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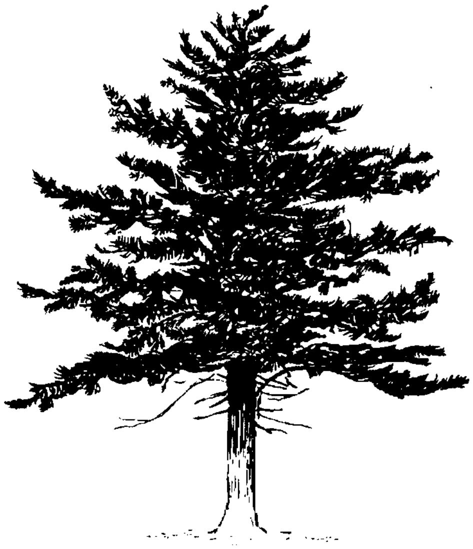

Nonrenewability in Forest Rotations: Implications for Economic and Ecosystem Sustainability

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Implications for Economic and Ecosystem Sustainability

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Nonrenewability in Forest Rotations:

Implications for Economic and Ecosystem Sustainability

The forest rotations problem has been considered by generations of economists, including Fisher (1930), Boulding (1966), and Samuelson (1976). Traditionally, the forest resource across all future harvest periods is assumed to grow without memory of past harvest periods. This paper integrates economic theory and intertemporal ecological mechanics, linking current harvest decisions with future forest growth, financial value, and ecosystem health. Results and implications of a nonrenewable forest resource are reported. (*JEL* Q23, C61, D92)

Traditional financial models of the forest resource assume perfect renewability in forest growth following infinite optimal rotations of constant length. Forest ecology, however, suggests that rotations can affect future growth, product quality, and forest health. For instance, alteration of successional sequences, nutrient cycles, and other components of ecosystem function are influenced by rotation length, harvest intensity, and cutting frequency. These cross-harvest interactions suggest a nonrenewable forest growth specification, an omission in the economist's model of the forest which can lead to sub-optimal management decisions. Section I addresses this omission, leading to the addition of a marginal benefit of recovery to the traditional optimal rotation decision rule.

In Section II, an integrated forest succession, product, and price model for the northern hardwood forest ecosystem is developed to evaluate the impact of increasing density of pioneer species following disturbance on rotation length and timber profits. The success of early successional species in disturbance-recovery cycles from short, repetitive rotations have the effect of delaying forest development and entrance into late successional, higher quality, higher return species. Accordingly, a missing variable valuing forest recovery is specified and estimated.

Section III presents the results of solving the discrete horizon rotations problem. From a nonrenewable growth specification a marginal benefit of recovery emerges and has the effect over traditional models of lengthening forest rotations, adjusting profits downwards, and valuing the long-term maintenance of ecosystem processes.

By incorporating ecosystem modeling into traditional forest economics, a clearer management picture results through capturing the influence of rotation length and number on forest recovery. Furthermore, cost estimates of moving from short-term economic rotations to long-term ecological rotations suggest the level of incentive required for one aspect of ecosystem management. A net private cost of maintaining ecosystem health emerges and, for public policy purposes, can be compared to measures of non-timber amenity values and social benefits exhibiting increasing returns to rotation length.

I. The Marginal Benefit of Recovery

For the commercial forest manager, the principal economic question centers on harvest timing. The majority of the economic literature on this question is grounded in the model developed in the 19th century by the German tax collector Martin Faustmann (1849). Faustmann was concerned with estimating the bare-land expected profits[1] of a forthcoming forest. Assuming land is to remain in forestry, the problem is to solve for rotation length (T) over an infinite stream of future profits from harvesting a renewable resource.[2]

Assuming a continuous-time discount factor ($e^{-\delta t}$) and a continuously twice differentiable stand profit function ($\pi(t)$), the choice of an infinite number of rotation lengths converges to the choice of one constant length (T), and the infinite horizon profit maximization problem converges to:

$$(1) \qquad \text{Max} \quad \Pi = \frac{\pi(t)}{e^{\delta t}-1}$$

where

$$\pi(t) \quad = P\,Q(t).$$

[1] The term "value" has been used to represent forest profits (e.g. Clark, 1990) in economics. Here, "value" is reserved for problems incorporating non-forest amenities and other positive externalities. For example, forest profits include only income from the sale of timber, where forest value would include non-market goods such as aesthics, biodiversity, or recreation.
[2] Note: All symbols used throughout the text are also summarized in Appendix A by order and equation of appearance.

Stumpage price (P) is assumed to reflect cutting costs and thus equals net price per unit volume. In the most general case of the multi-species, multi-grade problem, P represents a matrix of stumpage prices and, likewise, Q(t) models a matrix of timber volumes across species and quality classes.

Solving (1) produces the following first-order condition, know as the Faustmann formula:

$$(2) \qquad \pi'(t) = \delta\,\pi(t) + \frac{\delta\,\pi(t)}{e^{\delta t} - 1}.$$

From (2), a single optimal rotation length (T) maximizes net present value (Π) by equating the marginal benefit of waiting to the marginal opportunity cost of delaying the harvest of the current stand (i.e., interest forgone on current profit) plus the marginal opportunity cost of delaying the harvest of all future stands (i.e., interest forgone on all future profits, often called site value).[3]

Adaptations and expansions to this model include modeling non-timber benefits (e.g., Hartman, 1976; Calish et al., 1978; Berck, 1981), multiple-use forestry (e.g., Bowes and Krutilla, 1989; Snyder and Bhattacharyya, 1990; Swallow and Wear, 1993), stochastic price paths (e.g., Clarke and Reed, 1989; Forboseh et al., 1996), market structure (e.g., Crabbe and Long, 1989), and uneven aged forestry (e.g., Montgomery and Adams, 1995). However, all these improvements in the basic Faustmann formula share a strong assumption of perfect growth renewability - a constant growth function (Q(T)) across all future planning periods.

Evidence from the study of forest ecology and management, however, indicates a strong relationship between rotation length, rotation frequency, and

[3] If real stumpage prices are assumed to grow at a rate r, then the Faustmann formula simply becomes: $\pi'(t) = (\delta - r)\,\pi(t) + \frac{(\delta - r)\,\pi(t)}{e^{(\delta - r)t} - 1}$. Equation (15) in the empirical analysis introduces price growth.

harvest magnitude in current harvest periods, with the growth and maintenance of the forest in future periods (e.g., Kimmins, 1987, p. 480; Bormann and Likens, 1979, p. 221). This is particularly the case where natural regeneration seeds the new forest, or soil renewability is compromised. In the Faustmann framework, this ecological knowledge implies a forest stand profit function dependent on rotation-time (T) and rotation-number (i), given constant technology and harvest magnitude.

To illustrate, consider a cubic functional form for undiscounted profit at constant prices:

(3) $\pi(t) = \beta_1 t + \beta_2 t^2 + \beta_3 t^3$.

Figure 1 illustrates three plots of (3) following a harvest at T_0 assuming different parameter values for β_1, β_2, and β_3. Suppose T_{1A} is an optimal Faustmann rotation in the first harvest cycle (i=1). Therefore, a longer rotation in this first cycle (for instance, T_{1B}) would be sub-optimal as it would decrease the marginal value of waiting below the sum of first harvest and future harvest opportunity costs.

However, there may be an additional marginal variable to consider in the first rotation decision. Suppose rotation length in the first harvest cycle influences the form of the functional stand profit function in subsequent cycles. For instance, suppose the choice of T_{1A} in cycle i=1 results in the profit function $\pi(T_{i=2} | T_{1A})$ in cycle i=2. A longer rotation such as T_{1B}, however, results in a higher profit function $\pi(T_{i=2} | T_{1B})$. In this case, a longer first rotation has the benefit of allowing the forest more time to recover from the initial cut at T_0. Now, waiting until T_{1B} to harvest during the first cycle has the benefit of shifting the second cycle curve upwards to $\pi(T_{i=2} | T_{1B})$. A sufficiently long first rotation would result in an identical second rotation profit function. Without taking into account this cross-harvest impact, the Faustmann solution of T_{1A} would lead to a sub-optimal decision.

