Public Forest Land Allocation:
A Dynamic Spatial Perspective on
Environmental Timber Management

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Abstract

The complicated process of public forest land allocation involves competing economies of scale. While harvesting cost economies of scale may benefit harvesters, where average costs decline as contiguous harvested acreage increases, larger harvested areas can generate diseconomies in terms of environmental and ecosystem damage. This paper extends existing timber rotation models to more completely account for spatial synergies. Simulations are used to illustrate potential impacts. Simulations find that adjacency economies of scale may be an important determinant of the optimal spatial harvest configuration and intertemporal harvest sequence. The consequences of scheduling harvests ignorant of fixed costs are also discussed.

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I. Introduction

Public forest land allocation is a complicated process which involves conflicting economies of scale that result in an intertemporal trade-off of timber revenues for the environment. On the one hand, harvesters benefit from cost economies of adjacency where average costs decline as contiguous harvested acreage size increases. On the other hand, larger harvested tracts lend themselves to diseconomies of adjacency in the form of increased environmental and ecosystem damages. Larger continuous cuts, while appealing to harvesters because of lower average capital costs, may increase erosion and water siltation, adversely affect the growth of future forest stands, fragment wildlife habitat, disrupt environmental/ecosystem services, and decrease other use and non-use values of the forest (e.g. global carbon sequestration value, aesthetic value, and existence value). These diseconomies of adjacency are social costs of harvesting. Common to all of the factors mentioned are spatial and time dimensions within and between the forest stands which determine the magnitudes of the factor values.

Observed forest management practices are driven by management objectives, which vary across private and public forest holdings. U.S. public forest managers, however, are legally obligated to account for both timber and nontimber benefits. Specifically, the National Forest Management Act of 1976 mandates that forest planning be carried out in accordance with the National Environmental Policy Act of 1969 (NEPA). The principles of NEPA are:

(1) To consider all resources (including non-commodity resources) and how they interact when making management decisions.

(2) To develop and evaluate alternatives for managing resources and meeting public demands.

(3) To analyze the environmental effects of each alternative, including economic, social and physical effects.

(4) To actively involve the public in the planning and decision-making process.

As NEPA mandates, timber gains should not be reaped without consideration of the costs and benefits to non-timber products and services. This research will study this dichotomy using a dynamic spatial model, which accommodates synergies between forest stands. While the focus of this research is on public forests, many pieces of this discussion will be applicable to private forest management.

Traditional forestry economic models (Faustmann, 1849 and Hartman, 1976) characterized the forest in terms of independent stands. Hence, management of the forest for timber and nontimber benefits was simply a problem of the unique management of each stand. The recognition of the importance of spatial interdependence between stands and geographic proximity and location of stands refocused management emphasis to the forest level (Bowes and Krutilla, 1985, 1989; Swallow and Wear, 1993; Swallow, Talukdar, and Wear, 1997). To date, spatial dependence has manifested itself through nontimber benefits functions (Swallow and Wear, 1993; Swallow, Talukdar, and Wear, 1997; Bettinger, Sessions, and Johnson, 1998) and spatial fixed harvesting cost considerations have been absent from the decision modeling.

Independent stand models treat fixed cost changes as they do per unit timber price changes (Clark, 1990). This is appropriate given the model's assumptions. However, with spatial models, the role of fixed costs must be revisited. Spatial management models, which

simultaneously determine the harvesting decisions on multiple stands, permit the exploitation of economies of scale in the harvesting of adjacent stands. Hence, by geographically consolidating harvests, harvesters can benefit from economies of adjacency.

This paper is motivated by a USAID research experience in Western Ukraine. Unlike the United States, all forest land in Ukraine is publicly owned. Each year, Forest Service officials offer forested tracts to loggers for harvest via centralized allocation. Government officials assemble what they deem "appealing" packages of tracts for each logging entity. At year's end, not all of the offered land is harvested: some is never accepted by the loggers or is accepted but uncut at the cost of a penalty. This experience presents two issues: first, what role do fixed costs play in the scheduling of multiple harvests? And second, could an efficient harvesting rights allocation mechanism be designed to relieve the seller of the burden of allocation while permitting loggers to exploit economies of adjacency and simultaneously protecting the flow of nontimber amenities?

The first question will be addressed—conceptually and with simulations—by this paper. Extending existing spatial models to account for economies of adjacency will provide insight into logger behavior and the complicated decisions of forest managers who practice multiple use management.[2] A clearer understanding and representation of the dynamic spatial forest allocation problem facilitates the development of better forest management policy for improving intergenerational welfare.

The next section modifies current theoretical models to accommodate economies of adjacency, developing decision rules for multiple stand management. The third section uses a simple recursive simulation procedure to illustrate the potential impact on harvesting decisions of

spatially relevant fixed costs. The last section offers conclusions and opportunities for further analysis.

II. Theoretical Model

Common to most timber and non-timber factors are spatial and time dimensions within and between the forest stands. These dimensions determine the magnitudes of the factor values. It is intuitive that, given the list of factors mentioned previously, omitting one or more from a forest land allocation decision could yield a very different allocation in addition to different social benefits and costs. This philosophy has motivated the incremental evolution of timber rotation models from Faustmann (1849), to Hartman (1976), to Bowes and Krutilla (1985, 1989), to Swallow and Wear (1993), to Swallow, Talukdar, and Wear (1997). The models in these papers progressively develop from a timber only model to a timber and non-timber amenity model in which non-timber amenities are determined by the forest condition. This research will pick up where Swallow, Talukdar, and Wear left off, adding an additional spatial interaction through harvesting costs.

Harvesting costs have historically been treated as constant per unit volume harvested marginal costs and stand specific constant logging or regeneration fixed costs. Hence, harvesting economies of adjacency have not been acknowledged. While Paarsch (1997) finds statistical evidence of economies of scale in harvest volumes, models have yet to explore the affect of spatial harvesting configurations on average costs and the actions of loggers. If there are significant rents from harvesting neighboring stands, then it seems reasonable that loggers will attempt to extract those benefits.

Consider a forest divided into well delineated stands. Ignore all the stands but one. When is the best time to harvest this stand?[3] Faustmann (1849) solves this problem, assuming that the growing conditions are unaffected by the frequency and number of harvests[4]. He finds an optimal rotation length (T*) to maximize the net present value of timber revenues from infinite identical rotations, where the price of raw timber (p), the re-planting or logging cost (c), and the discount rate (δ) are assumed fixed. See Table I for Faustmann's problem and the chronology of other objective functions that are to be discussed. Q(T) is the volume of merchantable timber after T years of growth, where Q(T) is continuous and twice differentiable. A possible form for Q(T) will be considered in the simulation exercises below. The autonomous first order condition equates the marginal timber value of delaying harvest with the financial opportunity cost of waiting—the interest income lost from postponing this and subsequent harvests:

$$pQ'(T) = \delta[pQ(T) - c] + \delta e^{-\delta T}[pQ(T) - c] / [1 - e^{-\delta T}].$$

Dividing through by price p, the optimal rotation T* becomes a function of the ratio c/p (Clark, 1990, pp. 268-74):

$$Q'(T) = \delta[Q(T) - c/p] + \delta e^{-\delta T}[Q(T) - c/p] / [1 - e^{-\delta T}].$$

In this form, it is clear that a cost increase (decrease) is similar to a price decrease (increase). The result of either is to increase T*. This treatment of fixed costs remains unchanged to date.[5]

Hartman (1976) adds stand independent non-timber benefits to Faustmann's model (Table I). The resulting infinitely repeated optimal rotation length T* depends of the nontimber amenity function a(t). For example, if a(t) is monotonically increasing (decreasing) as the stand ages then a longer (shorter) rotation is optimal. However, the variety of benefits that can be

Table I: Chronology of Forest Management Objective Functions

$$\underset{\{T\}}{\text{Max}}\, e^{-\delta T}\,[pQ(T)-c]\,/[1-e^{-\delta T}\,]$$

Faustmann (1849)

$$\underset{\{T\}}{\text{Max}}\{e^{-\delta T}\,[pQ(T)-c]+\int_{0}^{T}a(t)e^{-\delta t}\,dt\}\,/[1-e^{-\delta T}\,]$$

Hartman (1976)

$$\underset{\{T_i\}}{\text{Max}}\sum_{i=1}^{\infty}\left\{e^{-\delta T_i}\,[pQ(T_i)-c]+\int_{0}^{T_i}a(t;\tau(i,t))e^{-\delta t}\,dt\right\}e^{-\delta\sum_{j=1}^{i-1}T_j}$$

Swallow and Wear (1993)

$$\underset{\{T_{si}\}}{\text{Max}}\sum_{s=1}^{S}\sum_{i=1}^{\infty}\left\{e^{-\delta T_{si}}\,[pQ_s(T_{si})-c]+\int_{0}^{T_{si}}a_s(t_s,\tau_{si})e^{-\delta t_s}\,dt_s\right\}e^{-\delta\sum_{j=1}^{i-1}T_{si}}$$

Swallow, Talukdar, and Wear (1997)

$$\underset{\{T_{si}\}}{\text{Max}}\sum_{s=1}^{S}\sum_{i=1}^{\infty}\left\{e^{-\delta T_{si}}\,[pQ_s(T_{si})-c_s(\tau_{si})]+\int_{0}^{T_{si}}a_s(t_s,\tau_{si})e^{-\delta t_s}\,dt_s\right\}e^{-\delta\sum_{j=1}^{i-1}T_{si}}$$

This paper

represented by a(t) cannot be characterized by strictly one functional form when considered in aggregate. Hence, the result will depend on what non-timber benefits are included in a(t) (see Swallow, Parks, and Wear, 1990, and Calish, Fight, and Teeguarden, 1978, for some alternatives for a(t)).

