t h_t - C(h_t) + V_H(g_t) + V_M(g_t) + V_{ES}(g_t) + e^{-\delta}\Theta^*_{t+1}(h_t) \qquad (2)$$

where t, S, a_t, a_{st+1}, h_t, P, $C(h_t)$, and δ are unchanged from Equation (1), and

$\Theta_t = \Theta_t(h_t;a_t)$

$Q_t = Q(a_t) = (Q_1(a_{1t}), \ldots, Q_S(a_{St}))$

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[10] One could represent selective harvesting as a continuous variable defined over the interval [0,1]. In the case of selective harvesting, the degree of harvesting on a stand will determine the stand level marginal harvesting cost and timber volume as well as the forest-wide nontimber amenities. Marginal logging costs are represented by the net unit price P. For a given harvesting strategy, marginal logging costs are a function of tree size, wood volume, tree density, and skidding distance (Capp and Gadt, 1987; Hartsough, Gicqueau, and Fight, 1998). The more selective the harvesting strategy, the greater the marginal cost. Also, younger stands yield smaller diameter logs which can attract a lower market price. However, for simplicity, we assume that P is fixed across stand ages.

[11] Since Hartman (1976), non-timber benefits have commonly been conceptualized as an integral of the discounted instantaneous non-timber values accrued over the time interval between decision periods. Using our notation, this representation looks like $V(h_t) = \int_0^1 V(a_{1t}(1-h_{1t})+\varepsilon, \ldots, a_{St}(1-h_{St})+\varepsilon)e^{-\delta\varepsilon}\mathrm{d}\varepsilon$.

[12] See Erickson (1999) for a discussion of the impacts of the frequency and number of harvests on successional growth and the optimal timing of rotations on a single stand.

$\Theta^{*}_{t+1}(h_t) = \Theta^{*}_{t+1}(a_{t+1}(h_t))$	
$V_H(g_t) = V_H(g(h_t;a_t))$	Hunting value of game species in period t following the harvest decisions in period t (\$).[13]
$V_M(g_t) = V_M(g(h_t;a_t))$	Use and nonuse value of standing mature growth (net endangered species value) in period t following the harvest decisions in period t (\$).
$V_{ES}(g_t) = V_{ES}(g(h_t;a_t))$	Nonuse value of endangered interior forest species in period t following the harvest decisions in period t (\$).
$g_t = g(h_t;a_t) = (g_{1t}, \ldots, g_{St})$	Timber ages on all stands in period t after the beginning of period harvesting decisions (years), where the age on stand s in period t after harvesting decision h_{st} is $g_{st} = a_{st}(1-h_{st})$.

In Equation (2), the merchantable timber on any stand ($Q_s(a_{st})$) is solely a function of the harvest decision on and age of that stand. However, the total fixed harvesting costs ($C(h_t)$), the hunting value of game ($V_H(g_t)$), the value of old growth ($V_M(g_t)$), and the value of endangered interior species ($V_{ES}(g_t)$) are functions of the harvests on and subsequent ages of all of the stands. Each of the functions in Equation (2) are specified and described below.

Merchantible timber volume on stand s grows according to a cubic growth function estimated for forest stands of Douglas fir:[14]

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[13] Note that h_t are the harvest decisions in period t, and H is a subscript in V_H denoting hunting value.

$$Q_s(a_{st}) = \eta_{0s} a_{st} + \eta_{1s} a_{st}^2 + \eta_{2s} a_{st}^3 . \qquad (3)$$

where $\eta_{0s} > 0$, $\eta_{1s} > 0$, and $\eta_{2s} < 0$ are slope, concavity, and inflexion parameters respectively. The meaning of the age of stand variable a_{st} remains unchanged. It is assumed that this is the only merchantible timber product. This assumption does not preclude the presence of other tree species during successional stages.[15] Figure 1 illustrates the growth of timber value for different growing conditions.[16]

The fixed harvesting costs in period t depend on the configuration of harvests h_t such that, with harvesting cost economies of adjacency, fixed costs may be spread across neighboring stands and the fixed cost for harvesting any two adjacent stands i and j will be less than the sum of the costs for harvesting the stands separately, $c_{it} + c_{jt}$. Formally, for each possible harvest configuration h_t, the stands considered for harvest may be grouped into disjoint harvesting blocks, where $B(h_t)$ is the number of blocks.[17] A harvesting block may consist of multiple stands or a single stand depending on whether or not neighboring stands will be cut respectively. Because of adjacency, the total cost of harvesting a block in any period is less than the sum of the costs for individually

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[14] This equation was taken from Tietenberg (2000, p.256), and was originally drawn from data in Clawson (1977).

[15] Thomas (1979) defines a successional stage as a stage or recognizable condition of a plant community which occurs during its development from bare ground to climax. For example, the coniferous forests of the Blue Mountains of Oregon and Washington progress through six recognized stages: grass-forb, shrub-seedling, pole-sapling, young, mature, and old-growth.

[16] The dip in timber value portrayed by the dashed gray lines in Figure 1 is characteristic of the decay of older stands. However, this phenomenon is not represented in the simulations. Instead, the maximum value is maintained once it is reached. Also, we do not allow for intermediate harvesting treatments, which can enhance the growth of the remaining trees but can be costly. All monetary values are measured in United States dollars.

[17] We consider harvesting blocks to be disjoint if they do not geographically overlap and they are separated by standing forest.