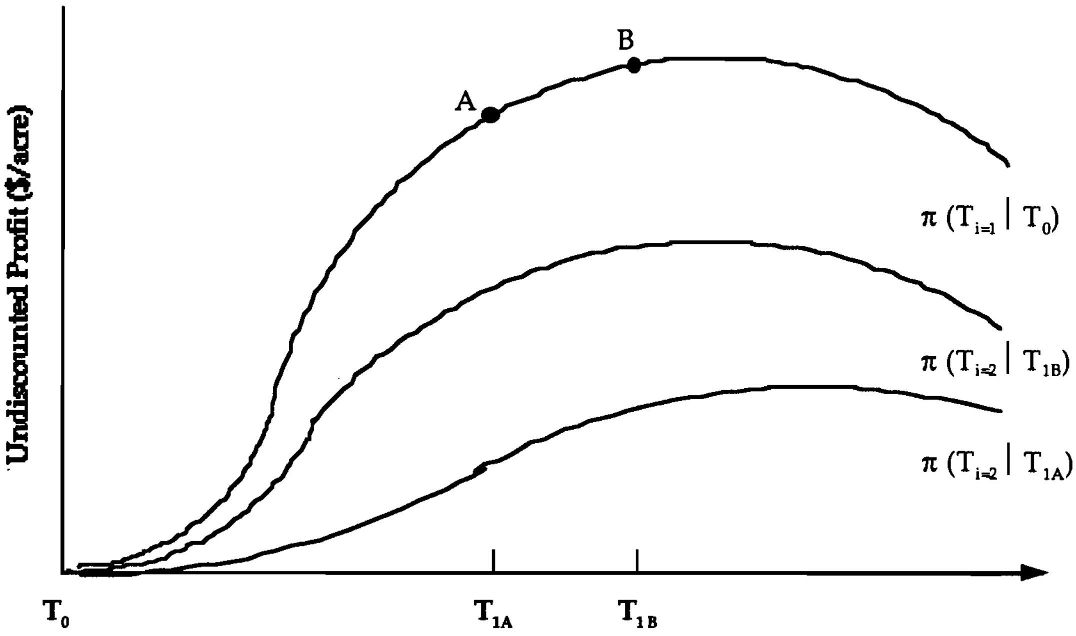

FIGURE 1. CUBIC FOREST UNDISCOUNTED PROFIT FUNCTIONS

To incorporate this interaction between current harvest length and subsequent profit functions consider equation (4). The function $f(T_{i-1}, i\text{-}1)$ is added as a variable to the period i profit function. The level of $f(T_{i-1}, i\text{-}1)$, or ecological impact, depends on the length of last period's rotation (T_{i-1}), and the number of rotations since the first cut at T_0 to take into account any cumulative impacts. It influences the cubic function parameters (β_1, β_2, and β_3) of the stand profit function through an ecological impact represented by the parameters α_1, α_2, and α_3.

(4) $\pi(t_i, f(T_{i-1},i-1)) = (\beta_1 + \alpha_1 f(T_{i-1},i-1))\, t_i + (\beta_2 + \alpha_2 f(T_{i-1},i-1))\, t_i^2 + (\beta_3 + \alpha_3 f(T_{i-1},i-1))\, t_i^3$

where

$f(T_0,0) = \Omega,$

$f(T_{i-1},i-1) \geq \Omega \qquad \dfrac{\partial f(T_{i-1},i-1)}{\partial T_{i-1}} < 0 \qquad \dfrac{\partial^2 f(T_{i-1},i-1)}{\partial T_{i-1}^2} > 0$

$\dfrac{\partial f(T_{i-1},i)}{\partial (i-1)} > 0 \qquad \dfrac{\partial^2 f(T_{i-1},i-1)}{\partial (i-1)^2} < 0,$

and $\alpha_1 < 0, \alpha_2 <> 0, \alpha_3 < 0$

for $i = 1, 2, 3, \ldots$

Stand profit in the current rotation cycle (i) now depends on the current rotation length (T_i), the previous rotation length (T_{i-1}), and the number of rotations (i-1) since the pre-disturbance period (i-1=0). The ecological impact function, f( ), represents a forest recovery relationship based on physical and biological parameters. For example, f( ) might measure the impact on forest regeneration from pioneer species rebound (stems/acre), from soil nutrient loss (nutrients/m^2) or erosion (soil depth), or possibly from a general index of resource renewability.

The first-order conditions for f( ) imply that as the previous period rotation length (T_{i-1}) increases, the negative ecological impact decreases. Also, as the number of rotations since the pre-disturbance period (i-1=0) increases, the ecological impact increases. An initial condition (Ω) is assumed which defines the level of f( ) following the initial harvest at T_0. This parameter can be considered a forest health endowment from the previous land manager. In the case of inheriting a mature forest not previously managed, Ω could be considered the ecological effect on forest growth from natural disturbance.

Assuming this nonrenewable, rotation-time dependent, stand profit specification over an infinite horizon, the profit maximization problem becomes:

$$(5) \qquad \text{Max} \quad \Pi = \pi(t_1, f(T_0,0))\, e^{-\delta T1} + \pi(t_2, f(T_1,1))\, e^{-\delta T2} + \pi(t_3, f(T_2,2))\, e^{-\delta T3} + \ldots$$

Under an assumption of perfect renewability, $f(T_0,0) = f(T_1,1) = \ldots = f(T_\infty,\infty) = \Omega$, and the profit maximization problem converges to equation (1), from which the usual Faustmann result of a constant rotation length in equation (2) is obtained.

Under the assumption of nonrenewability, however, the selection of the optimal rotation length set (T_i for i = 1, 2, 3, . . .) now considers the impact on each subsequent period's profits through the addition of a marginal benefit of recovery (MBR). The marginal benefit of recovery in period i from a rotation length in the previous period i-1 is represented as:

$$(6) \qquad MBR_i = \frac{\partial f(T_{i-1}, i\text{-}1)}{\partial T_{i-1}} \{\alpha_1 T_i + \alpha_2 T_i^2 + \alpha_3 T_i^3\} > 0.$$

Thus, balancing the benefits to recovery from longer rotations against the opportunity costs of delaying current and future harvests will determine the optimal rotation set.

In the forest ecology literature, Kimmins (1987, p. 480) outlines the distinction between a Faustmann type rotation where net present value is maximized, and an ecological rotation, the time required for a site managed with a given technology to return to the pre-disturbance ecological condition. Figure 2 demonstrates the concept of an ecological rotation, and the hypothetical case of rotating before a successional sequence is completed. Succession is defined as the orderly replacement over time of one species or community of species by another, resulting from competitive interactions between them for limited site resources (Marchand,

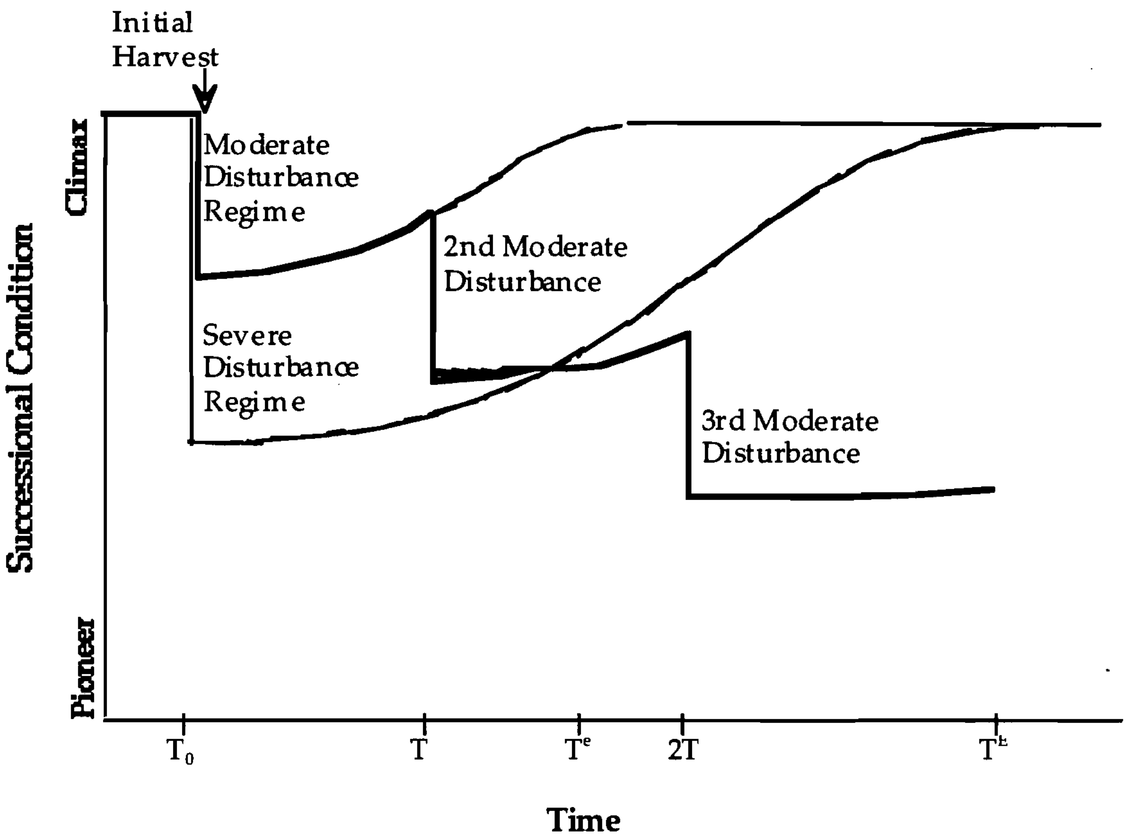

FIGURE 2. KIMMINS' (1987) ECOLOGICAL ROTATION VERSUS SUCCESSIONAL RETROGRESSION

1987, p. 19). The vertical axis of Figure 2 delineates a range from early successional species (pioneer) to late successional species (climax).