Instead of choosing rotation lengths, Bowes and Krutilla (1985,1989) choose the acreage of harvested stock each period to maximize recreation and timber harvest returns. While mathematically similar to optimization with respect to rotation lengths, their approach represents a crucial recognition of the importance of spatial aspects in forestry management. In this setting, they show that a greater mix of different aged stands favors non-timber benefit production. Also, they find that rules of thumb generally do not apply. However, their model does not consider the implications of alternative spatial configurations of the optimal harvest acreage, which is the primary issue taken up by this paper.

One directional spatial relationships are first presented by Swallow and Wear (1993), who determine a single stand's rotation as a function of the exogenous ages of neighboring stands. These ages enter through the non-timber amenity function, where $a(t;\tau(i,t))$ is the new non-timber amenity function and $\tau(i,t)$ is a vector of the ages of neighboring stands (Table I). The age of a neighboring stand corresponds to tree age t during rotation i on the primary stand. The non-timber status of any stand s is captured by the age of that stand. As a whole, the status of other stands determines the trajectory of amenity benefits on stand s. For example, if $a(t;\tau(i,t))$ is monotonically increasing in t then a harvest of a related neighboring stand shifts the amenity curve either up or down depending on whether the amenity benefits from different

stands are regarded as substitutes or complements respectively. The implication is that stand interaction in amenity production creates substitution and income effects.

In addition, they show that optimal harvest patterns are influenced by the initial forest condition (i.e. stand ages), the non-timber benefits function formulation, and beliefs about what management strategies are guiding activity on neighboring stands. Notice that a single rotation in perpetuity is not practical here, since the rotations depend on the condition of the surrounding forest. However, Swallow and Wear show that a steady state sequence of rotations results.

Swallow, Talukdar, and Wear (1997) take the next step, to two directional spatial relationships, by considering all rotations endogenously. They achieve this by simultaneously determining rotations on all stands. Let there be S stands, $s=1...S$, and t_s the age of stand s between harvests. Let τ_{si} be a vector of the ages of all stands but stand s at the time of harvest number i on stand s. This vector is a function of the age of stand s as well as all the rotations on all the stands, i.e. $\tau_{si} = \tau_{si}(t_s; T_{11}, T_{12}, ..., T_{21}, T_{22}, ..., T_{S1}, T_{S2}, ...)$ where T_{si} is the rotation length of rotation i on stand s (Table I).

Like Swallow and Wear, they find that location is important, a stable sequence of rotations results, and periodic (i.e. not time invariant) production specialization, where production is limited to timber or non-timber output exclusively, may result on stands. In addition, they illustrate the effects of timber productivity and relative value of timber to non-timber benefits on harvest sequences.

Swallow, Talukdar, and Wear's model is well conceived and readily accommodates an important addition—harvesting economies of adjacency. Fixed equipment and transportation

costs can be significant, and larger contiguous harvests can allow these costs to be increasingly

spread, i.e. there may exist declining average fixed costs (Cubbage, 1983).

Define $c_s(\tau_{si})$ as the fixed cost associated with harvest T_{si} given the ages (or histories) of

the other stands τ_{si}. Different harvesting configurations on other stands will determine the fixed

cost of harvesting stand s. For example, if a neighboring stand was scheduled for harvest at the

same time as stand s, a delay in the harvest of the neighboring stand can mean an increase in the

average fixed cost for stand s. However, the delay may shift the harvest of the neighbor stand to

a time where an even greater overall reduction in average fixed costs can be realized given the

harvest configuration created for the future. Adding spatial cost influences, the objective

function for maximizing net present value can be written as (Table I, line 4):

$$NPV = \underset{\{T_{si}\}}{Max} \sum_{s=1}^{S} \sum_{\acute{e}\, i=1}^{\infty} \left\{ e^{-\delta T_{si}} \left[pQ_s(T_{si}) - c_s(\tau_{si}) \right] + \int_0^{T_{si}} a_s(t_s, \tau_{si}) e^{-\delta t_s} dt_s \right\} e^{-\delta \sum_{j=1}^{i-1} T_{sj}}. \qquad (1)$$

To better understand the competing forces behind the harvest decision, consider the first order

condition with respect to T_{si}:

$$p(\partial Q_{si} / \partial T_{si}) + a_{si} - (\partial c_{si} / \partial \tau_{si})$$

$$+ \sum_{i' > i} \left\{ \begin{array}{l} -(\partial c_{si'} / \partial \tau_{si'}) e^{-\delta T_{si'}} \\ + \int_0^{T_{si'}} (\partial a_{si'} / \partial \tau_{si'}) e^{-\delta t_s} dt_s \end{array} \right\} e^{-\delta \sum_{j=i+1}^{i'-1} T_{sj}}$$

$$+ \sum_{s' \neq s} \sum_{i' \in \Omega}^{\infty} \left\{ \begin{array}{l} -(\partial c_{s'i'} / \partial \tau_{s'i'}) e^{-\delta T_{s'i'}} \\ + \int_0^{T_{s'i'}} (\partial a_{s'i'} / \partial \tau_{s'i'}) e^{-\delta t_{s'}} dt_{s'} \end{array} \right\} e^{-\delta \left[\sum_{j=1}^{i'-1} T_{s'j} - \sum_{j=1}^{i} T_{sj} \right]} \qquad (2)$$

$$= \delta[pQ_{si} - c_{si}] + \delta \sum_{i' > i} \left\{ e^{-\delta T_{si'}} [pQ_{si'} - c_{si'}] + \int_0^{T_{si'}} a_{si} e^{-\delta t_s} dt_s \right\} e^{-\delta \sum_{j=i+1}^{i'-1} T_{sj}}$$

where notation has been simplified with $Q_{si} = Q_s(T_{si})$, $c_{si} = c_s(\tau_{si})$, $a_{si} = a_{si}(T_{si}, \tau_{si})$, and

$(\partial \tau_{si} / \partial T_{si}) = 1$ for all s, s', i, and i'. Ω is the set of all current and future rotations on stands other

than s at the time of rotation T_{si}. Ω can be written as $\Omega = \Omega(s, s', i) = \left\{ i' \in R^{++} : \sum_{j=1}^{i'} T_{s'j} \geq \sum_{j=1}^{i} T_{sj} \right\}$.

The left-hand-side of equation (2) is the somewhat convoluted marginal benefit of delaying

rotation i on stand s. The right-hand-side is the more traditional marginal cost of delaying

rotation i on stand s. The first line consists of the current period changes in stand s' timber

value, nontimber value, and fixed costs associated with delaying rotation i on stand s. The

second and third lines respectively capture the impact of delaying stand s' rotation i on

discounted fixed costs and nontimber values for future rotations on stand s and other stands. The

forth line, i.e. right hand side, is the lost discounted interest net timber and nontimber income of

delaying current and future harvests on stand s.

Consider c_{si} to display increasing returns to "scale" at a decreasing rate, where scale is

measured as the number of contiguous stands harvested.[6] When considering the simultaneous

harvest of stand s with other stands, the average fixed cost associated with the harvest of stand s

will increase when delaying the harvest of an adjacent stand, i.e. $(\partial c_{si} / \partial \tau_{sj}) > 0$ for all s, and i,

and be unchanged when delaying the harvest of a non-adjacent stand, i.e. $(\partial c_{si} / \partial \tau_{sj}) = 0$. Or we

could write, $(\partial c_{si} / \partial A_s) > 0$ and $(\partial^2 c_{si} / \partial A_s^2) < 0$, where A_s is the number of harvested stands

contiguous to stand s. In summary, fixed costs, which exhibit increasing returns to adjacency,

encourage larger contiguous harvest areas.

Clearly the problem has increased in difficulty, but this additional complication illustrates

the importance spatial economies and diseconomies of adjacency can have: dictating timber and

non-timber benefits. The above structure has been theoretically convenient for capturing the intricate trade-offs of multiple use forest management. However, it is not operationally convenient for application. Fortunately, recursive methods produce a practical formulation.

III. Simulations

III.1 Design

This section restates the new forest management model presented above as a recursive problem. Simulation results illustrate the impact of the economies of adjacency extension.

The above problem can be characterized as a period by period problem. Each period the manager chooses which stands to harvest given the ages and histories of all stands composing the forest. Let h_{sn} designate the binomial harvest decision for stand s in period n, where h_{sn} equals 1 for full harvest and 0 for no harvest.[7] The (Sx1) vector of harvest decisions will be represented by $\mathbf{h_n}$: $\mathbf{h_n}' = [h_{1n}\ h_{2n}\ \ldots\ h_{Sn}]$. Each period there are three state variables: $\mathbf{t_n}' = [t_{1n}\ t_{2n}\ \ldots\ t_{Sn}]$, a (Sx1) vector of timber ages on all stands in period n; $\mathbf{\tau_n}' = [\tau_{1n}\ \tau_{2n}\ \ldots\ \tau_{Sn}]$, a (Sx1) vector of harvest histories on all stands through period n; and $\mathbf{i_n}' = [i_{1n}\ i_{2n}\ \ldots\ i_{Sn}]$, a (Sx1) vector of counters which keep track of the number of rotations performed on each stand to date (initialized to zero). Stand ages evolve according to the following law of motion: $t_{sn+1} = (t_{sn} + 1)(1-h_{sn})$. The history vector for each stand τ_{sn} is the set of all rotations that have occurred to date on all stands but s. Hence, $\tau_{sn} = \{T_{s'i} > 0$ for all $s' \neq s$: $\Sigma^I_{i=1}\ T_{s'i} < D$ for $I=1,2,\ldots\}$ where D is the number of periods that have transpired since management began. The rotation count on each stand is updated each period as $i_{sn+1} = i_{sn} + h_{sn}$. And the corresponding current rotation length variable T_{si} is updated according to $T_{si} = t_{sn}h_{sn}$.