Figure 1: Harvested Timber Value

for a one hectare stand, timber price (P) = $4/cubic foot

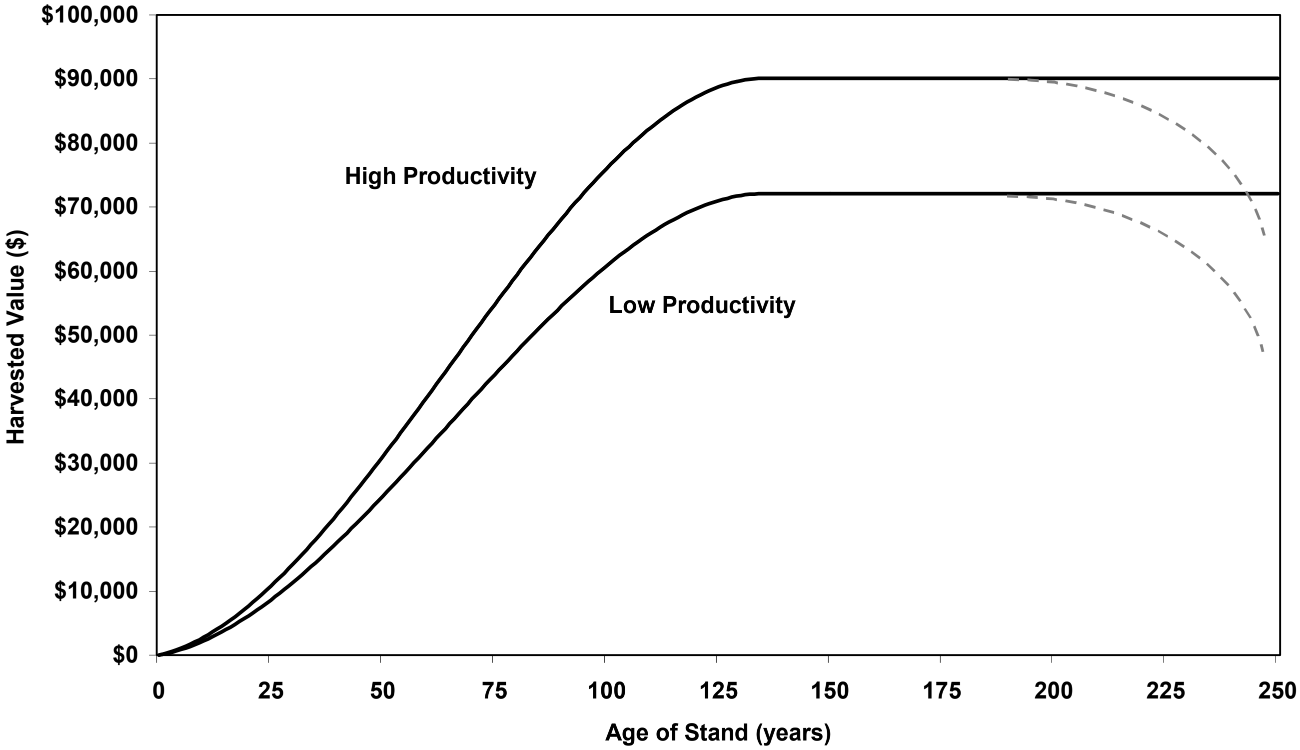
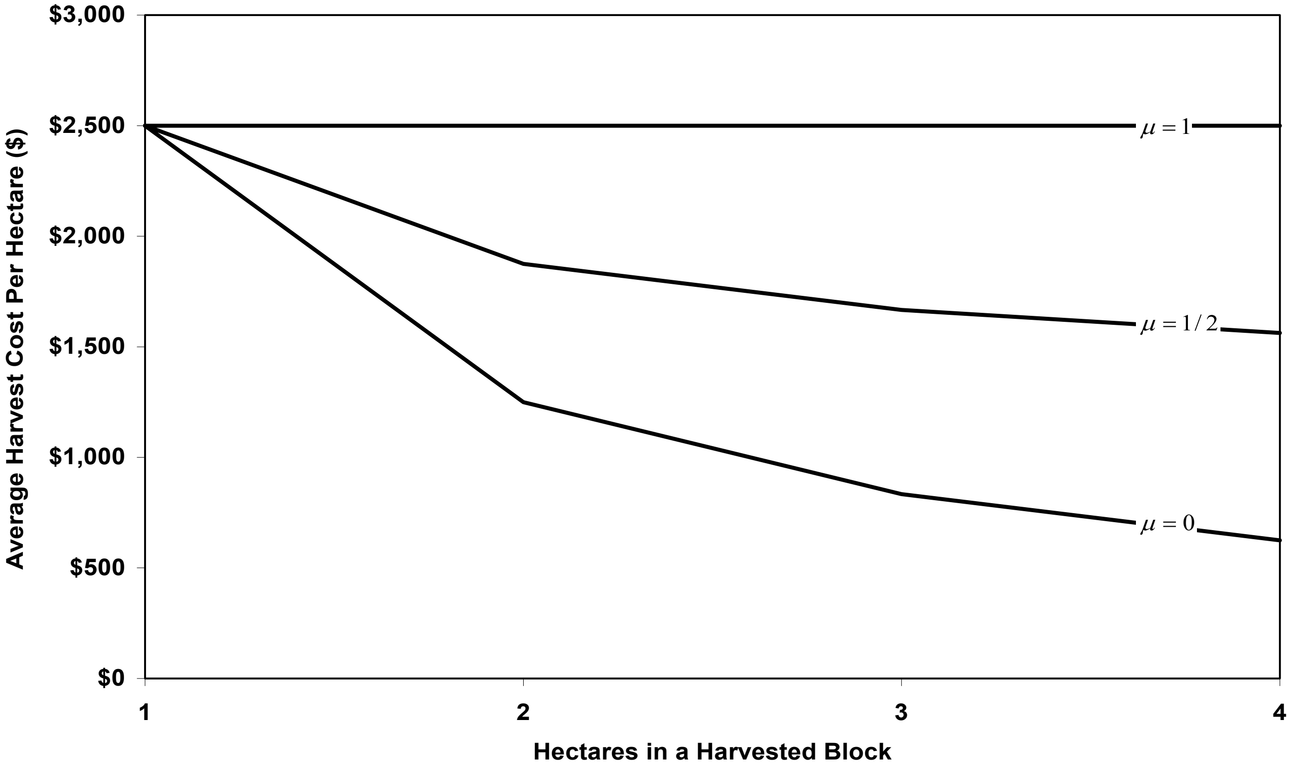


Figure 2: Economies of Adjacency in Harvest Area Size

c = $2,500



harvesting the stands in the block. For any block b, the fixed cost of harvesting will be the sum of the highest cost of harvesting any of the individual stands in block b, $c_{max,b}$, plus a fraction μ_s of each of the other individual stand harvesting costs associated with the block:

$$C(h_t) = \begin{cases} \sum_{b=1}^{B(h_t)} \left[c_{\max,b} + \sum_{(s \neq \max) \in S_b} \mu_s c_s \right] & \text{if } \; B(h_t) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where

$B(h_t)$ = number of disjoint harvest blocks given h_t (scalar), $b \in B(h_t)$,

S_b = set of harvested stands in harvest block b, where, for each block, $h_{st} = 1$ for all $s \in S_b$,

c_s = fixed cost for harvesting stand s independently (\$),

$c_{max,b}$ = $\max\{c_s\text{: } s \in S_b\}$, and

μ_s = proportion of c_s added to this period's total harvesting cost if stand s is harvested, $\mu_s \in [0,1]$.

For the simulations, we simplify Equation (4) by using identical fixed costs and identical economies of adjacency proportions for all stands, i.e. $c_s = c$ and $\mu_s = \mu$.[18] Different degrees of economies of adjacency in harvest area size can be represented by varying μ. In Figure 2, for c = \$2,500, the average cost per hectare is lower with a smaller μ.

The hunting value for game species such as deer, elk, grouse, and rabbits in period t is $V_H(g_t)$. The value of hunting sites is assumed to be a function of game populations, which in turn is a function of the supply of adjacent forage and tree cover acreage:

$$V_H(g_t) = \frac{H(g_t) + e^{-\delta} H(g_t + 1)}{2}. \tag{5}$$

Equation (5) computes the average discounted game benefits from this period's harvest actions. In period t, age configuration g_t produces forage and therefore a consumer surplus for hunting $H(g_t)$.[19] Total forage is the sum of the forage production from each stand. Stand level forage production (animual-unit-months, aum) peaks at an early stand age and then declines asymptotically to zero. The consumer surplus for hunting $H(g_t)$ in

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[18] We assume that the harvesting technology is fixed. Technology choice is not essential to the conceptual conflicts we wish to characterize. However, another important management decision is choosing the optimal harvesting technology. For an example of the productivity and cost implications of different harvest technologies see the PHARVEST software, which estimates harvesting costs for management planning of ponderosa pine (Fight, Gicqueau, and Hartsough 1999; Hartsough, Gicqueau, and Fight, 1998). The software estimates cost per cubic foot of timber for four logging systems: clearcut yarding, partial cut yarding, whole tree system, and cut-to-length.

[19] Equation (5) is one alternative for estimating the integral of the discounted hunting benefits in period t: $V_H(g_t) = \int_0^1 H(g_t + \varepsilon)e^{-\delta\varepsilon}\mathrm{d}\varepsilon$. It is worth noting that, like us, Talukdar (1996) and Swallow, Talukdar, and Wear (1997) use an average to estimate hunting benefits in their simulations.

any period is calculated by integrating a downward sloping marginal value function ($/aum/year) from zero to the period t total forage quantity. $H(g_t)$ and hence the annual hunting value of game are maximized when forage is provided from younger stands with adjacent cover from older stands, i.e. edge-contrast is provided. In Figure 3, the consumer surplus for hunting is largest when both cover and forage are available. In the Figure the age of Stand 2 is artificially fixed at various levels to illustrate the effect different age pairings can have on hunting value. Appendix B describes and discusses the exact specifications of the value and quantity of forage functions used in the simulations. Given the parameterization used in the simulations, the maximum annual hunting value is $26 (Figure 3).

The value of mature growth is derived from the eclectic assortment of nontimber services, products, and nonuse values provided by mature forests (Table 1). However, in order to capture the consequences of extinction, we separate out the value of endangered species. The value of endangered species is discussed further below. The remaining value of contiguous mature growth in period t, $V_M(g_t)$, depends upon the number of hectares n_{wt} and the average age $\bar{g}_{wt}$ of the mature stands in each block w of contiguous mature growth:[20]

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[20] All the nontimber benefits associated with mature growth do not grow alike over time and acreage (with respect to growth rate, minimum age, or minimum acreage requirements). For example, it is unlikely that recreation benefits, aesthetic value, and the benefits of watershed and soil management accumulate identically. However, for simplicity, we assume that the growth functions of all nontimber benefits from mature stands (excluding endangered species) are identical.