Under a moderate disturbance regime (for instance, stem-harvesting or selective cutting), T and 2T represent two Faustmann rotations. The declining path of "backwards" succession is referred to as successional retrogression. For a moderate disturbance, an ecological rotation is represented by T^e, the time when the forest recovers to the original successional condition. A more severe disturbance regime (for instance, whole-tree harvesting or clear-cutting) is also represented where a longer ecological rotation (T^E) would necessarily be required for successional rebound. Ecological observations also suggest the possibility that severe or repeated disturbance could shift the biotic community into a different domain in which the mature (climax) phase of succession is very different than the pre-disturbance condition (Perry et al., 1989). For instance, a clear-cut of a mature forest resulting in the permanent replacement of grasslands might be represented in Figure 2 as a path that never rebounds.

While Figure 2 focuses on a potential decay in successional pathways due to short forest rotations, a similar diagram could model other ecosystem retrogressions. For example, Federer et al. (1989) describe the effects of intensive harvest on the long-term soil depletion of calcium and other nutrients, and the potential limiting effect on forest growth.

In Section II, a model is developed to investigate the ecological mechanisms and economic consequences behind a rotation-dependent profit function in the spirit of the Kimmins' successional retrogression hypothesis. Knowledge of the relationship between rotation length and future profit functions may influence rotation decisions, with both economic and ecological benefits. Furthermore, valuing ecosystem recovery may benefit non-timber amenities exhibiting increasing returns in T as described elsewhere (often referred to as the Hartmann model after Hartmann, 1976). Lastly, the cost and benefits of moving from economic rotations to ecological rotations can be obtained and used for public policy extensions.

II. An Ecological-Economic Model of the Northern Hardwood Forest

To explore the impact of including benefits from recovery on the forest rotation decision, the Northern Hardwood forest ecosystem is modeled. This forest type is the dominant hardwood component of the larger Northern Forest stretching west to northern Minnesota, east through New England, south into parts of the Pennsylvania Appalachians, and north into Canada.[4] It is characterized by sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), and yellow birch (*Betula alleghaniensis*) predominance, with varying admixtures of other hardwoods and softwoods. The model includes components to account for forest growth, pioneer species introduction, conversion from biomass to merchantable timber and pulpwood, and stumpage price growth.

A. *Growth Simulation*

The forest growth simulator JABOWA is used to model succession and growth following a clear-cut in the Northern Hardwood forest. Model development, parameters, and forest species characteristics are described in Appendix B. Growth algorithms for each species consist of the following components (adapted from Botkin et al., 1972).

(7) $\Delta d = G(\sigma, L, d_{max}, h_{max}) \bullet r(L(I, Z)) \bullet \eta(D, D_{min}, D_{max}) \bullet S(A, \theta)$

(8) $G(\,) = \sigma L \{1 - [(d \bullet h)/(d_{max} \bullet h_{max})]\}$

(9) $r(\,) = 1 - e^{-4.64(L - 0.05)}$ {shade-tolerant}

$= 2.24\,(1 - e^{-1.136(L - 0.08)})$ {shade-intolerant}

where $L = I\,e^{-kZ}$

[4] The hardwood component of the Northern Forest type dominates low to mid elevations in deep, well drained soils.

$$(10) \quad \eta(\,) = \frac{4(D - D_{min})(D_{max} - D)}{(D_{max} - D_{min})^2}$$

$$(11) \quad S(\,) = 1 - A/\theta$$

Equation (7) represents the annual change in species diameter at breast height (d). Only growth in diameter is modeled because it will be used to predict merchantable volume (Q) by species and product class for estimating the stand profit function in equation (1). The function G represents a growth rate equation for each species under optimal conditions, depending on a solar energy utilization factor (σ), leaf area (L), and maximum values for diameter (d_{max}) and height (h_{max}).

The remaining right-hand side functions act as multipliers to the optimal growth function to take into account shading, climate, and soil quality. The shading function, r, is modeled separately for shade-tolerant and intolerant species and depends on available light to the tree (a function of annual insolation (I) and shading leaf area (Z)[5]). The function η accounts for the effect of temperature on photosynthetic rates, and depends on the number of growing degree-days (D)[6] and species specific minimum and maximum values of D for which growth is possible. Finally, S is a dynamic soil quality index.[7]

Stochastic dynamics of stand growth enter the model through stem birth and death subroutines, and are described in more detail in Appendix B. Given this stochasticity, simulation data vary widely with each model run. Data specific to defining equations in the remainder of this section can be obtained from the author, and are based on ten runs (ten 100 m^2 plots). This builds an approximately 1/4 acre

[5] A sum of leaf areas of all taller trees on the 100 m^2 plot.
[6] Approximated by the number of days per year exceeding 40°F, which is in turn approximated by using January and July average temperatures for a site.
[7] Dependent on total basal area (A; stem cross-sectional area at breast height) on the plot and maximum basal area (θ) under optimal growing conditions.

plot, which is subsequently expanded to a full acre by assuming each tree represents four trees per acre.

B. *Successional Retrogression*

Building on the JABOWA model, the challenge is to incorporate an ecological mechanism to capture Kimmins' hypothesis of rotation dependent succession and growth. Such a mechanism is evident in the early succession rebound of pioneer species. A possible succession of dominant species is represented by Figure 3, adapted from Marks (1974).

During the first 15 - 20 years following a clear-cut, the recovering forest is dominated by pioneer species such as raspberry bushes, birches, and pin cherry. These fast growing, opportunistic species, play a critical role in ecosystem recovery from a clear-cut by reducing runoff and limiting soil and nutrient loss (Marks, 1974). However, their initial density will also influence stand biomass accumulation and

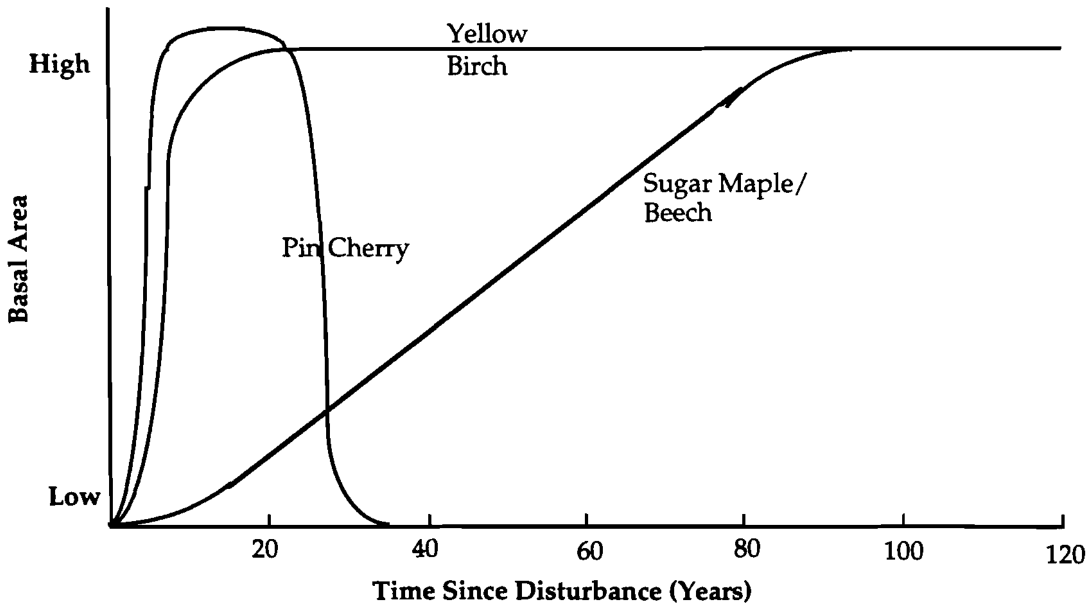

FIGURE 3. NORTHERN HARDWOOD SUCCESSION FOLLOWING CLEAR-CUT

growth of commercial species (Wilson and Jensen, 1954; Marquis, 1969; Mou, Fahey, and Hughes, 1993; Heitzman and Nyland, 1994).

In this application to the Northern Hardwood forest, pin cherry (*Prunus pensylvanica*) is assumed to be the dominant pioneer species. As a particularly fast-growing, short-lived, shade intolerant species with no commercial value, the effect of its growth following a clear-cut on forest succession and future harvest profits can be significant. Tierney and Fahey (1996) demonstrate the influence of short rotations on the survival of its seeds, and its subsequent germination and growth at very high density in young stands. This forest ecology research indicates that pioneer species densities may stabilize at low levels following a 120-year or more rotation regime (comparable to a Kimmins' ecological rotation), while rotations at 60-year intervals (closer to a Faustmann economic rotation) result in increasing pioneer species densitities toward a carrying capacity asymptote.

The dependence of the initial density of a pioneer species (PS) on the previous harvest rotation length (T_{i-1}) and the number of previous harvests (i-1) is used to represent the more general case of successional retrogression from Figure 2. The following ordinary least squares model was estimated to capture the hypothesis of a rotation-dependent ecological impact function proposed in equation (4). Ecological assumptions and research results are reported in Appendix C.

$$(12) \quad PS = f(T_{i-1}, i-1) = 100 = \Omega \qquad \text{for } T_i > 140 \text{ years}$$

$$= 7342.27 - 89.18\, T_{i-1} + 0.25\, T_{i-1}^{2} + 550\,(i-1) \qquad \text{for } T_i \leq 140 \text{ years}^{8}$$

[8] All parameters are significant at α=.10; R^2=0.98; F=65.05.