Given ages, histories, and rotations, a manager solves this period's problem:

$$\Theta_n(t_n,\hat{o}_n,i_n) = \underset{h_n}{\text{Max}} \begin{bmatrix} pQ_1(t_{1n})h_{1n} + ... + pQ_S(t_{Sn})h_{Sn} - C(h_n) \\ + \int_0^1 a(t_{1n}h_{1n}+\varepsilon,...,t_{Sn}h_{Sn}+\varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta^*_{n+1}(t_{n+1},\hat{o}_{n+1},i_{n+1}) \end{bmatrix} \quad (3)$$

where $C(h_n)$ denotes the total fixed cost in period n of harvest configuration h_n and

$\Theta^*_{n+1}(t_{n+1},\tau_{n+1},i_{n+1})$ is the net present value of optimal harvest decisions in the future given the

resulting state of the forest from this period's decisions. To simplify notation, let $Q(t_n)$ be the

(1xS) vector of merchantable timber volumes. Equation (3) becomes[8]

$$\Theta_n(t_n,\hat{o}_n,i_n) = \underset{h_n}{\text{Max}} \begin{bmatrix} pQ(t_n)h_n - C(h_n) \\ + \int_0^1 a(\text{diag}[t_n h_n'] + \varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta^*_{n+1}(t_{n+1},\hat{o}_{n+1},i_{n+1}) \end{bmatrix}. \quad (4)$$

Simulations were constructed for two adjacent single acre stands and only incorporated

the stand ages state variables. 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 one only, harvest stand two only, or do not

harvest. Table II characterizes these alternatives for managing timber and nontimber benefits

given stand ages and histories in period n.[9] 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

net present value. Integer programming guarantees an optimal solution even when the solution

space is non-convex, as is likely the case when nontimber benefits are included.[10]

Table II: Harvesting Alternatives for Timber and Nontimber Management

Case	h_{1n}	h_{2n}	Period n Net Present Value
1	1	1	$\Theta_n(\mathbf{t_n}, \hat{o}_n, \mathbf{i_n}) = p[Q_1(t_1) + Q_2(t_2)] - C([1,1]') + \int_0^1 a(0+\varepsilon, 0+\varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta_{n+1}^*((1,1), \hat{o}_{n+1}, \mathbf{i_{n+1}})$
2	1	0	$\Theta_n(\mathbf{t_n}, \hat{o}_n, \mathbf{i_n}) = pQ_1(t_1) - C([1,0]') + \int_0^1 a(0+\varepsilon, t_2+\varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta_{n+1}^*((1, t_2+1), \hat{o}_{n+1}, \mathbf{i_{n+1}})$
3	0	1	$\Theta_n(\mathbf{t_n}, \hat{o}_n, \mathbf{i_n}) = pQ_2(t_2) - C([0,1]') + \int_0^1 a(t_1+\varepsilon, 0+\varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta_{n+1}^*((t_1+1,1), \hat{o}_{n+1}, \mathbf{i_{n+1}})$
4	0	0	$\Theta_n(\mathbf{t_n}, \hat{o}_n, \mathbf{i_n}) = \int_0^1 a(t_1+\varepsilon, t_2+\varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta_{n+1}^*((t_1+1, t_2+1), \hat{o}_n, \mathbf{i_n})$

The timber and nontimber functional forms and parameter estimates were taken from Swallow, Parks, and Wear (1990) and Swallow and Wear (1993). These papers utilized the same timber and nontimber production functions. The timber production function was generated from USDA Forest Service mixed ponderosa pine and douglas fir timber growth data for dry stable soils. For nontimber production, they choose to represent a single spatially relevant benefit—grazing value. The grazing value production function was estimated from Lolo National Forest cattle grazing yield data. Both sets of data were used for planning by Forest Service managers at Lolo National Forest in Western Montana. While the following analysis is restricted to these functions and parameters, the essence of the influences of cost economies of adjacency on harvest scheduling is not dependent upon functional choice and parameterization.[11]

A logistic timber growth function is used,

$$Q_s(t_{sn}) = K_s / [1 + e^{(\alpha_s - \theta_s t_{sn})}],$$

where $Q_s(t_{sn})$ is the merchantable timber volume (mbf, thousand board feet), K_s is the stands carrying capacity of 15.055 mbf/acre, and α_s and θ_s were estimated by Swallow, Parks, and Wear as 6.1824 and 0.0801 respectively. Lower timber productivity can be captured by reducing θ_s. Figure 1 depicts the timber growth function for the two θ_s utilized in the simulations.

Swallow, Talukdar, and Wear (1997) suggest that grazing benefits represent the value of hunting sites, which is a function of wildlife populations, which in turn is a function of the supply of adjacent forage and cover acreage. Therefore, forage production in animal-unit-months (aum) per year on stand s can be written as

$$g_s(t_{sn}) = \beta_{0s} t_{sn} e^{-\beta_{1s} t_{sn}}$$

Figure 1: Timber Production, $Q_s(t_s)$
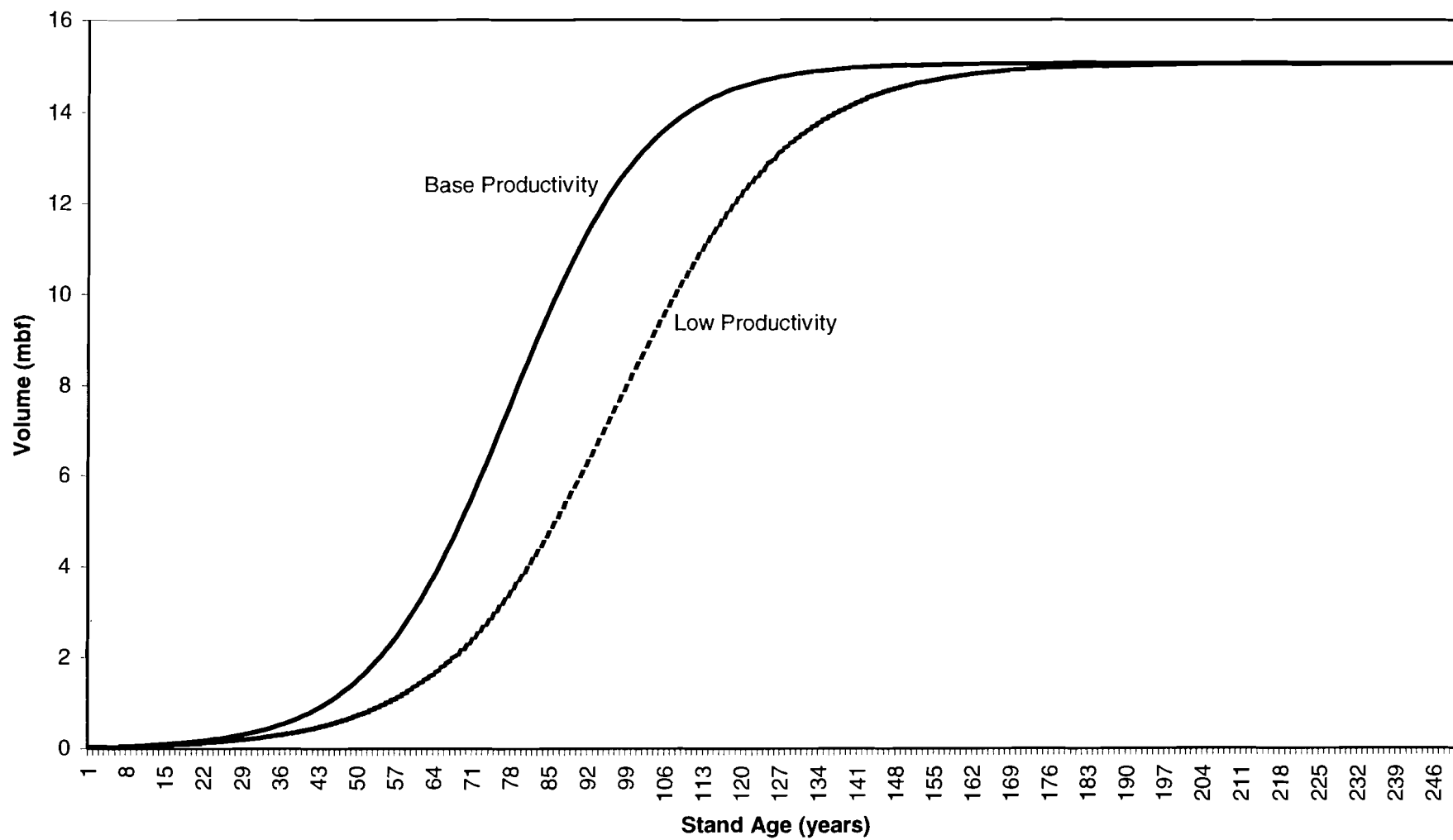
where β_{0s} and β_{1s}, as estimated by Swallow, Parks, and Wear, are 0.0770 and 0.0850

respectively. Lower forage productivity can be captured by reducing β_{0s} (Figure 2).