Figure 3: Hunting Value

given the age of stand 2 (a_{2t}), each stand is one hectare, high level productivity on stand 1, low level productivity on stand 2

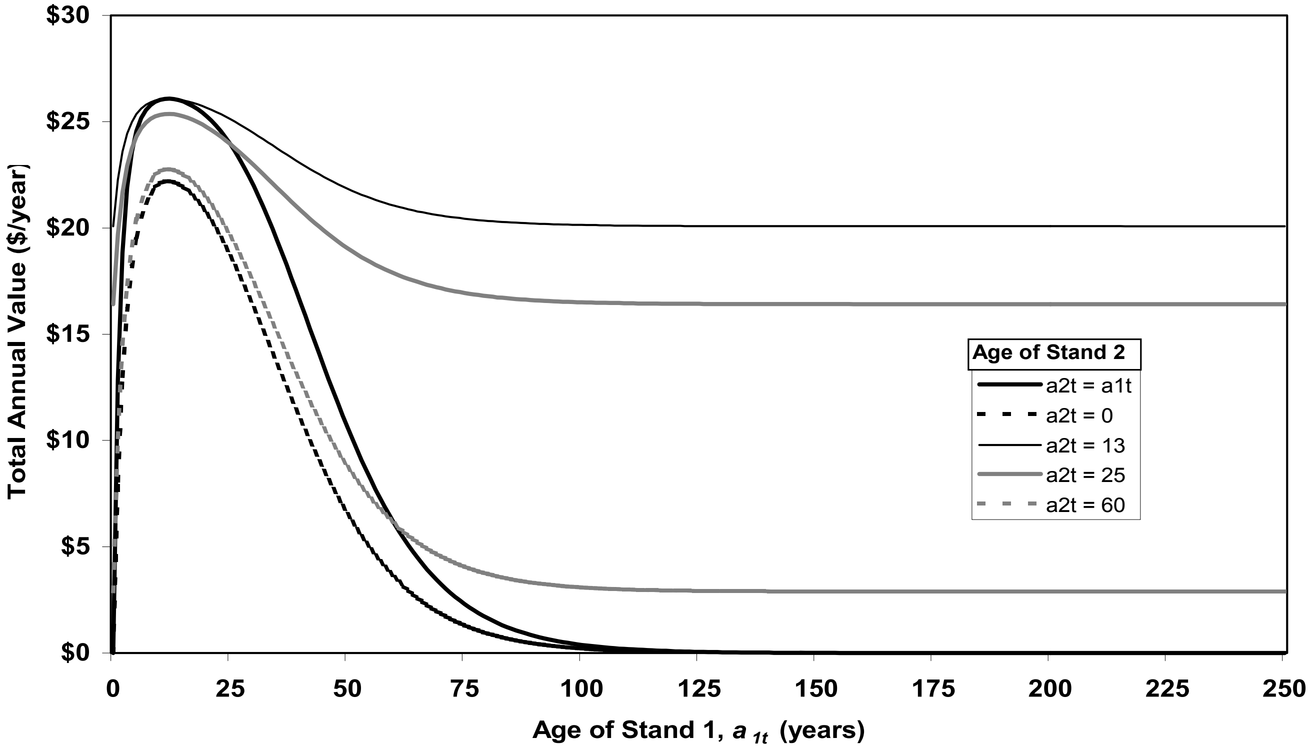
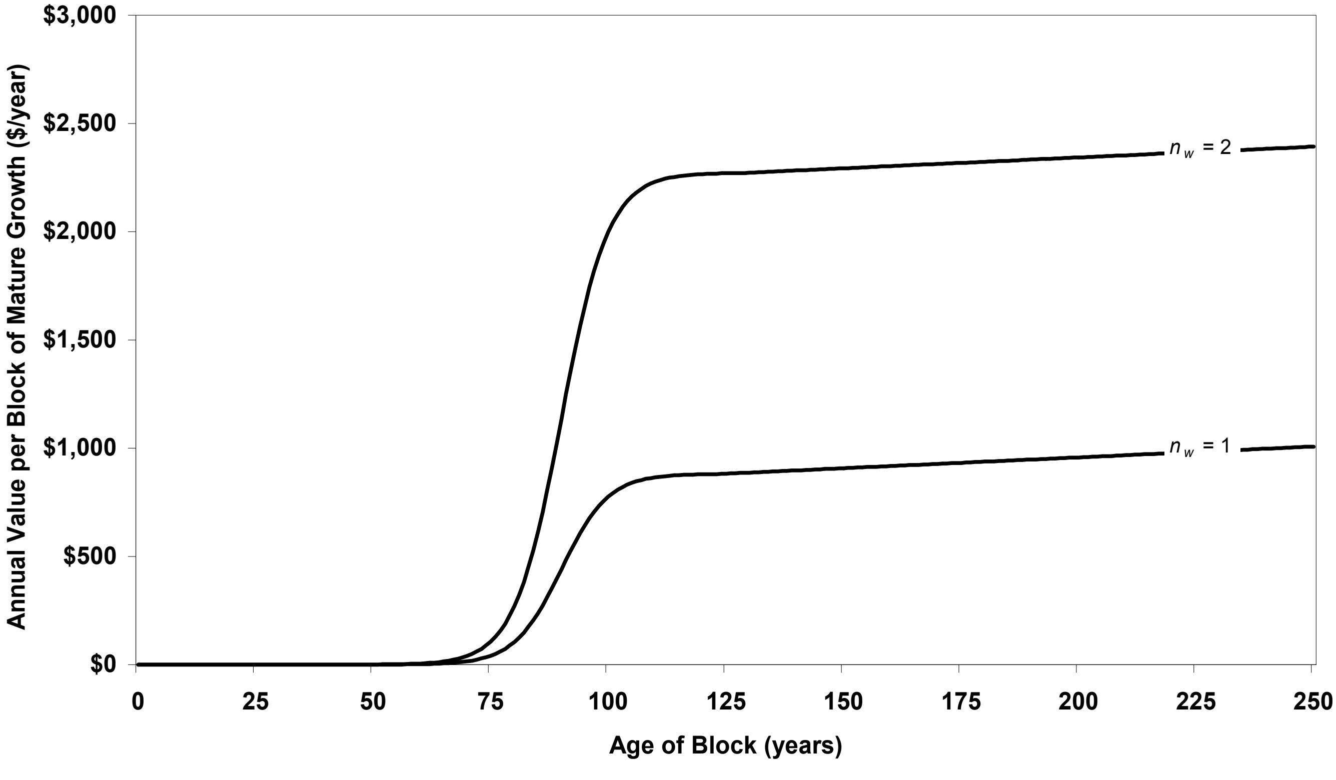


Figure 4: Value of Mature Growth

(excluding endangered species) for each block of size n_w hectares



$$V_M(g_t) = \begin{cases} \sum_{w=1}^{W(g_t)} V_M^w(\overline{g}_{wt}) & \text{if} \quad W(g_t) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where

$W(g_t)$ = number of discrete blocks of mature growth in period t following harvest decision h_t (scalar), $w \in W(g_t)$,

$V_M^w(\overline{g}_{wt})$ = mature growth value of block w given the average age of the mature stands in block w ($),

$\overline{g}_{wt}$ = average age of the mature stands in mature growth block w (years),

$$\overline{g}_{wt} = \frac{1}{n_{wt}} \sum_{s \in S_w} g_{st} \, ,$$

n_{wt} = the number of hectares in mature growth block w (hectares),

S_w = the set of stands in mature growth block w, where, for each block, $g_{st} \geq a_{M,min}$ for all $s \in S_w$, and

$a_{M,min}$ = the minimum age for mature stands (years).

A stand is considered mature if its age is greater than or equal to a threshold age of $a_{M,min}$ years. Mature growth benefits from each block w of area size n_w are determined by the average age of the mature stands in that block, $\overline{g}_{wt}$. Benefits grow logistically in age and acreage respectively.[21] This formulation allows for a gradient of mature growth values that increases with both age and acreage (Figure 4). However, after the logistic growth in age for a given block size is complete, the value of mature growth continues to grow linearly with age, reflecting the novelty value and nonuse value of extremely old growth.[22] See Appendix B for the functional specification of the per block mature growth value $V_M^w(\bar{g}_{wt})$.