C. *Multi-Product, Stochastic Quality Model*

The third model component converts stem diameter output from JABOWA into economic output. The financial value of standing timber depends on age, size, species, and quality distributions. A typical northern hardwood stand can provide sawtimber, pulpwood, and firewood. Depending on the market and the land owners motivations, any combination of these three product classes may be managed. Equation (13) is used to estimate stand profit.

$$(13) \quad \pi(t, PS) = \left\{ \sum_{S=1}^{9} \sum_{C=1}^{6} Q_{S,C}[d, M, PS] \right\} \bullet \mathbf{P}_t$$

Profit [$\pi(t, PS)$] is defined at a year following a clear-cut and before the next ($t = 0, 1, 2, \ldots T$), given initial pioneer species density (PS). As in equation (1), total stand profit ($/acre) is the product of a price matrix (P_t) and merchantable volume (Q) for each commercial species (S=1, 2, . . ., 8) and noncommercial species group (S=9) in each product category (C=1, 2, . . . 6).[9] Commercial species numbers correspond to species listed in Table B2 in Appendix B. Product categories comprise of grade 1 through 3 timber (C=1-3), below grade sawtimber (C=4), and hardwood (C=5) and softwood (C=6) pulp. Firewood output was not considered.

Merchantable volume (Q) is modeled on stem diameter (d), provided for each tree by a growth simulation, and merchantable length (M), which is also modeled on d. The level of initial pioneer species density (PS) is predicted from equation (12) based on the previous periods rotation length (T_{i-1}) and number (i-1). PS influences diameter growth through the dynamics of the forest growth simulator, as well as

[9] Note, a matrix of all volumes across species and product classes implicit in equation (13) is the same as Q(t) from equation (1).

influencing merchantable volume calculations through impacting forest site quality. The procedures for converting diameter estimates to merchantable volume by species and product class are described in detail in Appendix D.

D. *Parameterization*

Integrating the first three components of the model outlined above, merchantable stand volumes were generated at 10 year intervals from year 20 to 250, at initial pioneer species densities of 0, 10, 20, 50, 100, 200, 500, 1000, 2000, and 5000 initial stems per 100 m^2. Volume within each species, product class, and year was then converted to profit by multiplying a net price matrix of 1995 prices. The initial distribution of net prices (P_0) across product classes and species is summarized in Table 1. Stand profit for each year was then summarized across all products and species to generate data for $\pi(t, PS)$ at each PS value run.

TABLE 1—INITIAL SAWTIMBER STUMPAGE AND PULPWOOD PRICES (P_0)

Species	Below Grade	Grade 3	Grade 2	Grade 1	Pulp
	($/Thousand Board Feet)				($/cord)
Sugar Maple	125	298.30	471.5	650	7
Beech	20	38.15	56.3	75	7
Yellow Birch	50	99.50	149.0	200	7
White Ash	75	182.30	289.5	400	7
Balsam Fir	30	53.10	76.2	100	12
Red Spruce	30	53.10	76.2	100	12
Paper Birch	45	56.55	68.1	80	7
Red Maple	50	83.00	116.0	150	7
Noncommercial	-	-	-	-	7

Note: Sawtimber prices in each quality class were calculated from ranges of stumpage prices reported in NYDEC (1995) for the Adirondack region. Within each range: Min = Below Grade price, 33rd Percentile = Grade 3 price, 66th Percentile = Grade 2 price, and Max = Grade 1 price.

The following cubic model was fitted using ordinary least squares, with results reported in Table 2.

$$(14) \quad \pi(t, PS) = (\beta_1 + \alpha_1 PS)\, t \; + \; (\beta_2 + \alpha_2 PS^2)\, t^2 \; + \; (\beta_3 + \alpha_3 PS)\, t^3$$

This specification results in a 264 X 6 explanatory variable matrix. Figure 4 plots $\pi(\,)$ at some illustrative PS values. Here $\pi(\,)$ represents stand profit at 1995 prices. Price growth is taken up separately in the next section.

TABLE 2—ORDINARY LEAST SQUARES RESULTS FOR $\pi(t, PS)$

Variable	Estimate	t-statistic	p-value
β_1	7.718	1.797	0.073
α_1	-0.0025	-6.085	4.2×10^{-9}
β_2	0.2194	4.251	3.0×10^{-5}
α_2	1.52×10^{-9}	5.476	1.1×10^{-7}
β_3	-0.00082	-5.457	1.1×10^{-7}
α_3	-1.40×10^{-8}	-1.258	0.209
# of observ.	264	F-Value	59.19
R^2	0.58	Adj.-R^2	0.57

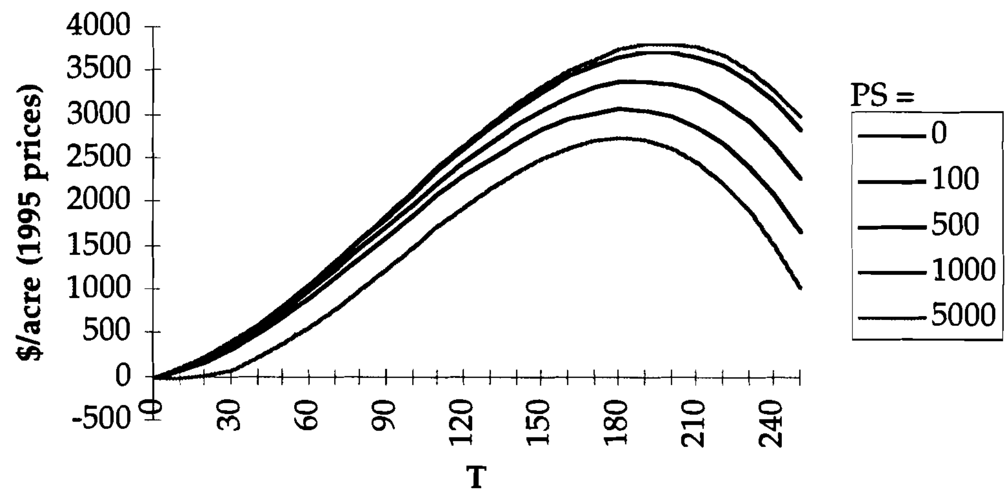

FIGURE 4. π(T, PS) AT FIVE INITIAL PIONEER SPECIES (PS) DENSITIES

E. *Price Growth (P_t)*

The influences on stumpage prices at the forest stand level are complex. They might include: timber quality, volume to be cut per acre, logging terrain, market demand, distance to market, season of year, distance to public roads, woods labor costs, size of the average tree to be cut, type of logging equipment, percentage of timber species in the area, end product of manufacture, landowner requirements, landowner knowledge of market value, property taxes, performance bond requirements, and insurance costs (NYDEC, 1995). At the macroeconomic level, exports, mill stocks, and aggregate demand are typically explanatory variables (Luppold and Jacobsen, 1985). Emerging effects on northeast stumpage prices include increasing substitution of recycled fibers in paper making, board feet restrictions on removals in the Pacific Northwest, and continued growth in global wood demand.

For the purposes of this model, the P_t matrix will depend on an initial price distribution at t=0 (see Table 1), and algorithms for growth in three product classes. As a stand matures, it is assumed to enter three stages of product development: (1) pulpwood, (2) low quality sawtimber, and (3) high quality sawtimber. To illustrate, consider Figure 5. Here prices are assumed to remain constant over a 250 year horizon, no additional pioneer species are added, and only sugar maple and total hard pulp values are plotted. Initially the stand generates mostly hard pulp. Below grade sugar maple sawtimber rises steadily over time, surpassed first by Grade 3 lumber, and eventually by Grade 2 and 1 as the stand matures.

To capture these dynamics, an exponential model for stand profit growth with a shifting growth rate is assumed. In the northeastern U.S., from 1961 through 1991, Sendak (1994) reports average real hardwood stumpage prices for sawtimber rose 4.3% per year, and for pulpwood rose 1.3% per year (see Figure 6).