Forage value is given by the economic scarcity or demand function

$$f(t_{1n}, t_{2n}) = f_0 e^{-\gamma[g_1(t_{1n}) + g_2(t_{2n})]},$$

where f_0 is the upper bound on the value of forage. Swallow and Wear estimate f_0 and γ as 30

and –2 respectively. These parameters provide them with a range of marginal forage values from

$8.00 to $29.00 per aum. Note, forage value abides by the law of demand, i.e. the inverse

relationship between quantity and price (Figure 3). Hence, additional forage is highly valued

when scarce and vice versa. Since the alternative to early successional growth (i.e. forage) is

mid to late successional growth (i.e. cover), the reciprocal holds: additional cover is highly

valued when scarce.

The final grazing benefit function is the product of the forage production and demand

functions:

$$a(t_{1n}, t_{2n}) = f(t_{1n}, t_{2n})[g_1(t_{1n}) + g_2(t_{2n})].$$

Since grazing benefits depend on the age of both stands a three-dimensional surface results for

$a(t_{1n}, t_{2n})$. Figures 4 and 5 depict indifference curves for the nontimber grazing benefits function

for the two productivity scenarios considered in the simulations. The maximum possible grazing

value is approximately $5.52/year.

The simulations will consider base and low levels of timber and grazing productivity.

Low productivity levels are computed as eighty-percent of the base level. Hence the low

productivity parameters are $\theta_s = 0.064$ and $\beta_{0s} = 0.0616$ for timber and grazing respectively.

Figure 2: Forage Production, $g_s(t_s)$

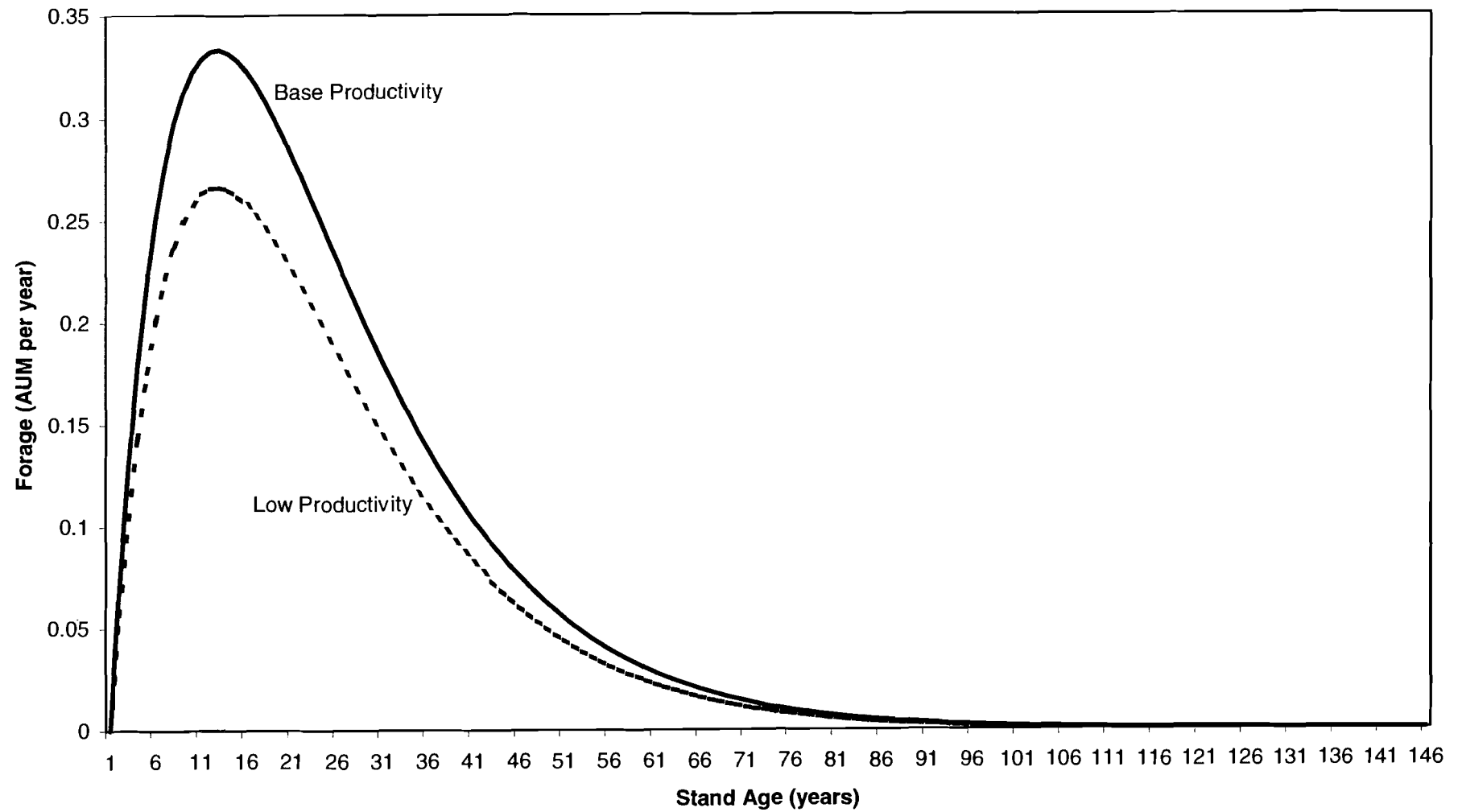Base Productivity

Low Productivity
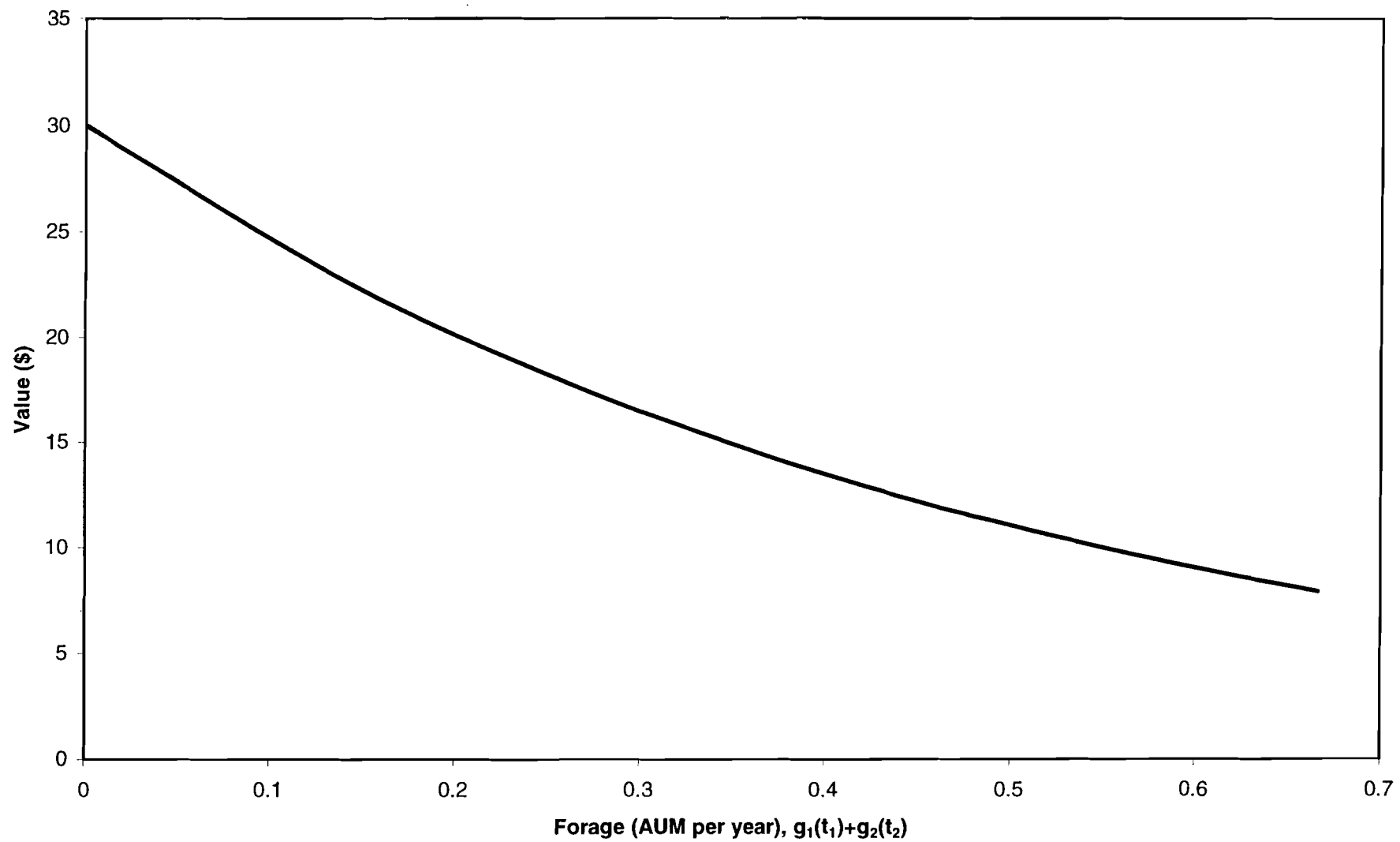
Figure 3: Forage Value, $f(t_1, t_2)$