In any period, the extinction of endangered interior forest species may result if insufficient habitat is provided. We represent insufficient habitat as the absence of an adequately aged ($\geq a_{ES,min}$) and sized ($\geq n_{ES,min}$) block of contiguous mature growth. We assume that, as long as one adequate habitat block is provided in the management area at any moment, the species will remain viable. If extinction has not occurred in a previous period, each discrete habitat block this period generates benefits $E > 0$:

$$V_{ES}(g_t) = \begin{cases} D(g_t)E & \text{if} \quad D(g_{t-j}) > 0 \quad \text{for all } j = 1, \ldots, t \\ \\ 0 & \qquad \text{otherwise} \end{cases} \tag{7}$$

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[21] See Loomis and Gonzalez-Caban (1998), Pope and Jones (1990) and Walsh, Loomis, and Gillman (1984) for evidence of recreation and nonuse values that increase at a diminishing rate with increased wilderness acreage. The study areas in these papers range from 1000 acres to 16 million acres. To our knowledge, there are no studies evaluating the effects of acreage changes with very small acreage on recreation and nonuse values.

where

$D(g_t)$ = number of discrete blocks of suitable endangered species habitat in period t following harvest decision h_t (scalar), $d \in D(g_t)$, where a suitable habitat is defined by minimum age and acreage requirements $g_{st} \geq a_{ES,min}$ for all $s \in S_d$ and $n_{dt} \geq n_{ES,min}$ respectively,

$a_{ES,min}$ = the minimum age for supporting endangered species (years),

S_d = the set of stands in endangered species habitat block d, where, for each block, $g_{st} \geq a_{ES,min}$ for all $s \in S_d$ and $n_{dt} \geq n_{ES,min}$,

n_{dt} = the number of hectares in endangered species habitat block d (hectares),

$n_{ES,min}$ = the minimum number of hectares for supporting endangered species (hectares), and

E = the maximum value of endangered species if extinction has not occurred previously (\$).

Equation (7) states that, if there was insufficient habitat in an earlier period, then interior species are already extinct and will continue to be so. However, if the forest has provided adequate interior species habitat through the current period, benefits of E are generated from each block of suitable habitat (Figure 5).

Three types of adjacency incentives are represented in the above model. First, for timber harvesting, cost economies of scale in harvest area size provide an incentive to

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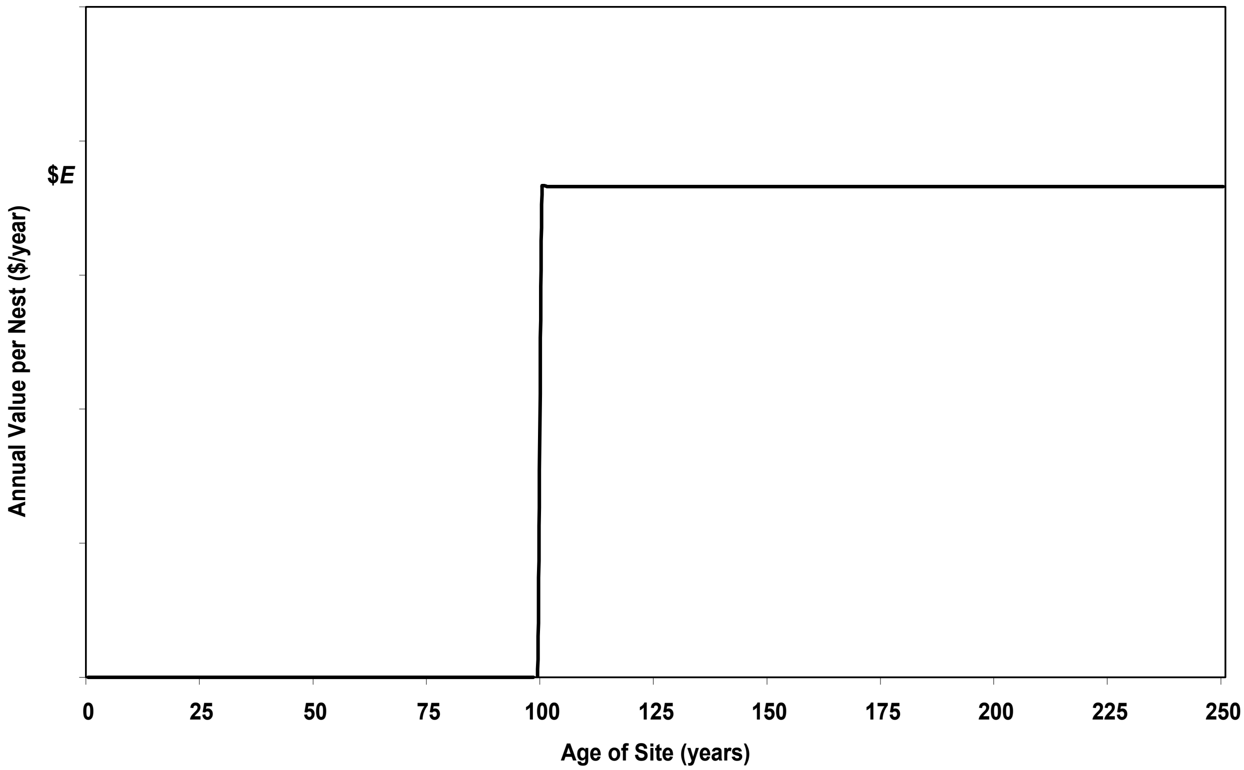
[22] An even-aged stand of mature growth will decay all at once unless selective cutting is undertaken to produce the vertical diversity of an uneven-aged mature forest capable of providing old growth habitat in perpetuity. The cost of these intermediate cuttings can be accounted for simply by subtracting their discounted value from the maximum mature growth value for a given block size $M(n_g)$ in $V_M^w(\bar{g}_{wt})$ (see Appendix B).

Figure 5: Endangered Species Value

for a single nesting site, assuming the size of the habitat satisfies the minimum acreage requirement



harvest adjacent stands (Equation 4). Second, game benefits provide an incentive to provide edge habitat with adequate age contrast between adjacent stands for the provision of both cover and forage (Equation 5). Lastly, old growth amenities, services, and endangered species provide an incentive for the provision of contiguous mature forest (Equations 6 and 7). Management decisions that enhance one value can reduce the other values. In effect, the management goal in Equation (2) seeks to incorporate complex, competing externalities in decision making.

IV. Finding the Optimum

IV.1 Simulations

Simulations were constructed for two adjacent one hectare stands.[23] A final period *N* was given and each year net present values were calculated recursively for each possible action and permutation of stand ages. To bound the number of calculations (via permutations), a maximum rotation age was decided upon such that this age was inconsequential in the results. Given two stands, there are four possible decisions each period: harvest both stands, harvest Stand 1 only, harvest Stand 2 only, or do not harvest.[24] Each alternative determines current period timber and nontimber benefits, fixed costs, and an optimal path for future returns. The optimization is a nonlinear integer programming problem which chooses the alternative that produces the greatest

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[23] This analysis assumes that the surrounding land is not within our jurisdiction and has no impact on timber and nontimber benefits. If it was under our jurisdiction, we should manage this land simultaneously. If not in our jurisdiction but important to the determination of our benefits, we should adjust our harvest timing and configurations to exploit the exogenous condition of the surrounding forest (Swallow and Wear, 1993).

net present value. Although operationally impractical because the computation procedure is easily over-taxed (by additional decision variables per period, longer rotation lengths, and additional decision periods), integer programming guarantees an optimal solution even when the solution space is non-convex, as is likely the case when nontimber benefits are included.[25]

With two stands and assuming identical stand specific fixed costs and economies of adjacency proportions for all stands, i.e. $c_1 = c_2 = c$ and $\mu_1 = \mu_2 = \mu$, period t fixed costs are:[26]

$$\mathrm{C}(h_t) = \begin{cases} 0 & \text{if } h_{1t} = 0 \text{ and } h_{2t} = 0 \\ c & \text{if } h_{1t} = 1 \text{ and } h_{2t} = 0 \\ c & \text{if } h_{1t} = 0 \text{ and } h_{2t} = 1 \\ c + \mu c & \text{if } h_{1t} = 1 \text{ and } h_{2t} = 1, \mu \in [0,1] \end{cases} \quad . \qquad (8)$$

The parameter values for the simulations are presented in Table B1 in Appendix B. Figures 1 through 5 were created using these parameters. The annual endangered species value E is \$1.83 million. This amount is the annualized cost of protecting enough habitat for a single Northern spotted owl nest site with a 95% probability of survival (Montgomery, Brown, and Adams, 1994). The gross value of protecting a pair of

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[24] With X stands and a binomial decision variable (clearcut or not), there are X^2 possible harvest actions each period. Given a maximum rotation length of Y, there are Y^X age permutations possible at the beginning of each period. Given horizon length N, there are $X^2 * Y^X * N$ possible decisions over the horizon.

[25] Swallow, Parks, and Wear (1990) discuss the dangers of local optima when optimizing timber and nontimber benefits. See Murray (1999) for a discussion of heuristic forest management optimization techniques.