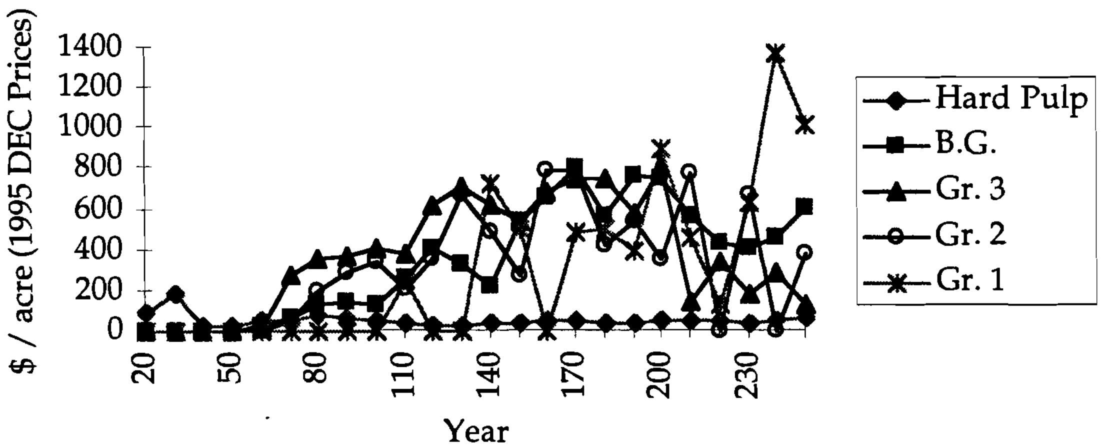

FIGURE 5. SUGAR MAPLE STUMPAGE AND HARD PULP VALUE, PS=0, 1995 PRICES

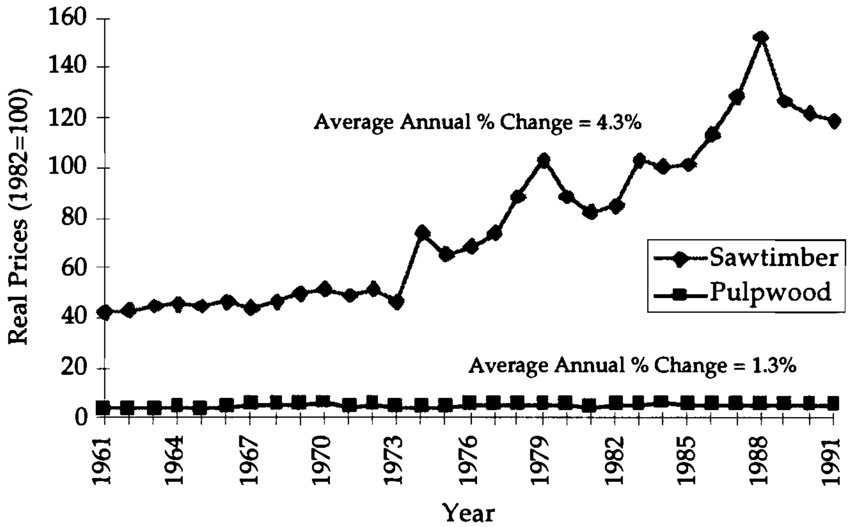

FIGURE 6. NORTHEAST AVERAGE HARDWOOD STUMPAGE ($/MBF) AND HARD PULPWOOD ($/CORD) REAL PRICE GROWTH, 1961-91

As these rates are an average across all quality classes and species, the following price growth model is assumed to apply to the entire price matrix.

(15) $P_t = P_0 e^{r(t)t}$

$$\text{where} \quad r(t) = \begin{cases} 1\% \text{ if} & t \le t_L + \Delta_i \\ 3\% \text{ if} & t_L + \Delta_i < t \le t_H + \Delta_i \\ 4\% \text{ if} & t > t_H + \Delta_i \end{cases}$$

$$\text{and} \quad \Delta_i = PS/250$$

The parameters t_L and t_H represent the number of years since harvest when the growing forest stand shifts into higher quality product classes. Following a clear-cut, the recovering forest stand can only produce pulpwood, a product class where prices are growing slowly at an exponential growth rate of r(t) = 1%. At t_L, the stand shifts into a low quality sawtimber phase (below grade and grade 3), and the exponential growth rate jumps to 3%. As the stand continues to mature, high quality timber becomes more prevalent until a time t_H is reached when timber prices grow at a rate more characteristic of high quality timber.

As continued short rotations enhance pioneer species abundance, species competition pushes commercial species development further into the future, thus delaying the entrance into higher quality product classes. To capture this successional retrogression hypothesis, a shift variable (Δ_i) is assumed to add years to t_L and t_H depending on pioneer species density at the beginning of each rotation.

This model is applied by mapping three exponential growth functions over the planning horizon at each rate. The function is applied as a multiplier to the initial species by product price matrix (P_0), with r depending on t. Figure 7 outlines a price growth sequence over a 150 year horizon assuming $t_L = 30$, $t_H = 100$, and PS = 0. In a subsequent rotation, where PS>0, both boundaries between product phases would shift outward due to a positive Δ_i.

The assumption of exponential profit growth is perhaps most relevant to high quality timber. As global forest productivity declines due to short-sighted management practices, the supply of high quality timber will fall and its price will perhaps behave more like a scarcity multiplier of a nonrenewable resource. On a regional scale, short rotation cycles due to high discount rates may limit high quality timber supplies. In fact, under a successional retrogression hypothesis and short rotation lengths, as Δ_i continues to increase, the third or fourth harvest may only yield pulpwood.

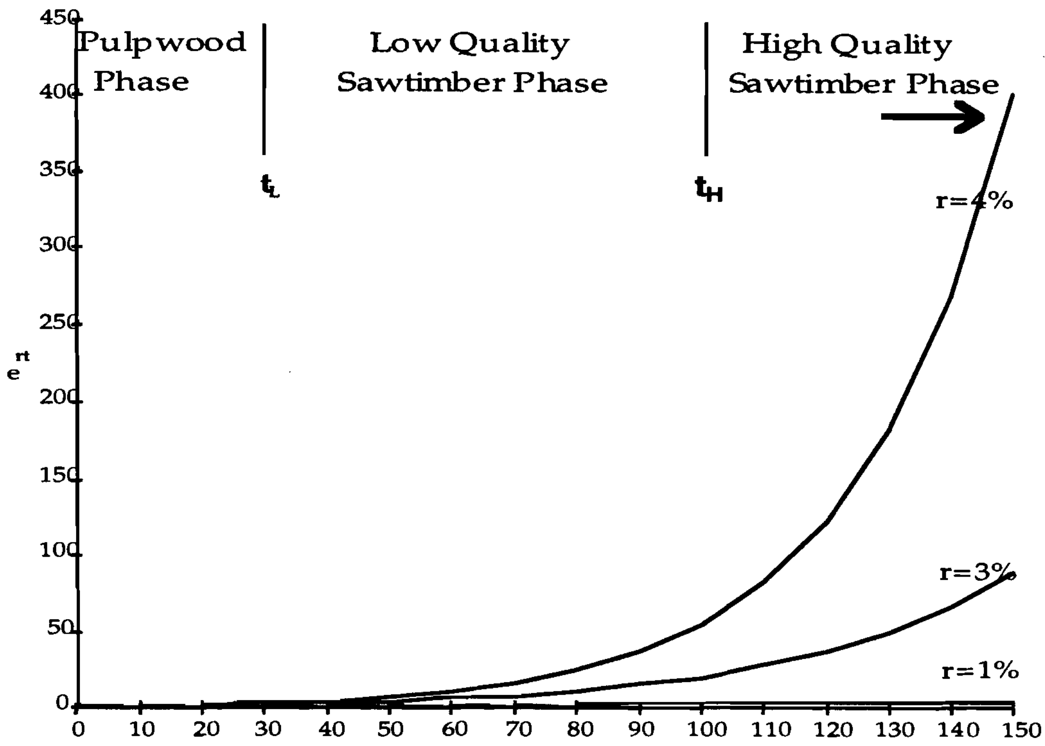

FIGURE 7. EXPONENTIAL PRICE GROWTH MODEL ACROSS ONE HARVEST CYCLE

III. Rotation Analysis

With the nonrenewable stand value specification of equation (14) and the price growth model assumed in equation (15), the analysis turns to estimating and comparing rotation lengths. The question posed from the start was: do the benefits from recovery in future harvest periods influence the harvest timing decision in current periods? As discussed, the infinite horizon problem from which the Faustmann result emerges cannot be solved without the assumption of perfect renewability in growth. However, assuming four harvest cycles does a reasonable job of estimating the first rotation length, since a positive discount rate causes profits from harvest cycles beyond four periods to have a negligible effect on the choice of rotation lengths in earlier periods.

Therefore, assuming cutting costs are internalized in stumpage price and high labor costs would prohibit thinning young dense stands, the problem is to choose the rotation set that maximizes the present value of profits over four harvest cycles:

(16) $\text{Max}\,\Pi =$

$$\frac{e^{r(T_1)T_1}\pi(T_1,PS_0)}{e^{\delta T_1}}+\frac{e^{r(T_2)(T_1+T_2)}\pi(T_2,f(T_1,1))}{e^{\delta(T_1+T_2)}}+\ldots+\frac{e^{r(T_4)(T_1+T_2+T_3+T_4)}\pi(T_4,f(T_3,3))}{e^{\delta(T_1+T_2+T_3+T_4)}}$$

$$=e^{(r(T_1)-\delta)T_1}\pi(T_1,PS_0)+e^{(r(T_2)-\delta)(T_1+T_2)}\pi(T_2,f(T_1,1))+\ldots+e^{(r(T_4)-\delta)(T_1+T_2+T_3+T_4)}\pi(T_4,f(T_3,3))$$

A. *Risk and Choosing an Economic Optimum*

The difficulty in solving equation (16) over four periods is that as r varies within each rotation cycle (from 1% to 3% to 4%), the possibility of multiple optimums arises. To illustrate, take the case of maximizing profit over just a single rotation. Figure 8 plots the present value over each price growth phase, assuming PS=100, δ=5%, t_L=30, and t_H=100. Two optimums emerge, however, the global optimum of T=196 is obvious. Under the model assumptions, a 196 year harvest cycle stabilizes the pin cherry seed bank at "natural" background levels. In this case the optimal economic rotation length is also an ecological rotation.