Figure 4: Nontimber Grazing Value Indifference Curves
Base productivity on both stands
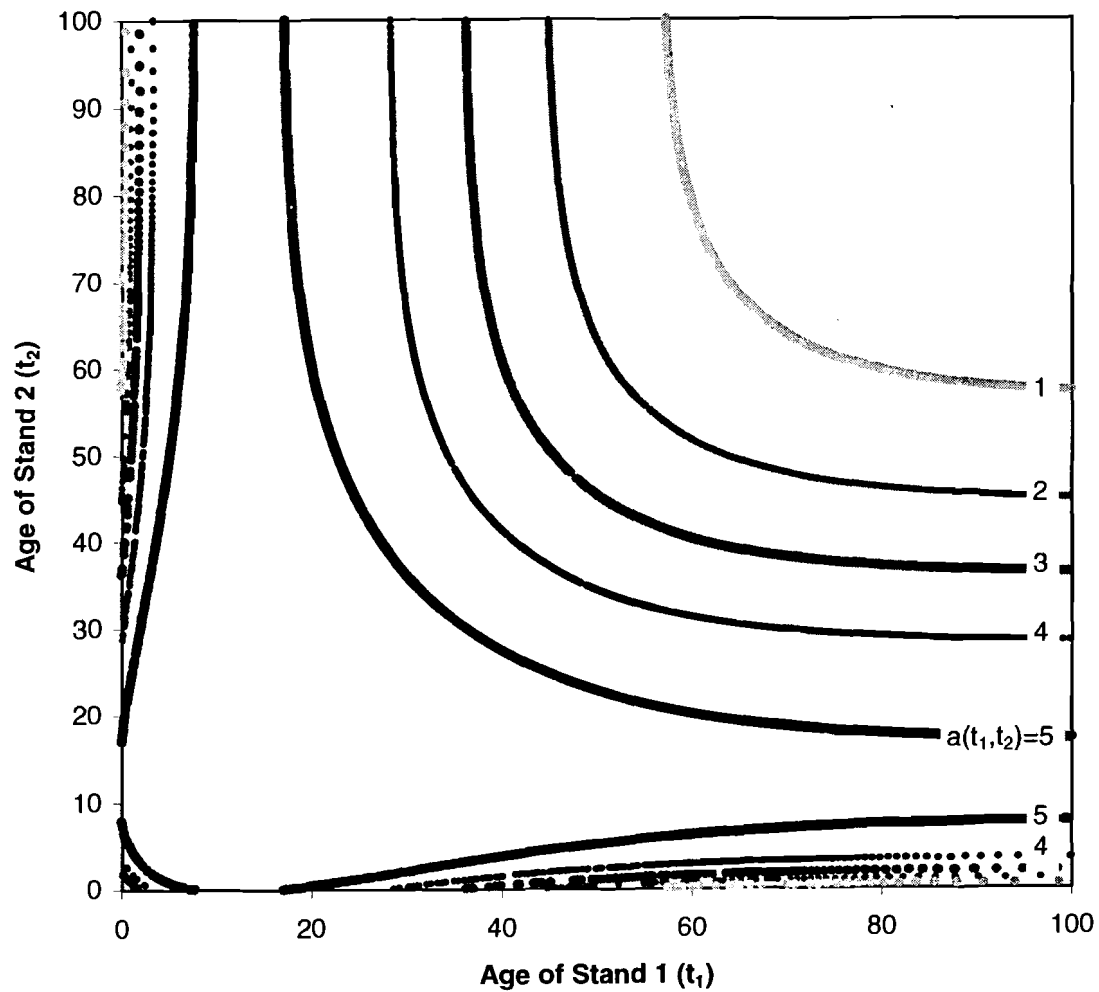
Figure 5: Nontimber Grazing Value Indifference Curves
Base productivity on stand 1, Low productivity on stand 2
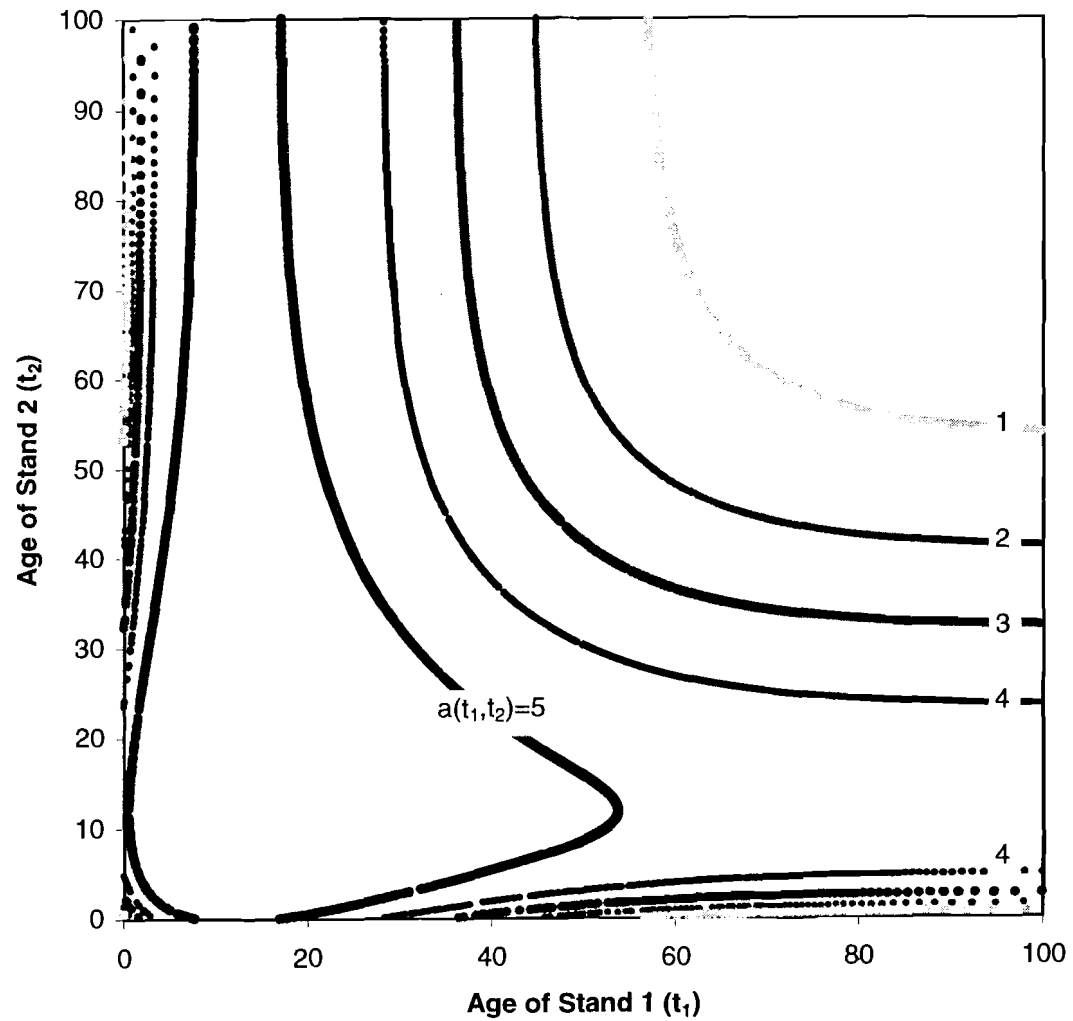
Harvesting cost economies of adjacency are represented using a simple formulation. Let K>0 be the fixed cost for any level of harvesting. The cost function $C(\mathbf{h_n})$ in this two stand environment is

$$C(\mathbf{h_n}) = \begin{cases} 0 & \text{if } h_{1n} = 0 \text{ and } h_{2n} = 0 \\ K & \text{if } h_{1n} = 1 \text{ or } h_{2n} = 1 \end{cases}.$$

Hence, fixed cost K is incurred for any level of harvesting and, as desired, average costs, $C(\mathbf{h_n})/Q(t_n)\mathbf{h_n}$, exhibit increasing returns to scale in harvested volume. Figure 6 depicts the average cost function for various K. The timber price and discount rate were assumed to be constants of \$60/mbf and 0.04 respectively.

III.2 Results

Tables 3 and 4 present simulation results. The following is an explanation of how to the read the tables. The tables report the optimal sequence of harvests given different management objectives, fixed harvesting costs, and initial stand ages. Stand ages at the time of harvest are reported when a harvest occurs on either stand. When only one stand is harvested, the age of the uncut stand appears in parentheses. Harvests are reported until a steady-state harvesting sequence results. In all scenarios a steady-state sequence of harvests is eventually reached (a result also found in the simulations of Swallow and Wear, 1993; Talukdar, 1996; and Swallow, Talukdar and Wear, 1997). The steady-state sequence of harvests for each scenario is contained in the box of the corresponding row. Simulations recorded in Table III use base level timber and nontimber production parameters. For Table IV, only the first stand possesses base level productivity: the second stand has both low level (i.e. 80%) timber and low level nontimber productivity.[12]