[26] Tracts of different sizes and shapes would require heterogeneous fixed costs. Also, analysis of a larger forest would require specification of a tract size limit for exploiting harvesting cost economies of adjacency.

Northern spotted owls may be even larger (Hagen, Vincent, and Welle, 1992). We justify the large *E* value by assuming that the nest is located on the two stands being managed and that survival requires both stands to be at least one hundred years old. If natural resettlement by the species is possible, logging may not result in extinction.

The maximum annual hunting value of $26 was drawn from Haynes and Horne's (1997, p. 1783) average annual hunting value of approximately $5/acre for federal lands in the Columbia River Basin. The mature growth parameters produce values of approximately $2,443 and $1,058 for two hectares and one hectare of 300 year old growth respectively. The discount rate is 2%.

IV.2 Results

The optimal harvest sequences and patterns are found, first, for each of the objective values separately, i.e. timber value, hunting value, mature growth value, or endangered species value, and then, for all possible combinations of the values. Selected results are presented for discussion, beginning with the maximization of timber value.

The following conditions are used for all of the simulations. Both stands are initially 100 years old. The stands are heterogeneous in timber and hunting value productivity: Stand 1 exhibits high productivity and Stand 2 exhibits low productivity. Unless indicated otherwise, harvesting decisions are made every year. Lastly, the fixed cost of harvesting an individual stand is either $0 or $2,500, and the cost of simultaneously harvesting both stands varies as indicated.

The value of timber is maximized in Table 2 for four harvesting cost scenarios, where different degrees of cost economies for adjacent harvesting are available. The cost scenarios are: no cost sharing, partial cost sharing, full cost sharing, and no cost.

The net present value of timber is maximized with each cost scenario. For example, for "no cost sharing," the cost of a single stand harvest is $2,500 and the cost of a simultaneous harvest of both stands is $5,000. The optimal harvest sequence consists of a simultaneous harvest in year 0, harvests of Stand 1 in year 51 and again every 51 years, and harvests of Stand 2 in year 53 and again every 53 years. The greater productivity of Stand 1 leads to a shorter rotation. The resulting overall net present timber value is $161,395. Incidentally, the harvest pattern also generates a hunting net present value of $1,073, a mature growth net present value of $1, and no endangered species value. Although maximizing the value of timber is the objective, these additional social benefits are produced, raising the net social value to a total of $162,469.

Comparing cost scenarios, the differences in the total net present values can almost entirely be attributed to the differences in the net present values of timber. In all scenarios, both stands are harvested in year 0. This has the combined effect of yielding current net timber benefits and regenerating timber growth (and incidentally, hunting value with renewed forage production). Across the scenarios, for a given harvest decision, higher harvesting costs decrease the marginal cost of postponing harvests, and subsequently generate longer rotations (compare the no cost sharing and no cost scenarios). However, increasing cost economies for simultaneous harvesting raises the

Table 2: Maximize Timber Value With Varying Cost Economies of Adjacency

initially mature stands that are 100 years old, high level productivity on stand 1, low level producivity on stand 2, management decisions made every year

	No Cost Sharing	Partial Cost Sharing	Full Cost Sharing	No Cost
Single Harvest Fixed Cost (*c*)	$2,500	$2,500	$2,500	$0
μ	1	1/2	0	--
Simultaneous Harvest Fixed Cost	$5,000	$3,750	$2,500	$0
First Harvests				
Age of Stand 1	100	100	100	100
Age of Stand 2	100	100	100	100
Second Harvests				
Age of Stand 1	51	50	49	44
Age of Stand 2	53	50	49	44
Steady-State Harvest Sequence				
Age of Stand 1	51[A]	50	49	44[B]
Age of Stand 2	53	50	49	44
Number of Years before Steady-State	51	50	49	44
Net Present Values				
* **Timber**	$161,395	$163,342	$165,331	$169,453
Hunting	$1,073	$1,081	$1,087	$1,118
Mature Growth	$1	$0	$0	$0
Endangered Species	$0	$0	$0	$0
Total	$162,469	$164,423	$166,418	$170,571

* This value is maximized.

[A] In the steady-state, the stands are managed independently: stand 1 is harvested every 51 years, stand 2 is harvested every 53 years.

[B] In the steady-state, the stands are managed independently: both stands are harvested every 44 years. The harvests are simultaneous because the intial ages of the stands are identical.

marginal cost of postponement and hence, encourages simultaneous and shorter rotations (compare the partial and full cost sharing scenarios).[27]

Faustmann rotations, i.e. independent infinitely repeated rotations under timber only management, are produced in the no cost sharing and the no cost scenarios.[28] Although the other scenarios appear to yield Faustmann rotations as well, the stands are not managed independently. In additional simulations (not shown), despite heterogeneous initial stand ages, the cost economies ($\mu = ½$ and 0) discourage independent stand management and produce simultaneous harvests.

Note that small positive hunting value is found in every case. Also, larger hunting values correspond with shorter rotations. However, mature growth and endangered species values are non-existent. As defined by the model, these optimal harvest patterns do not provide standing forest that is old enough or large enough to supply mature growth benefits (e.g. recreation, environmental services, or nonuse) or endangered species habitat. The discounted mature growth value of $1 produced under the no cost sharing scenario is derived from Stand 2's 53 year rotations, which just satisfy the 50 year minimum age threshold for mature growth value.

The optimization of hunting value is presented in Table 3. Ignoring timber prices and harvesting costs, the initial period harvest of both stands regenerates the supply of forage and expedites the achievement of optimal conditions for game species. Short alternating harvests follow, providing an ideal mix of forage and cover, with Stand 1's

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[27] The initial simultaneous harvest of the 100 year old stands generates most of the timber value: $131,800 for "no cost sharing," $133,050 for "partial cost sharing," $134,300 for "full cost sharing," and $136,800 for "no cost." If management begins with bare ground, the initial net timber harvests and hence returns are absent, but the remainder of the optimal harvest pattern is preserved.

[28] See Faustmann (1849).

Table 3: Maximize Hunting Value

initially mature stands that are 100 years old, high level productivity on stand 1, low level producivity on stand 2, management decisions made every year

	No Cost
Single Harvest Fixed Cost (*c*)	$0
μ	--
Simultaneous Harvest Fixed Cost	$0
First Harvests	
Age of Stand 1	100
Age of Stand 2	100
Second Harvests	
Age of Stand 1	25
Age of Stand 2	15
Steady-State Harvest Sequence	
Age of Stand 1	23[A]
Age of Stand 2	23
Number of Years before Steady-State	48
Net Present Values	
Timber	$165,650
*** Hunting**	$1,211
Mature Growth	$0
Endangered Species	$0
Total	$166,860

* This value is maximized.

[A] The steady-state consists of alternating harvests, the unharvested age of stand 1 is 12 years when stand 2 is harvested at 23 years and the unharvested age of stand 2 is 11 years when stand 1 is harvested at 23 years.

unharvested stage slightly longer than Stand 2's in order to exploit Stand 1's greater forage productivity. In the steady-state, the stands gradually shift the distribution of forage production back and forth.

The maximum present value for hunting is a modest \$1,211; a gain in hunting value of \$100 over that produced incidentally under no cost timber management in Table 2, but a loss in timber value of \$3,800.[29] Nonetheless, the maximization of hunting value yields substantial timber value of \$165,650.

The maximization of only mature growth value or endangered species value results in no harvesting (not shown). Beginning with stands of initially one hundred years, the present values of mature growth and endangered species are \$114,697 and \$92,418,040 respectively. The large endangered species value is the discounted value of an infinite stream of \$1.83 million per year.

A quick comparison of the maximized present values for each independent objective gives a preview of how management might proceed when maximizing the sum of any combination of values. A simple ranking of the independent maximums turns out to be a good predictor of the outcome. From largest to smallest, the ranking of values is endangered species, timber, mature growth, and hunting.

Table 4 presents the results of maximizing the sum of the timber and hunting values. The influence of hunting benefits on management decisions is barely noticeable, deviating only slightly from the optimal timber management decisions (Table 2). Preferring shorter and staggered harvests, the value of hunting is insufficient for overcoming cost economies of simultaneous harvesting and can only shorten the rotations

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[29] Or \$9,950, \$10,640, or \$11,380 if the harvesting cost scenario is $\mu = 1$, ½, or 0 respectively.