However, is this a realistic rotation length? Indeed, at a discount rate of 5% a rotation length of T=70 is perhaps more characteristic of the end of most commercial rotations for large landowners in the northern hardwood forest.

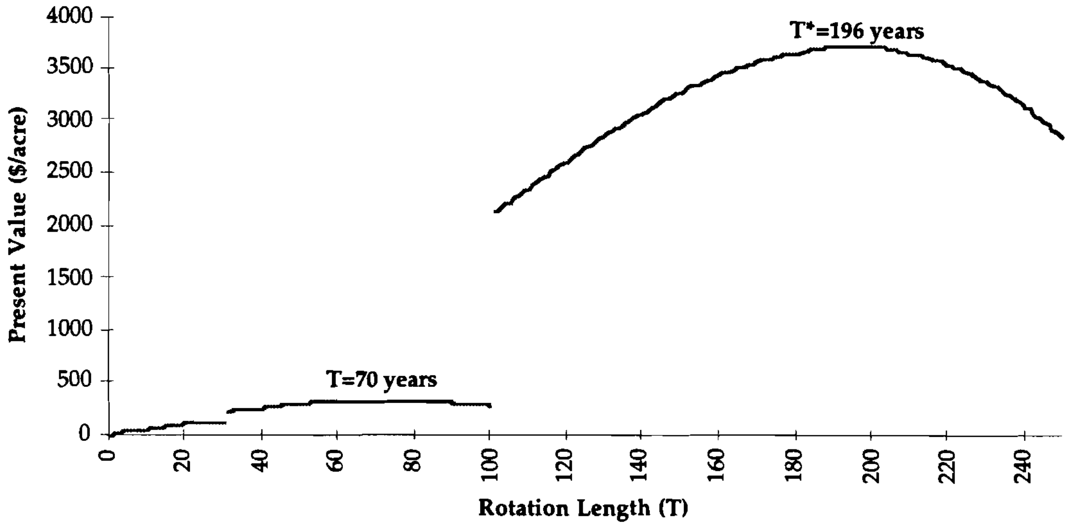

FIGURE 8. PRESENT VALUE OF A SINGLE ROTATION, PS=100, δ=5%, t_L=30, AND t_H=100

Are managers behaving irrationally? Not when risk and uncertainty are taken into account. A landholder will not face a profit maximization problem with perfectly forcasted profits. Risk and uncertainty increase in later periods through market, government, and environmental variability, effectively raising the discount rate. For example, as a forest matures its potential for yielding high quality wood increases, but so does the likelihood of disease, aging effects, or blowdown. Furthermore, given the public's preference for old growth forests, there may be a risk of tighter regulations as a stand ages. As present value declines during the interval 63 < T < 100 at a constant r=3%, the landowner must also evaluate the expectation that prices will jump (in this case to a growth rate of r=4%) at some age t_H. These types of risks can and should be reflected in the owners discount rate.[10]

[10] If stochastic growth was carried through, or stochastic price growth introduced, risk could be modeled with option value methodology by including growth or price variance. Clarke and Reed (1989) found an optimal stopping frontier assuming brownian motion for age-dependent growth and geometric brownian motion for price evolution, and an optimal stopping rule under deterministic growth.

In the single rotation example of Figure 8, consider the effect of simply raising the landowners discount rate in the high quality timber phase (T > 100 years) by two percentage points. One optimum at T=70 results, illustrated in Figure 9. This line of reasoning is helpful in solving the multi-rotation problem.

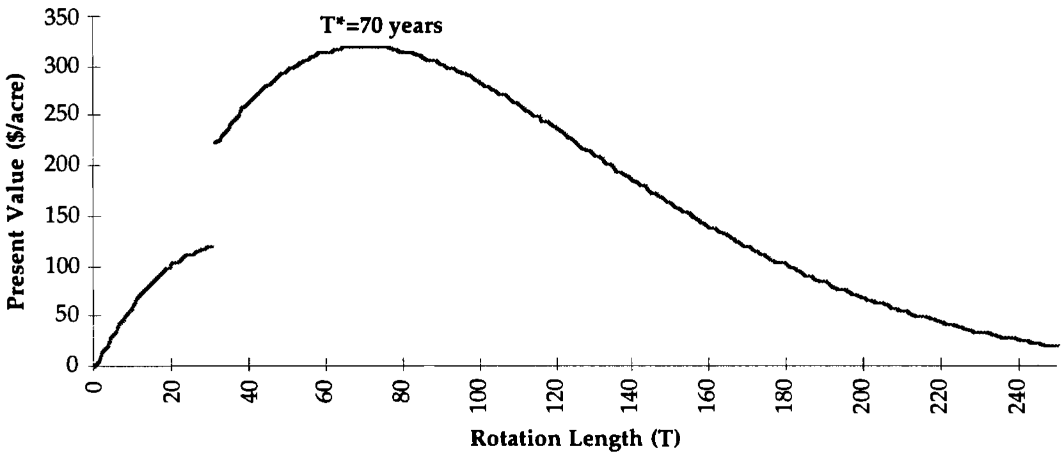

FIGURE 9. PRESENT VALUE OF A SINGLE ROTATION WITH A 2% RISK FACTOR IN PERIODS T>100 YEARS, PS=100, δ=5%, t_L=30, AND t_H=100

B. *The Optimal Rotation Set with Risk, and the Marginal Benefit of Recovery*

Assume that because of risk and uncertainty the hypothetical landowner will maximize profits in either the low quality timber or pulpwood price phases. The task is to solve equation (16) for T_1, T_2, T_3 and T_4. Parameter values are as follows: δ=5%, PS_0=100, t_L=30, and t_H=100.

Table 3 outlines the optimal rotation set under two cases. The first is the successional retrogression hypothesis with $\pi(T_i, f(T_{i-1}, i-1))$. The second is the traditional perfectly renewable growth hypothesis with $\pi(T_i, PS_i=100)$. The sum of present value over four periods reveals a 17.5% overestimate of stand profits in the misspecified problem. Rotation lengths differ by as much as 24 years in the second cycle, and become longer in future cycles as prices continue to grow exponentially and profit from future rotations goes to zero. The rotation length for T_4 simply maximizes profits in this cycle.

TABLE 3—FOUR HARVEST PERIOD SOLUTION
WITH 2% LONG-RUN RISK FACTOR

Rotation	Rotation Dependent Specification $\pi(T_N, f(T_{N-1}, N-1)$	Renewable Growth Specification $\pi(T_N, PS_N=100)$
	(years)	
T_1	58	40
T_2	68	44
T_3	70	51
T_4	83	70
Net Present Value	$ 400.3/acre	$470.2/acre

Compare the first cycle rotation lengths with that of the single rotation problem represented in Figure 9, where T equaled 70 years. The effect of considering profits in cycles 2, 3 and 4 at considerably higher prices and identical growth conditions reduces T_1 from 70 to 40 years. This is the result of considering three period future profits. When successional retrogression is assumed, the shift from 40 to 58 years is the result of including a marginal benefit of recovery.

Differentiating equation (16) by T_1 and setting the result to zero yields the first order condition for T_1. The terms can be arranged so that the marginal benefit of waiting another period equals the marginal cost of delaying first cycle profits plus the marginal cost of delaying all future profits (site value), as was the case in the traditional Faustmann formula, and the addition of a marginal benefit of recovery in the second cycle:

$$\text{(17)} \quad e^{RT_1}\frac{\partial\pi(T_1,PS_0)}{\partial T_1} = Re^{RT_1}\pi(T_1,PS_0) + R\phi + e^{R(T_1+T_2)}\frac{\partial\pi(T_2,f(T_1,1))}{\partial f(T_1,1)}\frac{\partial f(T_1,1)}{\partial T_1}$$

where

$r(T_1) = r(T_2) = r(T_3) = r(T_4) = r,$

$R = r - \delta,$

$\phi = e^{R(T_1+T_2)}\pi(T_2,f(T_1,1)) + e^{R(T_1+T_2+T_3)}\pi(T_3,f(T_2,2)) + e^{R(T_1+T_2+T_3+T_4)}\pi(T_4,f(T_3,3))$

= three period site profit.

At the optimal first cycle rotation (T_1=58) the marginal benefit of waiting another year until harvest is \$7.50. It equals the marginal cost of delaying first cycle profits of \$6.30, the marginal cost of delaying the next three harvests (site value) of \$1.70, and the marginal benefit of recovery in future cycles of \$0.50. Site value well exceeds MBR because of the effect of exponential price growth.