Figure 6: Average Fixed Costs, $K/[Q_1(t_1)+Q_2(t_2)]$

Timber Volume (mbf), $Q_1(t_1)+Q_2(t_2)$
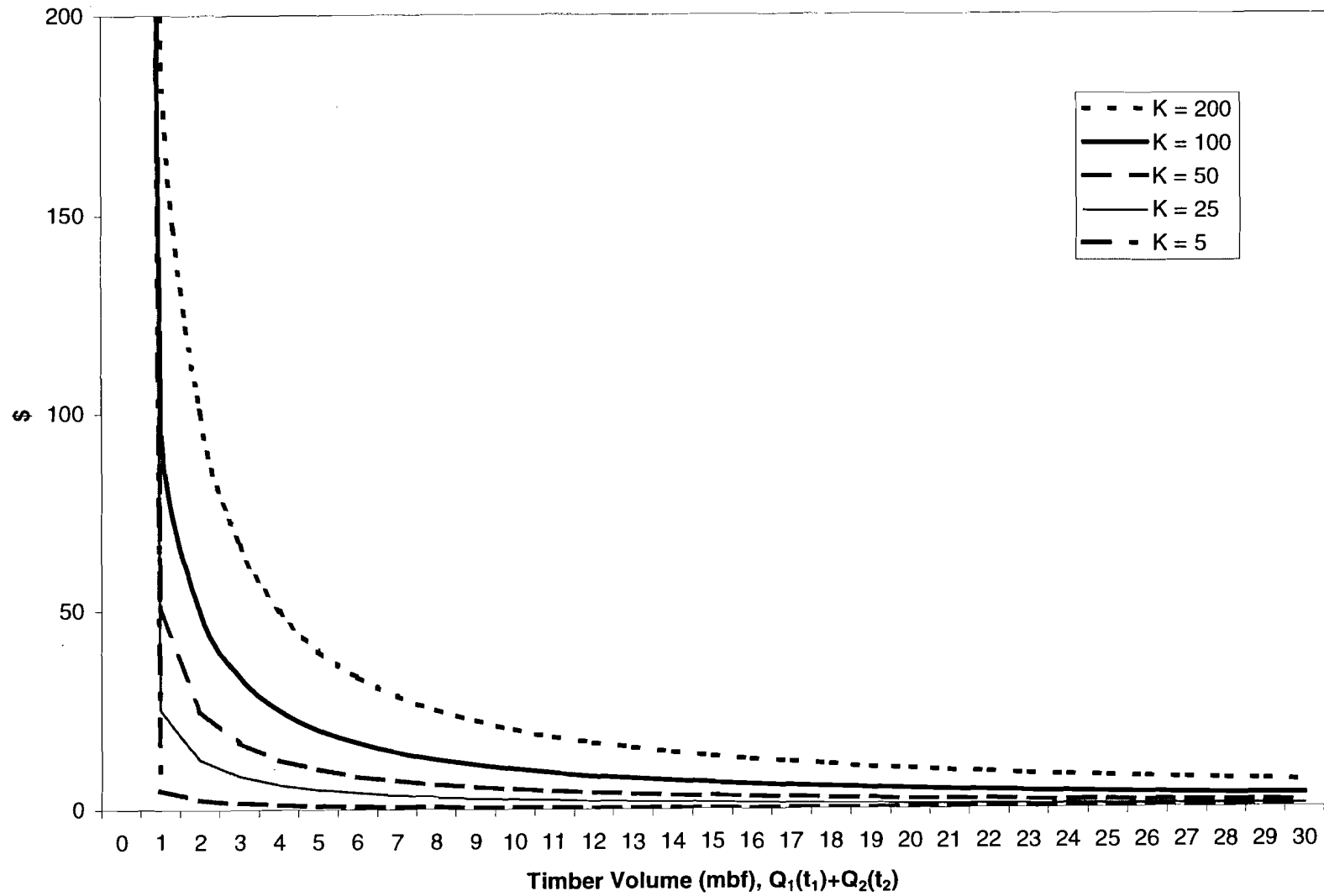
In both tables, the zero cost scenarios for managing only timber are equivalent to Faustmann's problem of infinite identical rotations. With base and low level timber productivity, the Faustmann rotation ages are 76 and 87 years respectively, regardless of the initial ages of the stands. In addition, Talukdar's (1996) results are reproduced in both tables in the zero cost scenarios for managing timber and nontimber benefits with various initial age pairs.[13] Of these, the initial bare ground scenarios are also reported in Swallow, Talukdar, and Wear (1997).

The impact of management objective is most clearly seen in the absence of fixed costs. In Table III, the steady state rotations when managing exclusively for timber when fixed costs are zero are Faustmann rotations of 76 years. In contrast, when maximizing the net present value of nontimber grazing benefits with zero fixed costs, substantially shorter alternating steady state rotations of 33 years produce the optimal mix of forage and cover lands. And, when the sum of timber and nontimber benefits is maximized with zero fixed costs, the timber benefits dominate the length of rotations while the nontimber benefits slightly shorten rotations from the Faustmann length and generate alternating harvests. The result is steady-state alternating 73 year rotations. Because stands are regarded as independent under timber management, harvesting decisions are unaffected by the condition of the forest. However, grazing benefits depend on the status of neighboring stands and are greatest when both cover and forage are available and adjacent. Older stands supply primarily cover, while younger stands supply primarily forage. Once a stand is old enough to provide cover (and minimal forage), little additional cover value is gained by letting the stand age. Hence, short, alternating harvests are preferred for maximizing grazing benefits. Joint management of timber and nontimber benefits yields a harvest sequence which is a compromise between the exclusive management scenarios.

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Table III: Harvest Schedule Under Different Management Regimes and Fixed Harvesting Costs
Base Level Timber and Nontimber Productivity on Both Stands

Fixed Cost	Initial Stand Ages (1, 2)	Harvest Sequence * 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th	18th
Timber only Management																			
0	0,0	76,76																	
5	0,0	76,76																	
25	0,0	77,77																	
50	0,0	77,77																	
100	0,0	79,79																	
200	0,0	81,81																	
0	0,45	(31),76	76,(45)																
5	0,45	(31),76	76,(45)																
25	0,45	(32),77	77,(45)																
50	0,45	(34),79	79,(45)																
100	0,45	(36),81	81,(45)																
200	0,45	(40),85	87,47	81,81															
0	0,75	(1),76	76,(75)																
5	0,75	(1),76	77,(76)	76,76															
25	0,75	(2),77	78,76	77,77															
50	0,75	(4),79	79,75	77,77															
100	0,75	(6),81	82,76	79,79															
200	0,75	(10),85	86,76	81,81															
Nontimber only Management																			
0	0,0	8,(8)	6,(14)	(17),31	33,(16)	(17),33													
5	0,0	29,(29)	(19),48	40,(21)	(21),42	42,(21)													
25	0,0	42,42																	
50	0,0	50,50																	
100	0,0	80,80																	
200	0,0	never																	
0	0,45	(1),46	(9),8	(14),5	31,(17)	(16),33	33,(17)												
5	0,45	(16),61	38,(22)	(21),43	42,(21)	(21),42													
25	0,45	31,76	42,42																
50	0,45	40,85	50,50																
100	0,45	71,116	80,80																
200	0,45	never																	
0	0,75	(1),76	(9),8	(14),5	31,(17)	(16),33	33,(17)												
5	0,75	(1),76	29,(28)	(19),47	40,(21)	(21),42	42,(21)												
25	0,75	30,105	42,42																
50	0,75	39,114	50,50																
100	0,75	70,145	80,80																
200	0,75	never																	
Timber and Nontimber Management																			
0	0,0	38,(38)	(35),73	73,(38)															
5	0,0	65,(65)	(12),77	68,(56)	(20),76	70,(50)	(25),75	71,(46)	(29),75	72,(43)	(31),74	72,(41)	(33),74	73,(40)	(34),74	73,(39)	(35),74	73,(38)	(35),73
25	0,0	73,73																	
50	0,0	74,74																	
100	0,0	76,76																	
200	0,0	79,79																	
0	0,45	(29),74	71,(42)	(32),74	72,(40)	(33),73	72,(39)	(34),73	72,(38)	(35),73	73,(38)								
5	0,45	(30),75	72,(42)	(32),74	72,(40)	(34),74	73,(39)	(35),74	73,(38)	(35),73									
25	0,45	(31),76	74,(43)	(33),76	74,(41)	(34),75	74,(40)	(35),75	74,(39)	(36),75	75,(39)								
50	0,45	(32),77	75,(43)	(34),77	76,(42)	(35),77	76,(41)	(36),77	76,(40)	(37),77	76,(39)	(37),76							
100	0,45	(35),80	78,(43)	(36),79	79,(43)														
200	0,45	(38),83	84,(46)	79,79															
0	0,75	(1),76	(37),36	73,(36)	(37),73														
5	0,75	(1),76	65,(64)	(13),77	68,(55)	(21),76	70,(49)	(26),75	71,(45)	(30),75	72,(42)	(32),74	72,(40)	(33),73	72,(39)	(34),73	72,(38)	(35),73	73,(38)
25	0,75	(1),76	74,73	73,73															
50	0,75	(3),78	76,73	74,74															
100	0,75	(6),81	79,73	76,76															
200	0,75	(10),85	83,73	79,79															

* Harvests are reported when either stand is harvested. At that time, the age of an unharvested stand is reported in parentheses. The final steady-state sequence of harvests for each scenario is contained in the box.

The introduction of fixed costs has a noticeable effect on harvesting decisions. Regardless of the management objective, initial age pair, and productivity levels, there is a positive correlation between fixed costs and rotation length and the likelihood of synchronized harvests in the steady-state. Longer rotations are one means of building up enough timber and nontimber benefits to cover fixed costs at the expense of delaying current and future rotations. The other means is simultaneous harvesting. Simultaneous harvests replace alternating harvests, which favor the nontimber grazing benefits. The initial ages of the stands, which determine available benefits, and the fixed cost dictate which phenomenon is preferred.

For timber management, longer rotations allow for additional tree growth and hence additional marketable timber volume. Additional growth may cover the fixed cost of harvesting at the expense of delayed timber returns. From Table III, increases in the fixed cost from zero through to 200 result in one, three, and five year increases in rotation lengths from 76 to 77, 79, and 81 years respectively regardless of the initial ages of the stands. Some of the steady-state harvest sequences consist of alternating harvests while others consist of simultaneous harvests.

If the initial ages are such that they are both "near" to the Faustmann harvest age (i.e. young, so soon after harvest; or old, so nearing harvest age), then simultaneous harvests in steady-state will be preferred to alternating longer rotations even when fixed costs are small. This is because the opportunity cost of a small reduction or delay in the rotation length on a single stand is modest compared to the benefits of synchronizing harvests. For example, with fixed costs of 25, simultaneous 77 year rotations result when the initial ages are (0,0) and (0,75). Compared to the alternating 77 year rotations which result when initial ages are (0,45).