Table 4: Maximize Timber and Hunting Values With Varying Cost Economies of Adjacency

	No Cost Sharing	Partial Cost Sharing	Full Cost Sharing	No Cost
Single Harvest Fixed Cost (*c*)	\$2,500	\$2,500	\$2,500	\$0
μ	1	1/2	0	--
Simultaneous Harvest Fixed Cost	\$5,000	\$3,750	\$2,500	\$0
First Harvests				
Age of Stand 1	100	100	100	100
Age of Stand 2	100	100	100	100
Second Harvests				
Age of Stand 1	50	50	48	44
Age of Stand 2	53	50	48	43
Steady-State Harvest Sequence				
Age of Stand 1	50[A]	50	48	44[B]
Age of Stand 2	53	50	48	43
Number of Years before Steady-State	50	50	48	43
Net Present Values				
*** Timber**	\$161,388	\$163,342	\$165,329	\$169,448
*** Hunting**	\$1,080	\$1,081	\$1,093	\$1,123
Mature Growth	\$1	\$0	\$0	\$0
Endangered Species	\$0	\$0	\$0	\$0
Total	\$162,469	\$164,423	\$166,422	\$170,571

* The SUM of these values is maximized.

[A] In the steady-state, the stands are managed independently: stand 1 is harvested every 50 years, stand 2 is harvested every 53 years.

[B] In the steady-state, the stands are managed independently: stand 1 is harvested every 44 years, stand 2 is harvested every 43 years.

on one or both of the stands by one year in three of the cost scenarios (the partial cost sharing decisions are unaffected).[30] The result is a small redistribution of the net present values from timber to hunting. Except for the full cost sharing scenario, the redistributions do not increase the total net present values. Note also, that timber management (Table 2) is almost as effective at producing hunting benefits.

The sum of the optimized combined values should always be greater than or equal to each of the optimized individual values. In this case, the no cost optimal value for timber and hunting is greater than the optimal value for hunting (Table 3) and equal to the no cost optimal value for timber (Table 2). After reviewing all of the scenarios, optimal timber and hunting management is as or more efficient than optimal timber and optimal hunting management respectively. However, only the full cost sharing scenario is a pareto improvement over its timber management counterpart, i.e. both the timber and hunting values increase.

The sum of timber, hunting, and mature growth is maximized in Table 5. The inclusion of mature growth value in the optimization has no impact on the steady-state harvest sequences (compare the results to Table 4). However, the benefits of mature growth optimally delay the initial harvests under the no cost sharing and partial cost sharing scenarios. The length of the delay decreases as the cost economies of adjacency increase: greater cost economies discourage the delay of the initial and steady-state harvests (compare the no cost sharing, partial cost sharing, and full cost sharing

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[30] The hunting value representation depicts local extinction, i.e. a temporary loss of species populations due to habitat loss. Game species return through dispersal and migration when the habitat is suitable again. Permanent extinction of hunting species may result if the management area is isolated such that natural repopulation is impossible. We simulated the extinction of game species and found that the threat of the lost future hunting value provided an additional incentive for providing edge habitat, hence an additional disincentive for clearing the entire management area.

Table 5: Maximize Timber, Hunting, and Mature Growth Value With Varying Cost Economies of Adjacency

	No Cost Sharing	Partial Cost Sharing	Full Cost Sharing	No Cost
Single Harvest Fixed Cost (*c*)	$2,500	$2,500	$2,500	$0
μ	1	1/2	0	--
Simultaneous Harvest Fixed Cost	$5,000	$3,750	$2,500	$0
First Harvests				
Age of Stand 1	104	101	100	100
Age of Stand 2	104	101	100	100
Second Harvests				
Age of Stand 1	51	50	48	44
Age of Stand 2	53	50	48	43
Steady-State Harvest Sequence				
Age of Stand 1	50[A]	50	48	44[B]
Age of Stand 2	53	50	48	43
Number of Years before Steady-State	57	51	48	43
Net Present Values				
*** Timber**	$153,582	$161,366	$165,329	$169,448
*** Hunting**	$994	$1,060	$1,093	$1,123
*** Mature Growth**	$7,999	$2,001	$0	$0
Endangered Species	$7,105,437	$1,830,000	$0	$0
Total	$7,268,013	$1,994,427	$166,422	$170,571

* The SUM of these values is maximized.

[A] In the steady-state, the stands are managed independently: stand 1 is harvested every 50 years, stand 2 is harvested every 53 years.

[B] In the steady-state, the stands are managed independently: stand 1 is harvested every 44 years, stand 2 is harvested every 43 years.

scenarios). Hence, positive mature growth benefits are optimal when the marginal benefit of a year of mature growth for a given age and acreage is greater than the marginal cost of postponing current and future harvests. When this relationship reverses, harvesting is optimal. The reversal results because, given our specification, net merchantible timber value grows faster than mature growth value.

As mentioned previously, an optimal redistribution of net present value must be at least as efficient as before the redistribution. All of the harvest sequences in Table 5 are as efficient as the results in Table 4. In fact, despite the reduced timber and hunting benefits in the no cost sharing and partial cost sharing scenarios, consideration of mature growth benefits produces overall efficiency gains as well as incidental endangered species benefits from the first three years and first year respectively with two mature hectares.[31]

The positive endangered species value in Table 5 is a by-product of managing for mature growth benefits and beginning management with 100 year old stands (see Figure 5). Recall that bare ground on either stand is inadequate for endangered species habitat and results in extinction.

Endangered species value is incorporated into the management decisions in Table 6, where the sum of the timber, hunting, and endangered species values are maximized.[32] Regardless of the cost scenario, the annual endangered species value dominates

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[31] To compute the efficiency gains, sum the timber, hunting, and mature growth net present values from Table 5 and subtract the sum of the timber and hunting net present values from Table 4.

[32] In Table 6, it is assumed that management (harvesting) decisions are made every ten years. Increased computation requirements necessitated this reduction in the frequency of decision making (from the annual decisions in the previous tables). The reduced management frequency substantially increases the computation speed of the optimization algorithm. The speed improvement is gained at the cost of precision in the timing of harvests, however, conceptually, the results in Table 6 are valid.

Table 6: Maximize Timber, Hunting, and Endangered Species Value With Varying Cost Economies of Adjacency

management decisions made every 10 years

	All Cost Scenarios
Single Harvest Fixed Cost (*c*)	$2,500 & $0
μ	1, 1/2, 0, & --
Simultaneous Harvest Fixed Cost	$5,000, $3,750, $2,500, & $0
First Harvests	
Age of Stand 1	never
Age of Stand 2	never
Second Harvests	
Age of Stand 1	never
Age of Stand 2	never
Steady-State Harvest Sequence	
Age of Stand 1	never
Age of Stand 2	never
Number of Years before Steady-State	--
Net Present Values	
*** Timber**	$0
*** Hunting**	$4
Mature Growth	$114,697
*** Endangered Species**	$92,418,040
Total Social Value	$92,532,741

* The SUM of these values is maximized.

management and indefinitely discourages harvesting.[33] Mature growth profits from the harvest moratorium, and hunting diminishes to zero with the dwindling forage supply. Despite the absence of timber and hunting value, a no harvest policy yields an unambiguous improvement in efficiency.[34]

For a given parameterization and initial condition, it is possible to find the minimum annual endangered species value *E* necessary for a harvest moratorium in each of the cost scenarios. In the current setting, the thresholds are \$3,721, \$3,760, \$3,799, \$3,879 for the no cost sharing, partial cost sharing, full cost sharing, and no cost scenarios respectively. Hence, for the full cost sharing scenario, an annual current endangered species value of \$3,799 will suffice for a permanent harvest stoppage to be optimal. The threshold values decrease as the net timber value decreases due to reduced harvesting cost economies.

V. Conclusions

Timber revenues, once the primary objective of forestry policy and management, must now compete with complementary and conflicting nontimber interests. This work has illuminated complementarities between, on the one hand, timber and hunting values, which favor harvesting and regeneration; and, on the other hand, recreation, scenic,

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[33] It is also possible to represent the re-introduction of an endangered species. In this case, extinction is ignored and endangered species benefits are generated once the habitat is suitable for species repopulation. When starting from bare ground in the current setting, the future annual endangered species benefit of $E =$ \$1.83 million is large enough to indefinitely discourage harvesting and induce old growth regeneration for species habitat. We thank Jon Conrad for suggesting we consider this situation.