C. *Economic and Ecological Indicators under various Discount Rates*

The discount rate measures the landowner's opportunity cost. A relatively low opportunity cost of δ=5% may be characteristic of a large landowner with many sources of income. For instance, the highest return for a pulp and paper mill in the northern hardwood forest is in making paper. As long as their mill is fed with a continuous, inexpensive supply of fiber, management can hold onto timber stands for speculation in the higher return sawtimber markets, particularly when land is drawing income between rotations, for instance, through recreational leasing.[11] Medium opportunity cost in the range of δ=10% may be more characteristic of a small primary forest product industry or small woodlot owner. A discount rate of 15%, may be characteristic of a landowner not necessarily in the timber industry. In this case it may be more profitable to use the land for an activity with a shorter investment horizon, for instance housing development.

Table 4 lists the results of the four cycle optimization when the discount rate is varied, assuming no risk factor. In the case of high opportunity cost (δ=15%), four pulpwood rotations are optimal at interior solutions of 8, 37, 30 and 30 years with a total present value of $24/acre. At δ=10% the optimal rotation set occurs in the low quality sawtimber phase at rotations of 31, 51, 48 and 51 years, all of which are corner solutions since t_L=30, Δ_1=21, Δ_2=18 and Δ_3=21. At δ =5%, the solution occurs at the corner of the high quality sawtimber phase.

The sum of present value over four cycles indicates the effect on profit of both shorter rotations with lower quality products and a higher discount rate. A second economic indicator, summarizing stand profit at year 105 (the end of the fourth cycle under δ=15%) with no discounting, indicates only the effect of shorter rotations and

[11] Personal communication with management of Finch, Pruyn and Co. of Glen Fall, N.Y. Finch-Pruyn owns over 160,000 acres of forest in the Adirondack Park of New York State, the majority of which is in hardwoods managed for sawtimber.

TABLE 4—THE OPTIMAL 4-CYCLE ROTATION SET AND LONG-RUN ECONOMIC AND ECOLOGICAL HEALTH, VARYING THE DISCOUNT RATE

Optimal Rotation Set	5%	δ 10%	15%
T_1	101 years	31 years	8 years
T_2	107	51	37
T_3	108	48	30
T_4	115	51	30
Economic Indicators:			
Net Present Value	$1,122.6/acre	$48.6/acre	$24.0/acre
Undiscounted Profit @ year 105	$5,909/acre	$1,592/acre	$500/acre
Ecological Indicators:			
$f(T_3, 3)$	2,224 stems/acre	5,277 stems/acre	6,538 stems/acre
$t_L + \Delta_3$	39 years	51 years	56 years
$t_H + \Delta_3$	109	121	126

lower quality products on profits. Under this second indication, just over one rotation of high quality sawtimber (at T_1=101 and T_2=4) produces 2.7 times more undiscounted profits than three and a half rotations under the low quality management case, and 10.8 times more undiscounted profits than four full pulpwood rotations.

Looking at the ecological indicators of the three management scenarios, the ecological benefits to longer rotations are evident. At the beginning of the fourth harvest cycle, pioneer species density is 2,224 stems under long rotations, 5,277 stems under medium length rotations, and 6,538 stems under short rotations. In the pulpwood harvesting case, entrance into both sawtimber phases is delayed a full 27 years by the fourth harvest cycle. The cases where δ=10% and δ=15% demonstrate the declining trend in successional integrity as suggested by the Kimmins' successional retrogression hypothesis, while the case where δ=5% perhaps approaches a set of ecological rotations.

D. *Single Period Management under Declining Forest Health*

Another method to solving the multiple rotations problem is to assume the values for PS_i over subsequent rotations are forest health endowments to new generations of owners or managers. In other words, a different owner during each cycle solves a single rotation problem, without consideration of site value or benefits to recovery. Here, the first order condition within each cycle becomes:

$$(18) \qquad \delta - \pi(T_i) = \frac{\pi'(T_i, PS_{i-1})}{\pi(T_i, PS_{i-1})}.$$

Again, assuming the landowner will manage either in the low quality sawtimber or pulpwood price growth phases, the four cycle interior solution for T is 70, 80, 80, and 83. The result: future landowners must wait longer to maximize profits due to poorer forest health endowments. Profits continue to increase in later cycles because of exponential price growth, but not as fast as they would under perfect growth renewability. By the fourth cycle, the pulpwood price phase is 70 years long, and initial pioneer species density is 3,979 stems/acre.

E. *Ecological Rotations and Valuing Non-Timber Amenities*

As was seen in the single period problem, given low constant discount rates ecological rotations may be economically optimal. Solving equation (16) with a constant discount rate of 5% yielded the rotation length set of 101, 107, 108 and 115 years with a total present value of $1122.6/acre. Assuming PS=100 and Δ_i=0 across all cycles (i.e., perfect renewability), the optimal set becomes 101, 101, 101 and 116 with a total present value of $1200.2/acre. Here the misspecification error results in only a 2% overestimate.

These rotation lengths are approaching what might be considered ecological rotations as described by Kimmins and illustrated in Figure 2. Without risk factored into the decision and preventively high forest maintenance costs assumed, such lengths are economically optimal as well. Therefore, the question remains: under what conditions will landowners rotate forests at 100+ years?

Perhaps including the value of non-timber amenities would make ecological rotations *socially* optimal, even at high discount rates. Amenity values that exhibit increasing returns to rotation length might include recreation value, provision for certain habitats, and watershed protection.

For example, referring to Table 4, consider the low discount rate solution (δ=5%) and middle discount rate solution (δ=10%) as the social and private optimal rotation sets. Next, evaluating the social rotation set at the private discount rate of 10% results in a total present value of just $5/acre. If a landowner was forced to rotate at these lengths, this would result in a private loss of $41/acre. However, if the sum of non-timber amenities exceeds this loss and the landowner experiences these benefits directly (for example, hunting or recreational use), then there may be a private incentive to lengthen rotations.

Alternatively, if the amenity values are of a strictly social nature (for example, watershed protection or biodiversity preservation) then there may be an opportunity for the government or an environmental group to accomodate the land owners loss in timber profits through a payment or incentive mechanism (for example, paying for a conservation easement or providing tax relief). In addition, alternative silviculture practices such as selective cutting may strike common ground between the interplay of social and private benefits. For instance, assessing the ecological impact of economic decisions contributes towards defining and assessing "new" or "sustainable" forestry, which touts management practices entrenched in ecological principles with sufficient economic and social policy returns (Franklin, 1989; Gillis, 1990; Gane, 1992; Fiedler, 1992; Maser, 1994).

IV. Concluding Remarks

Accounting for the ecological recovery of the northern hardwood forest over a series of harvests was shown to increase rotation lengths over the traditional Faustmann result. A positive marginal benefit of recovery offsets the marginal costs of delaying current and future rotations, creating a benefit to delaying rotations under a nonrenewable stand value growth specification.

Knowledge of benefits to ecosystem recovery can help define both ecological and economic rotation lengths under various scenarios of ecosystem retrogression. At one extreme, given low discount rates and risk, relatively long ecological rotations may be economically optimal. At the other extreme, a site managed with short rotations motivated by short term profits and a high discount rate may result in degraded forest stands with low value species - a detriment to long-run ecological health *and* social benefits.

When considering social welfare from multiple-use management, many non-timber benefits (i.e., recreation, aesthetics, biodiversity) have increasing returns in rotation length, and thus in forest health recovery. The benefit of recovery was shown to have a market value, and its inclusion more accurately estimates the optimal rotation set. Including this benefit, however, may not completely provide the private incentive to move from ecologically unsustainable to sustainable rotation lengths and practices, particularly when the net private cost of doing so is high. However, this net private cost can be compared to benefits from non-timber amenities and alternative management practices, or to costs of forest maintenance (i.e., thinning undesirable species), providing rationale for social management.

Questions of where to manage along ecological-economic dimensions in a forest will ultimately depend on a region's spatial ownership pattern, land holder motivations, policy variables, management costs, timber markets, and ecosystem characteristics. These modeling results suggest very different economic and ecological outcomes by varying opportunity cost and ecosystem recovery assumptions, and suggest a positive benefit to recovery. Estimating economic benefits across ecological gradients could contribute to valuing non-timber amenities and developing stewardship policies aimed at managing multiple, spatial benefits of a forest ecosystem.

APPENDIX A:
LIST OF SYMBOLS (by order of appearance)

Equation 1

T	= rotation length (years).
δ	= continuous discount rate (%).
t	= time (years).
$\pi(t)$	= forest stand profit function ($/acre) for harvest at time t.
Π	= total present value of future stream of profits from rotations.
P	= matrix of net prices per unit volume across species and product classes.
$Q(t)$	= merchantable timber output across species and product classes at t.

Equation 3

$\beta_1, \beta_2, \beta_3$	= parameters to cubic form of stand profit function ($\pi(t)$).

Equation 4

i	= number of forest rotations since predisturbance period (i=0) or harvest cycle.
$\pi(t_i, f(T_{i-1}, i-1))$	= nonrenewable profit specification.
$f(T_{i-1}, i-1)$	= ecological impact function.
α_i	= fixed impact parameters in nonrenewable profit specification, measuring the impact of $f(T_{i-1}, i-1)$ on the cubic profit function parameters ($\beta_1, \beta_2, \beta_3$).
Ω	= initial effect on cubic growth function parameters from the first disturbance (T_1); can also be considered as the effect on growth from a natural disturbance regime, for example, from hurricanes or fires.