Even when the starting ages are not "near" the Faustmann harvest age, large fixed costs can generate enough synchronization benefits to overwhelm the benefits of alternating harvests.

For example, fixed costs of 100 with initial ages (0,45) produce alternating 81 year steady-state harvests while fixed costs of 200 produce simultaneous 81 year steady-state harvests after two transitional set-up harvests. Longer rotations are sufficient when fixed costs are 100. However, the cost of single stand harvesting at 200 is prohibitive despite the opportunity cost of the first simultaneous harvest when the stands are ages 87 and 47 years respectively. Interestingly, 81 year rotations occur in both scenarios. This is because, in the 200 fixed cost scenario, harvesting cost gains of synchronization are sufficiently large that the lengths of the rotations do not need to be increased.

Nontimber management, like timber management, may find it optimal to delay harvest to extract greater discounted benefits before the discounted fixed cost of harvesting is incurred. Delaying rotations not only produces additional benefits, but also further discounts the fixed cost of harvesting. Timber and nontimber benefits are regenerated by harvesting, however, unlike timber benefits which are reaped at the time of harvest, nontimber grazing benefits are reaped prior to harvest. Therefore, a harvest delay has no effect on nontimber benefits that have accrued prior to harvest. Only the degree of discounting of the fixed costs for this and future harvests as well as the nontimber benefits produced subsequent to this harvest are affected.

Also, like timber management, this decision must account for the benefits and fixed cost effects of performing alternating or simultaneous harvests. Alternating harvests provide a mix of cover and forage. Simultaneous harvests exploit economies of adjacency but decrease the nontimber benefits by momentarily eliminating the supply of cover forest. Because nontimber grazing benefits peak at an early age and are modest relative to timber benefits (see Figure 4), fixed costs more easily dominate the results under nontimber management. Initial ages are only important in determining the transitional harvests before the steady-state sequence is reached.

The relatively small capacity for production of nontimber benefits results in dramatic harvest scheduling changes as fixed costs increase. For example, steady-state rotation lengths increase by nine years when fixed costs increase from zero to five. In addition, simultaneous harvests are optimal for all initial ages when fixed costs are greater than or equal to 25. Simultaneous harvests occur because nontimber benefits are unable to support the cost of individual stand harvesting. How long a harvest is delayed is a question of balancing the gains of regeneration via harvest against the gains from additional discounting of the fixed cost. Larger fixed costs beg greater discounting. For example, smaller fixed costs of 50 result in steady-state simultaneous 50 year rotations, while fixed costs of 100 result in steady-state simultaneous 80 year rotations. No harvesting occurs, in perpetuity, if fixed costs are large enough (e.g. when fixed costs are 200).

As for timber and nontimber management, enough discounted timber and nontimber benefits must accrue to cover the discounted fixed cost of harvesting. The results are a combination of the effects discussed previously. The nontimber grazing benefits discourage simultaneous harvests and longer rotations, but timber benefits dominate results when the fixed cost is large. The zero cost results in Table I for all initial ages, confirm Talukdar's (1996) finding of alternating 73 year rotations in the steady-state.[14] Larger fixed costs force harvest delays and/or simultaneous harvests depending on the opportunity cost of synchronization created by the initial ages. Rotations longer than those produced by nontimber grazing management postpone the renewal of nontimber benefits, but generate additional timber benefits. Additional timber benefits allow for alternating harvests to produce greater cover and forage benefits. These additional benefits allow for shorter rotations then those produced by timber management.

In Table IV, the Faustmann rotation for timber management on the low productivity stand 2 is 87 years. Zero cost nontimber management again produces shorter rotations and alternating harvests. However, the presence of the low productivity stand yields steady state rotations that are shorter at 28 years than the base productivity analog (Table III) where 33 years was optimal. Reduced forage production capability on stand 2 means that the nontimber benefit of delaying harvest on either stand has decreased. It is now more advantageous to renew nontimber production, capitalizing on early rapid growth. Lastly, when managing for timber and nontimber benefits with no fixed cost, heterogeneous productivity creates production specialization (after ten transitional harvests) with a steady-state sequence of three harvests (Talukdar, 1996; Swallow, Talukdar and Wear, 1997). The more productive stand 1 specializes in timber production with steady-state rotations of 74 years, while the less productive stand 2 specializes in forage with two steady-state rotations of 50 and 24 years for every rotation on stand 1. Note that, though they don't specialize in all production, both stands still produce both timber and nontimber benefits.

The same general phenomena observed in Table III appears here when fixed costs are introduced: longer alternating rotations with a tendency towards simultaneous harvests when the fixed cost is large. Heterogeneous productivity varies the results slightly from those in Table III. For example, longer rotations result under timber management with these heterogeneous stands. With fixed cost 50 and initially bare ground, steady-state synchronized rotations of 80 and 77 years result when stands have heterogeneous and identical base productivity respectively. Low timber productivity implies a slower rate of timber growth but a maximum production capacity equal to that of base timber productivity (see Figure 1). The result is that the marginal benefit of additional timber growth from older stands is greater than the marginal cost of delaying future

Table IV: Harvest Schedule Under Different Management Regimes and Fixed Harvesting Costs
Base Level Timber and Nontimber Productivity on Stand 1, Low Level Timber and Nontimber Productivity on Stand 2

Fixed Cost	Initial Stand Ages (1, 2)	Harvest Sequence * 1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th	18th	19th
Timber only Management																				
0	0,0	76,(76)	(11),87																	
5	0,0	76,(76)	(12),88	76,(64)	(24),88	76,(52)	(36),88	76,(40)	(48),88	76,(28)	(60),88	76,(16)	75,91							
25	0,0	79,79																		
50	0,0	80,80																		
100	0,0	82,82																		
200	0,0	86,86																		
0	0,45	(42),87	76,(34)																	
5	0,45	(43),88	76,(33)	(55),88	76,(21)	(67),88	76,(9)	77,86	76,(76)	(12),88	76,(64)	(24),88	76,(52)	(36),88	76,(40)	(48),88	76,(28)	(60),88	76,(16)	75,91
25	0,45	(45),90	77,(32)	(58),90	77,(19)	74,93	79,79													
50	0,45	(48),93	78,(30)	69,99	80,80															
100	0,45	(52),97	81,(29)	71,100	82,82															
200	0,45	63,108	86,86																	
0	0,75	(12),87	76,(64)																	
5	0,75	(13),88	76,(63)	(25),88	76,(51)	(37),88	76,(39)	(49),88	76,(27)	(61),88	76,(15)	75,90	76,(76)	(12),88	76,(64)	(24),88	76,(52)	(36),88	76,(40)	... **
25	0,75	(15),90	77,(62)	(28),90	77,(49)	(41),90	77,(36)	(54),90	77,(23)	72,95	79,79									
50	0,75	(18),93	79,(61)	(32),93	79,(47)	(46),93	78,(32)	67,99	80,80											
100	0,75	(21),96	82,61	82,82																
200	0,75	28,103	86,58	86,86																
Nontimber only Management																				
0	0,0	(11),11	26,(15)	(14),29	28,(14)	(14),28														
5	0,0	28,(28)	(18),46	37,(19)	(20),39	38,(18)	(20),38													
25	0,0	41,41																		
50	0,0	49,49																		
100	0,0	80,80																		
200	0,0	never																		
0	0,45	(1),46	(11),10	26,(15)	(14),29	28,(14)	(14),28													
5	0,45	(15),60	35,(20)	(19),39	38,(19)	(20),39	38,(18)	(20),38												
25	0,45	31,76	41,41																	
50	0,45	40,85	49,49																	
100	0,45	73,118	80,80																	
200	0,45	never																		
0	0,75	(1),76	(11),10	26,(15)	(14),29	28,(14)	(14),28													
5	0,75	(1),76	28,(27)	(18),45	37,(19)	(20),39	38,(18)	(20),38												
25	0,75	30,105	41,41																	
50	0,75	40,115	49,49																	
100	0,75	73,148	80,80																	
200	0,75	never																		
Timber and Nontimber Management																				
0	0,0	(22),22	(46),24	73,(27)	(26),53	(50),24	74,(24)	(24),48	(48),24	74,(26)	(25),51	(49),24	74,(25)	(25),50						
5	0,0	(31),31	(55),24	75,(20)	(28),48	(53),25	75,(22)	(28),50	(53),25											
25	0,0	(45),45	75,(30)	(48),78	76,(28)	(48),76														
50	0,0	75,75																		
100	0,0	78,78																		
200	0,0	82,82																		
0	0,45	(32),77	(54),22	74,(20)	(23),43	(47),24	73,(26)	(25),51	(49),24	74,(25)	(25),50									
5	0,45	(35),80	73,(38)	(38),76	73,(35)	(39),74	73,(34)	(39),73												
25	0,45	(39),84	75,(36)	(44),80	75,(31)	(47),78	76,(29)	(48),77	76,(28)	(48),76										
50	0,45	(42),87	77,(35)	(49),84	77,(28)	(55),83	78,(23)	68,91	75,75											
100	0,45	(47),92	79,(32)	64,96	78,78															
200	0,45	58,103	82,82																	
0	0,75	(12),87	(34),22	(56),22	75,(19)	(22),41	(46),24	73,(27)	(26),53	(50),24	74,(24)	(24),48	(48),24	74,(26)	(25),51	(49),24	74,(25)	(25),50		
5	0,75	(13),88	(42),29	74,(32)	(39),71	73,(34)	(39),73													
25	0,75	(16),91	72,(56)	(31),87	74,(43)	(40),83	75,(35)	(45),80	75,(30)	(48),78	76,(28)	(48),76								
50	0,75	(18),93	74,(56)	(33),89	76,(43)	(44),87	77,(33)	(51),84	77,(26)	66,92	75,75									
100	0,75	(21),96	78,57	78,78																
200	0,75	(27),102	83,56	82,82																