[34] The different benefits may be regarded as gross complements or gross substitutes. Timber and hunting may or may not be gross complements, where an increase in the value of one results in an increase in the consumption of both. However, mature growth and endangered species are gross complements. In addition, timber is a gross substitute for mature growth and endangered species (and sometimes hunting), where an increase in the value of timber results in a decrease in the consumption of mature growth and endangered species (and hunting). See Mas-Colell, Whinston, and Green (1995, p611) for the general definitions of gross complements and substitutes.

environmental service, nonuse, and endangered species' values, which favor contiguous undisturbed mixed age climax forest. Regeneration decisions are complicated further by harvesting costs. Higher costs can motivate longer rotations and infrequent harvesting, while cost economies in the harvest acreage can encourage larger harvest areas and more frequent harvesting. The distribution of benefits between timber and nontimber values will depend on the management objective. A single value or combination of values will determine the optimal intertemporal and spatial harvest pattern. However, overall efficiency will be maximized by including all social values in decision making.

In the simulations of this paper, a dominance hierarchy was observed. The value of endangered species dictated that no harvesting occur when this value was included in the management objective. After endangered species value, the order of dominance over harvesting decisions was timber, mature growth value, and then hunting value. It is worth noting that there was no change in these qualitative results when we used larger stands. For a particular forest area, the actual ranking of management decisions and outcomes will vary according to the natural resources, scenery, and ecosystem services (i.e. the parameters and functions appropriate to that area), as well as the proximity to population centers, and the ownership of the location (Haynes and Horne, 1997). However, while the measurement of nonuse benefits (such as for endangered species, bequest, existence, and use options) is controversial, mounting evidence suggests that these benefits are substantial and may dwarf timber values (Haynes and Horne, 1997; Niemi et al. 1999; Loomis and Gonzalez-Caban, 1998; Pope and Jones, 1990; Hagen, Vincent, and Welle, 1992; Walsh et al., 1990; Walsh, Loomis, and Gillman, 1984).

Haynes and Horne (1997) estimated that on average 47% of the total 1995 value for US Forest Service and Bureau of Land Management areas in the Interior Columbia Basin was nonuse value. Across study areas, the proportion ranged from zero to 65%. Meanwhile, timber returns generated on average only 11.5% of the total value (ranging from zero to 49%). The remainder was recreation value. Walsh et al. (1990) estimated that on average 72% of the annual recreation and preservation value for eleven National Forests in Colorado was nonuse value. Walsh, Loomis, and Gillman (1984) estimated average nonuse value to be 50 to 85% of recreation and preservation value for Colorado wilderness, where the proportion increased (at a decreasing rate) with the size of the wilderness area.

In this analysis, nontimber benefits ranged from less than 1% to 100% of total value, depending upon the specific objective sought by forest management (the nonuse benefits of endangered species ranged from 0% to 99.9% of total value). Accordingly, timber benefits ranged from 0% to 99% of total value, again depending upon management objectives.

The methodology utilized here is admittedly complex. In addition, the specification of parameters for a given forest area may be difficult. Hence, the applicability of our approach to the actual management of forest areas is probably circumscribed. We think that our greatest contribution may be intellectual: a conceptual methodology which provides a transparent picture of optimal decision making. It provides an objective rationale for results that may parallel on-the-ground forest management in today's world of both conflicting and complementary values.

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Appendix A: Notation Index

$a_{ES,min}$	minimum age for supporting endangered species (years)
$a_{M,min}$	minimum age for mature stands (years)
$a_{w,max}$	given mature growth block size n_{wt}, the age at which the logistic value growth first reaches maximum $M(n_{wt})$ and linear value growth takes over (years)
a_{st}	age of stand s in period t (years)
$a_{st+1} = a_{st}(1-h_{st}) + 1$	age of stand *s* next period (years)
$a_t = (a_{1t}, a_{2t}, \ldots, a_{St})$	vector of timber ages on all stands in period *t* (years)
b	index identifying a harvest block (scalar), $b \in B(h_t)$
$B(h_t)$	number of disjoint harvest blocks given h_t (scalar)
c_s	fixed cost of harvesting stand *s* independently ($)
$c_{max,b}$	maximum independent fixed harvesting cost from the stands in harvesting block *b* ($), max$\{c_s: s \in S_b\}$
$C(h_t)$	total fixed cost in period *t* over all stands for harvest configuration h_t ($)
d	index identifying a block of suitable endangered species habitat, $d \in D(g_t)$
$D(g_t)$	number of discrete blocks of suitable endangered species habitat in period *t* following harvest decision h_t (scalar), where a suitable habitat is defined by minimum age and acreage requirements $g_{st} \geq a_{ES,min}$ for all $s \in S_d$ and $n_{dt} \geq n_{ES,min}$ respectively
E	maximum value of endangered species if extinction has not occurred previously ($)
f_0	maximum value of forage ($/aum)
$F(\xi)$	marginal value of forage quantity ξ in period *t* ($/aum)
g_{st}	age of stand *s* in period *t* after harvesting decision h_{st} (years), $g_{st} = a_{st}(1-h_{st})$

$g_t = g(h_t;a_t) = (g_{1t}, \ldots, g_{St})$	timber ages on all stands in period *t* after the beginning of period harvesting decisions (years)
$\bar{g}_{wt}$	average age of the mature stands in mature growth block *w* (years)
$G(g_t)$	total available forage from all stands in period *t* given the post-harvest-decision ages of the stands (aum)
$G_s(g_{st})$	quantity of available forage on stand *s* in period *t* given the post-harvest-decision age of the stand (aum)
h_{st}	harvest decision on stand *s* in period *t*; if harvesting is undertaken it is at the beginning of the period, and $h_{st} = \begin{cases} 1 & \textit{clearcut} \\ 0 & \textit{no}\text{ harvest} \end{cases}$
$h_t = (h_{1t}, h_{2t}, \ldots, h_{St})$	vector of harvest decisions in period *t*
$H(g_t)$	hunting consumer surplus produced by the forest age configuration g_t in period t
$l_{smt} = a_{st}h_{st}$	length of rotation *m* on stand *s* (years)
$l_{st} = (l_{s1t}, l_{s2t}, \ldots, l_{smt})$	vector record of the lengths of rotations on stand *s* through period *t* (years), includes only the m_{st} rotations that have occurred prior to year *t*
$l_t = (l_{1t}, l_{2t}, \ldots, l_{St})$	matrix record of the lengths of all rotations on each stand through period *t* (years)
m_{st}	number of rotations that have occurred on stand *s* before period *t* (scalar)
$m_{st+1} = m_{st} + h_{st}$	number of rotations performed on stand *s* after the current period (scalar). Note, $m_{st+1} = \sum_{i=1}^{t} h_{si}$
$m_t = (m_{1t}, m_{2t}, , m_{St})$	vector of the number of rotations performed on each stand to date (scalar)
M	maximum value of all mature growth nontimber benefits excluding the value of endangered species ($)

$M(n_{wt})$	maximum value of n_{wt} hectares of contiguous old growth (similar to a carrying capacity parameter) ($\$$)
n_{dt}	number of hectares in endangered species habitat block d (hectares)
$n_{ES,min}$	minimum number of hectares for supporting endangered species (hectares)
n_{wt}	number of hectares in mature growth block w (hectares)
P	unit price of timber ($\$/f^3$)
$Q_s = Q_s(a_{st}, l_{st}, m_{st})$	merchantable timber volume on stand s in period t given the age, rotation record, and rotation count of the stand (mbf)
$Q_s = Q_s(a_{st})$	merchantable timber volume on stand s in period t given the age of the stand (f^3)
$Q_t = Q(a_t, l_t, m_t) = (Q_1(a_{1t}, l_{1t}, m_{1t}), \ldots, Q_S(a_{St}, l_{St}, m_{St}))$	vector of merchantable timber volumes on each stand in period t given the ages, rotation records, and rotation counts of all the stands (f^3), or
$Q_t = Q(a_t) = (Q_1(a_{1t}), \ldots, Q_S(a_{St}))$	vector of merchantable timber volumes on each stand in period t given the ages of all the stands (f^3)
s	index identifying a stand (scalar), $s \in S$
S	number of stands (scalar)
S_b	set of harvested stands in harvest block b, where, for each block, $h_{st} = 1$ for all $s \in S_b$
S_d	set of stands in endangered species habitat block d, where, for each block, $g_{st} \geq a_{ES,min}$ for all $s \in S_d$ and $n_{dt} \geq n_{ES,min}$,
S_w	set of stands in mature growth block w, where, for each block, $g_{st} \geq a_{M,min}$ for all $s \in S_w$
t	current decision period (year)

$V(h_t) = V(h_t;a_t,l_t,m_t)$	nontimber benefit value of the forest condition between harvest decisions ($)
$V_{ES}(g_t) = V_{ES}(g(h_t;a_t))$	nonuse value of endangered interior forest species in period t following the harvest decisions in period t ($)
$V_H(g_t) = V_H(g(h_t;a_t))$	hunting value of game species in period t following the harvest decisions in period t ($)
$V_M(g_t) = V_M(g(h_t;a_t))$	use and nonuse value of standing mature growth in period t following the harvest decisions in period t ($)
$V_M^w(\overline{g}_{wt})$	mature growth value of block w given the average age of the mature stands in block w ($)
w	index identifying a block of mature growth (scalar), $w \in W(g_t)$
$W(g_t)$	number of discrete blocks of mature growth in period t following harvest decision h_t (scalar)
β_{0s}	forage increasing growth parameter for stand s
β_{1s}	forage decreasing growth parameter for stand s
γ	exponential rate of change of forage value
δ	interest rate (%/100)
ε	an instant in time between decision periods (years), $\varepsilon > 0$
η_{0s}	slope parameter for the stand s merchantable timber volume growth function specification
η_{1s}	concavity parameter for the stand s merchantable timber volume growth function specification
η_{2s}	inflexion parameter for the stand s merchantable timber volume growth function specification
λ_1	location parameter for the age dependent logistic growth portion of the function specification for the value of mature growth on any mature growth block w

λ_2	rate of change parameter for the age dependent logistic growth portion of the function specification for the value of mature growth on any mature growth block *w*
$\Theta_t = \Theta_t(h_t;a_t,l_t,m_t)$	net present value ($) of this period's harvest decisions h_t given current state of the forest (a_t,l_t,m_t) and the present value of future optimal harvest decisions $\Theta^*_{t+1}(h_t)$, or
$\Theta_t = \Theta_t(h_t;a_t)$	net present value ($) of this period's harvest decisions h_t given current state of the forest (a_t) and the present value of future optimal harvest decisions $\Theta^*_{t+1}(h_t)$
$\Theta^*_{t+1}(h_t) = \Theta^*_{t+1}(a_{t+1}(h_t),l_{t+1}(h_t),m_{t+1}(h_t))$	net present value ($) of the optimal harvest decisions in the future given the resulting state of the forest $(a_{t+1},l_{t+1},m_{t+1})$ from this period's decisions, or
$\Theta^*_{t+1}(h_t) = \Theta^*_{t+1}(a_{t+1}(h_t))$	net present value ($) of the optimal harvest decisions in the future given the resulting state of the forest (a_{t+1}) from this period's decisions
μ_s	proportion of c_s added to this period's total harvesting cost if stand *s* is harvested, $\mu_s \in [0,1]$
ξ	an infinitesimal change in the total quantity of forage (aum), $\xi > 0$
π	slope parameter for the age dependent linear growth portion of the function specification for the value of mature growth on any mature growth block *w*
φ_1	location parameter for the acreage dependent logistic growth function specification for the value of mature growth on any mature growth block *w*
φ_2	rate of change parameter for the acreage dependent logistic growth function specification for the value of mature growth on any mature growth block *w*

Appendix B: Function Specification and Parameter Values

The following specifications were used in the simulations but were not specified in the main text.

The value of hunting (Equation 5) is estimated as the average consumer surplus of hunting between decision periods:

$$V_H(g_t) = \frac{H(g_t) + e^{-\delta} H(g_t + 1)}{2} \tag{B1}$$

where the hunting consumer surplus for stand age configuration g_t is the integral of the value of forage from zero to the current total quantity of forage $G(g_t)$:

$$H(g_t) = \int_0^{G(g_t)} F(\xi) d\xi\,. \tag{B2}$$

The value of forage $F(\xi)$, \$/aum/year, for quantity ξ is measured by the demand function (Swallow, Parks, and Wear, 1990; Swallow and Wear, 1993)

$$F(\xi) = f_0 e^{-\gamma\xi}, \tag{B3}$$

where f_0 is the maximum value of forage and γ is the rate of change.[35] Using the parameters in Table B1, the marginal value of forage ranges from \$2.80 to \$55.00. The quantity of forage (aum/year) $G(g_t) = \sum_{s=1}^{S} G_s(g_{st})$ is computed from stand level forage production functions (Swallow, Parks, and Wear, 1993)

$$G_s(g_{st}) = \beta_{0s} g_{st} e^{-\beta_{1s} g_{st}}. \tag{B4}$$

Forage output from stand *s* grows with age according to β_{0s} at a decreasing exponential rate β_{1s}, reaches a global maximum at 0.82 aum/year with high productivity (0.66 aum/year with low productivity) and declines asymptotically to zero.[36]

The total value of mature growth in the management area is the sum of the mature growth values from each of the blocks of mature growth stands (Equation 6). The value on mature growth block *w* grows logistically in both age and acreage:

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[35] The integral in Equation (B2) is computable and is equal to $(f_0/\gamma)[1-\exp(-\gamma G(g_t))]$.

$$V_M^w(\bar{g}_{wt}) = \begin{cases} M(n_{wt})/[1+e^{(\lambda_1-\lambda_2(\bar{g}_{wt}\text{-}a_{M,min}))}] & \text{if } \bar{g}_{wt} < a_{w,max} \\ M(n_{wt}) + \pi(\bar{g}_{wt} - a_{w,max}) & \text{otherwise} \end{cases} \tag{B5}$$

$$M(n_{wt}) = M/[1+e^{(\varphi_1-\varphi_2 n_{wt})}] \tag{B6}$$

where

w = index identifying a block of stands of mature growth, where $w \in W(g_t)$ and there are $W(g_t)$ discrete blocks of mature growth in period t following harvest decision h_t (scalar),

$\bar{g}_{wt}$ = average age of the mature stands in mature growth block w (years),

$$\bar{g}_{wt} = \frac{1}{n_{wt}} \sum_{s \in S_w} g_{st}$$

n_{wt} = the number of hectares in mature growth block w (hectares),

S_w = the set of stands in mature growth block w, where, for each block, $g_{st} \geq a_{M,min}$ for all $s \in S_w$,

$M(n_{wt})$ = the maximum mature growth value that can be attained on block w given that there are n_{wt} hectares in block w (similar to a carrying capacity parameter) ($),

$a_{M,min}$ = the minimum age for mature stands (years), and

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[36] The hunting value calculation used in this paper is a modification of that employed by Swallow and Wear (1993), Talukdar (1996), and Swallow, Talukdar, and Wear (1997). These authors estimate the hunting value at any point in time by multiplying price times quantity, i.e. $F(G_t(g_t))G_t(g_t)$, where the functions are defined as in this paper. However, this method captures only a part of the total consumer surplus for a given quantity of forage, leaving out the portion of the surplus for individuals with values greater than $F(G_t(g_t))$.

$a_{w,max}$ = given mature growth block size n_{wt}, the age at which the logistic value growth first reaches maximum $M(n_{wt})$ and linear value growth takes over (years),[37]

M = the maximum value of all mature growth nontimber benefits excluding the value of endangered species ($).

The parameters in Table B1 are used for the simulations. The low productivity value is eighty percent of the corresponding high productivity value.

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[37] Using the parameters in Table B1, the computed ages are 124 years and 129 years for one and two hectares blocks of mature growth respectively.

Table B1: Parameter Values Used in Simulations

$a_{ES,min}$	100 years
$a_{M,min}$	50 years
c_s	\$2,500
E	\$1.83 million/year
f_0	\$55/aum
M	\$5,000/year
$M(n_{wt})$	\$2,272/year (n_{wt} = 2 hectares), \$882/year (n_{wt} = 1 hectare)
$n_{ES,min}$	2 hectares
P	\$4/f^3
β_{0s}	0.077045 aum/year (high), 0.0616 (low)
β_{1s}	0.0850
γ	-2
δ	2%
η_{0s}	40 (high), 32 (low)
η_{1s}	3.1 (high), 2.48 (low)
η_{2s}	- 0.016 (high), - 0.0128 (low)
λ_1	8
λ_2	0.2
π	\$1
φ_1	2.9
φ_2	0.55