* Harvests are reported when either stand is harvested. At that time, the age of an unharvested stand is reported in parentheses. The final steady-state sequence of harvests for each scenario is contained in the box.
** The steady state harvest sequence here is the same as that listed for the timber management scenarios with fixed cost 5 and initial ages (0,0) and (0,45).

harvests on both stands. Mixed productivity makes simultaneous harvests efficient where

alternating harvests were efficient in Table III. For example, compare the results with fixed cost

of 25 and initial ages (0,45).[15]

Under timber and nontimber management with heterogeneous stands, output

specialization is optimal when there are no fixed costs. However, fixed costs change the nature

of specialization and even eliminate it. With fixed cost of 25, the steady-state sequence of three

harvests observed for the lower fixed cost is replaced by a two harvest sequence of 76 year

rotations. Specialization is still present in the unharvested ages of 28 and 48 years for stands 2

and 1 respectively. Stand 1 specializes in forage for 48 years while stand 2 provides cover and

stand 2 provides forage for 28 years while stand 1 provides cover. This arrangement exploits

stand 1's greater nontimber productivity, while the 76 year rotations exploit stand 1's greater

timber productivity. Stand 2 also supplies timber and forage benefits, but is primarily managed

to maximize stand 1's production. At larger fixed costs simultaneous harvests take over.

III.3 Implications

Overall, in the presence of fixed costs and economies of adjacency, longer rotations

and/or simultaneous harvests are optimal for maximizing timber and/or nontimber grazing

benefits. Yet, what are the implications of not accounting for fixed costs and economies of

adjacency?

Consider scheduling harvests for the two base productivity stands ignorant of fixed costs.

The believed "optimal" timber management harvest sequence when starting from bare ground

would be infinite simultaneous Faustmann 76 year harvests (Table III). The believed current

timber value of each synchronized harvest is $826.77 and the net present value today of infinite

rotations is $41.54. However, if the unrecognized fixed cost of performing any kind of harvest is $100, then the actual current timber value of a 76 year simultaneous harvest is $726.77 and the net present value of the identical infinite rotations is $36.51. If fixed costs had been accounted for initially, 79 year simultaneous harvests would have resulted ad infinitum with current timber value $830.91 and net present value $36.81.

More significant consequences result from this mistake under nontimber management and timber and nontimber management. For nontimber management, the owner disregards timber revenues and focuses on maximizing nontimber benefits. Nonetheless, harvests performed to maximize nontimber benefits still generate fixed costs. The believed net present value of the zero cost initially bare ground sequence is $130.63. However, consider a fixed cost of $25. The actual net present value of pursuing this incorrect sequence is $83.12. If the correct path of infinite synchronized 42 year harvests had been followed, the net present value would have been $119.77.[16]

Under timber and nontimber management, the believed current timber value of 38 and 73 year individual harvests with no fixed cost and initially bare ground are $36.05 and $361.91 respectively. The believed net present value of the "optimal" sequence is $159.44. However, with fixed cost $25, the actual current timber values of pursing these incorrect harvests are $11.05 and $336.91 respectively. The actual net present value is $152.23. If the correct path of infinite synchronized 73 year harvests had been followed the current timber and net present values would have been $698.81 and $157.31 respectively.

Now consider a forest owner who ignores fixed costs, planning harvests accordingly, and contracts out for logging operations. Suppose the owner is interested in nontimber management of base productivity stands. In year 8 the owner will want to harvest the first stand. However, at

this young age, the tree does not possess merchantable volume.[17] Hence, a logger will not be able to sell the felled small logs to cover the fixed cost of harvesting. To achieve their objective, the owner will have to pay the lowest cost logger at least enough to cover the fixed cost. If the owner pays exactly the logger's fixed cost of say $25, then the owner's current timber value of the first harvest will be -$25. The remaining rotations of 6, 31, and 33 years will yield current timber revenues for the logger of $0, $20.95, and $24.49 respectively. Hence, logging requires payments from the owner of $25, $4.05, and $0.51 respectively. The owner would have faired better with the infinite simultaneous 42 year harvests which produce current timber values of $72.81.[18]

Suppose the same ignorant owner manages the forest for timber and nontimber benefits. Assume the owner believes they will be able to sell the logging rights for the entire value of the timber. The owner will seek out a logger for the first time in year 38. The gross current value of the timber is $36.05. However, bidding loggers will at most be willing to pay the net current value of the timber. If the least cost logger has fixed cost $25, the highest bid will be $11.05. With timber returns like this, the planner should have chosen the infinite simultaneous 73 year harvests (discussed above).

IV. Conclusions

Spatial forest management models need to revisit the handling of fixed costs when economies of scale exist in harvesting adjacent stands. This paper illustrated theoretically and via simulations the role of economies of adjacency in intertemporal harvest decisions. Regardless of the management objective, larger fixed costs induced simultaneous harvesting. Given the nontimber grazing benefits function utilized, larger fixed costs also resulted in longer

rotations. The simulation procedure employed in this paper is readily adaptable to accommodate additional nontimber benefits and constraints, mixed tree species within and across stands, and partial harvesting. Additions might include a late successional harvest moratorium, minimum species populations, maximum sedimentation, constant timber supply, and/or minimum water flows.

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Talukdar, P. (1996), "Economics of Sustainable Resource Management in a Dynamic Optimization Framework", Ph.D. Dissertation, University of Rhode Island.

[2] In a later paper, a combinatorial auction will be offered in reply to the second question. This market instrument will be evaluated for its ability to satisfy societal timber and non-timber requirements. Specifically, can an auction instrument facilitate efforts to meet growing timber demand without compromising the supply of non-timber amenities? The proposed auction has the potential for improving logger profit margins, seller revenues, and societal welfare.

[3] 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.

[4] See Erickson (forthcoming) for a discussion of the impacts of harvest frequency and number on successional growth. Swallow, Talukdar, and Wear (1997) allude to these elements but do not implement them in their simulations. Nor do I.

[5] See Lewis and Schmalensee (1977) for a discussion of non-spatial non-convexities in renewable resource extraction when fixed extraction costs exist. Using their terminology, independent timber stand models follow a cyclical optimal harvest policy with zero re-entry cost and a single period optimal abandonment policy, i.e. harvest period. In this setting, the non-convexities associated with a positive fixed harvesting cost essentially disappear.

[6] A reasonable assumption given that a larger contiguous harvest area requires the movement of equipment over more acreage.

[7] One could represent selective harvesting as a continuous variable defined over the interval [0,1]. In this case, 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.

[8] For clearer exposition of the timber and nontimber trade-offs relevant to this period's harvesting decisions, harvesting is assumed to occur at the beginning of the period. Alternatively, Swallow, Talukdar, and Wear (1997) choose end of period harvesting, which does not effect the level of nontimber benefits in the current period. In their environment, equation (4) would be written as

$$\Theta_n(t_n, \ _n, i_n) = \underset{h_n}{\text{Max}} \left[\begin{array}{l} e^{-\delta}\{pQ(t_n + 1)h_n - C(h_n)\} \\ + \int_0^1 a(t_n + \varepsilon)e^{-\delta\varepsilon}d\varepsilon + e^{-\delta}\Theta^*_{n+1}(t_{n+1}, \ _{n+1}, i_{n+1}) \end{array} \right].$$

[9] For timber only management, the nontimber amenities integral is dropped, while for nontimber only management, the timber revenue term is dropped.

[10] Swallow, Parks, and Wear (1990) discuss the dangers of local optima when optimizing timber and nontimber benefits.

[11] Future research plans to examine the influence of including alternative nontimber benefits.

[12] The fourth table is included to give a feel for how fixed costs might effect the management of heterogeneous stands. There are many variations and types of heterogeneity that could be represented in this simulation structure.

[13] Minor variations of Talukdar's (1996) results were produced by these simulations due to improved numerical precision. These variations have no bearing on her conclusions.

[14] As mentioned, Swallow, Talukdar, and Wear (1997) report Talukdar's (1996) (0,0) initial age cases. You may note that the ages of the unharvested stands in steady-state are not identical across zero-cost initial age scenarios. The numerical value of the difference is negligible. The outcome is the result of the simulations attempting to get to 73 year rotations with minimal delay.

[15] Additional initial age pairs were tried for all management objectives and fixed costs. The general impact of fixed costs is similar even when reciprocal initial age pairs (e.g. 45,0) are used with the heterogeneous productivity used in Table IV. However, with fixed cost 5, timber and nontimber management with heterogeneous productivity produced a steady-state sequence of three harvests for the initial age pairs (75,0), (65,0), and (0,15). The sequence

was identical to that observed for initial ages (0,0). All other initial age pairs with fixed cost 5, produced the two

harvest steady-state sequence reported in Table IV.

[16] Nontimber management treats felled trees as worthless. If the logs are sold and timber revenues affect harvest

decisions then the management objective is timber and nontimber management.

[17] Prior to a threshold age, a tree does not possess merchantable volume (see, inter alia, Pearse 1967). The

simulations used a minimum age of 20 years as the threshold.

[18] The owner may recognize that there are fixed costs for harvesting but not know what the fixed cost of the lowest

bidder will be at the time of sale. In this case, the owner will have to plan according to expected fixed cost and

hence expected net current timber revenues. This issue will be taken up in the second paper which proposes a new

timber sales auction.

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