Equation 6

MBR_i	= marginal benefit of recovery in harvest cycle i from the choice of rotation length in the previous harvest cycle (i-1).

Figure 2

T^e	= ecological rotation from moderate disturbance. An ecological rotation is defined as the time required for a site managed with a given technology to return to the pre-disturbance ecological condition.
T^E	= ecological rotation from severe disturbance.

Equations 7 - 11

Δd	= annual change in tree diameter.
d	= diameter at breast height (4.5 feet above ground).
h	= height.

$G(\sigma, L, d_{max}, h_{max})$	= species growth rate equation under optimal conditions.
σ	= solar utilization factor.
L	= leaf area.
d_{max}	= maximum diameter.
h_{max}	= maximum height.
$r(L(I, Z))$	= shading function; models effect of shade on optimal growth.
$L(I, Z)$	= available light.
I	= annual solar insolation.
Z	= shading leaf area, which is the sum of leaf areas of all taller trees on the 100 m^2 plot.
$\eta(D, D_{min}, D_{max})$	= temperature function; models effect of temperature on optimal growth.
D	= number of growing degree days; approximated by the number of days per year exceeding 40°F, which is in turn approximated by using January and July average temperatures for a site.
D_{min}	= minimum temperature at which growth is possible.
D_{max}	= maximum temperature at which growth is possible.
$S(A, Q)$	= soil quality model.
A	= total basal area per 100 m^2, where basal area is the cross section area at breast height per plot.
θ	= maximum basal area under optimal growing conditions.

Equation 12

PS	= peak pioneer species density following clear cut (stems/acre).

Equation 13

$\pi(t, PS)$	= rotation time dependent specification of stand value function, using PS as an estimate of $f(T_{i-1}, i\text{-}1)$.
S	= species (1, 2, . . . 8) identified in Table B2 of Appendix B.
C	= product category (0=below grade sawtimber, 1=grade 1, 2=grade 2, 3=grade 3, 4=hard pulpwood, 5=soft pulpwood).
$Q_{s,C}$	= merchantable volume function by species and quality class.
M	= merchantable length.
$\mathbf{P}_t$	= matrix of prices across species and product categories at t.

Equation 15

$r(t)$	= exponent in exponential price growth equation.
t_L	= time since harvest when the new stand shifts to an r(t) more characteristic of low quality sawtimber (C=0 and 3) price growth.
t_H	= time since harvest when the new stand shifts to an r(t) more characteristic of high quality sawtimber (C=1 and 2) price growth.
Δ_i	= variable which shifts t_L and t_H further into the future as PS increases.

Equation 17

R	= fixed exponential price growth rate (r) less the discount rate (δ).
ϕ	= three period site value for i = 2, 3, and 4.

Equation D1

si	= species specific site index function.
SI(PS)	= stand site index, dependent on initial pioneer species density (PS) (see footnote 17 in Appendix D).
b_0	= parameter to species specific site index function.
g	= growth rate of reference tree class (i.e. maple-beech-birch group).
g_s	= growth rate of slower of faster growing tree class.

Equation D2

td	= minimum top diameter acceptable.
a_1, a_2, a_3	= parameters to merchantable length function.

Equation D3

ψ_i	= parameters to merchantable stem volume function (i = 0, 1, 2, 3, 4, 5).

Equations E1 - E3

G_p	= potential tree grade.
p_k	= probability that G_p equals k, where k = grade 1, 2, 3, or 4 (below grade).
f_j	= generalized logistic regression (GLR) model (j = 1, 2, 3).
χ_{j1}, χ_{j1}, χ_{j3}	= regression coefficients to GLR model.
n	= uniform random number.

APPENDIX B:
JABOWA FOREST GROWTH AND SUCCESSION SIMULATOR

The JABOWA model is from the popular family of "gap models" which simulate growth of individual trees on small plots and disturbance at the forest gap level.[12] Christ et al. (1995) developed a version of the model in PASCAL to test the accuracy of the original Botkin et al. (1972) model predictions against forest inventory data,[13] and determine if more recently added modifications improve those predictions. The model simulates growth of the Northern Hardwood forest, built on silvical data for the species of the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire.[14]

The Christ et al. (1995) model is used to simulate growth on 10 x 10 meter plots for thirteen species (including two softwoods). Table B1 lists species specific and environmental parameters. Each year, individual trees competing for light either become established[15], grow, or die. Species characteristics and chance determine the dynamics of these birth-growth-death cycles. As taller trees shade smaller ones, the amount of shading is dependent on the species' characteristic leaf number and area, and survival under shaded conditions depends on the shade tolerance of a species (photosynthetic rates in the shaded environment being higher in shade-tolerant species vs. intolerant; vice versa under bright conditions). Table B2 characterizes the relative shade tolerance, and maximum age and height of the species modeled.

New saplings randomly enter the plot within limits imposed by their relative shade tolerance and degree-day and soil moisture requirements. Tolerant species,

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[12] Gap refers to a hole in the forest canopy created by the felling of a tree, naturally or otherwise.
[13] One of the important results of this work is that JABOWA tends to grow trees too big, particularly yellow birch.
[14] One of the USDA's Northeast Forest Experiment Stations, and location of the Hubbard Brook Ecosystem Study.
[15] Trees enter the modeled stand at a diameter-at-breast-height (DBH) of 0.5 cm, a life stage which corresponds to stem establishment rather than birth or germination.

yellow and paper birch, and pin cherry are added randomly at the rate of 0-2 stems, 0-13 stems, and 60-75 stems, respectively. In assigning death probabilities for individual trees, it is assumed that no more than 2% of the saplings of a species will reach their maximum age. A second mechanism assigns a 1% chance of surviving 10 years for an individual whose annual increment remains below a minimum value.

TABLE B1—SPECIES AND ENVIRONMENTAL PARAMETERS IN JABOWA

Species Specific Parameters	
• Maximum age, diameter, and height	
• Relation between: height and diameter, total leaf weight and diameter, rate of photosynthesis and available light, relative growth and climate	
• Range of stem establishment requirements	
• Limit on number of saplings allowed under shading conditions	
Abiotic Environment	Assumption:
• Elevation	549 meters
• Soil Depth	3 meters deep
• Soil-moisture holding capacity	15 cm/m
• Percent rock in soil	5%
• Degree days (40° F base)	3,288 ° days
• Actual evapotranspiration	542.3 mm H_2O

TABLE B2—CHARACTERISTICS OF SPECIES MODELED WITH JABOWA

#	Species	Shade Tolerance	Maximum Known Age (years)	Maximum Known Height (ft.)
Commercial				
1	Sugar Maple (*Acer saccharum*)	Tolerant	200	132
2	Beech (*Fagus grandifolia*)	Tolerant	300	120
3	Y. Birch (*Betula alleghaniensis*)	Intermed.	300	100
4	White Ash (*Fraxinus americana*)	Intermed.	100	71
	Balsam Fir (*Abies balsamea*)	Tolerant	80	60
6	Red Spruce (*Picea rubens*)	Tolerant	350	60
7	Paper Birch (*Betula papyrifera*)	Intolerant	80	60
8	Red Maple (*Acer rubrum*)	Intermed.	150	120
Noncommercial				
9	Mountain Maple (*Acer spicatum*)	Tolerant	25	16
9	Striped Maple (*A. pensylvanicum*)	Tolerant	30	33
9	Pin Cherry (*Prunus pensylvanica*)	Intolerant	30	37
9	Chokecherry (*P. virginia*)	Intolerant	20	16
9	Mountain Ash (*Sorbus americana*)	Tolerant	30	16

Source: Adapted from Botkin et al. (1972).

APPENDIX C: DYNAMIC PIONEER SPECIES MODEL

Pin cherry (*Prunus pensylvanica*) is used as a representative pioneer species to estimate the ecological impact function, $f(T_{i-1}, i-1)$, in equation (4). The reproduction of pin cherry follows a buried seed strategy. Seed production begins at a very early age (~ 3 years), and are dispersed widely by birds. Some survive in the soil seed bank for periods of longer than 100 years. Germination occurs only when the right conditions are present (most significantly, light resulting from a large forest opening such as that created by severe windstorms or clear-cutting). The result in forest management terms: the shorter the forest rotation, the more seeds survive and germinate, and the denser initial pin cherry stands become in subsequent rotation-recovery cycles.

Figure C1 presents two forest rotation scenarios of pin cherry rebound, summarizing the soil seed bank dynamic modeling results of Tierney and Fahey (1996). Background level in the seed bank is assumed 5 pin cherry seeds/m^2 in stands greater than 170 years old. At the initial disturbance at T_0, one stem/m^2 becomes established. They further hypothesize that rotations greater than 120 years may allow enough depletion of the seed bank to stabilize pin cherry germination at 10 stems/m^2. At the other extreme, 60 year rotations may eventually triple the size of the pin cherry soil seed bank, resulting in peak stem densities (stems/m^2) of 30 at T_1=61, 42 at T_2=121, 48 at T_3=181, and approaching a limit of 50 at T_4=241.

Table C1 lists data used to estimate equation (12) based on three disturbance regimes: 60 and 120 year from Figure C1, and 170 year.

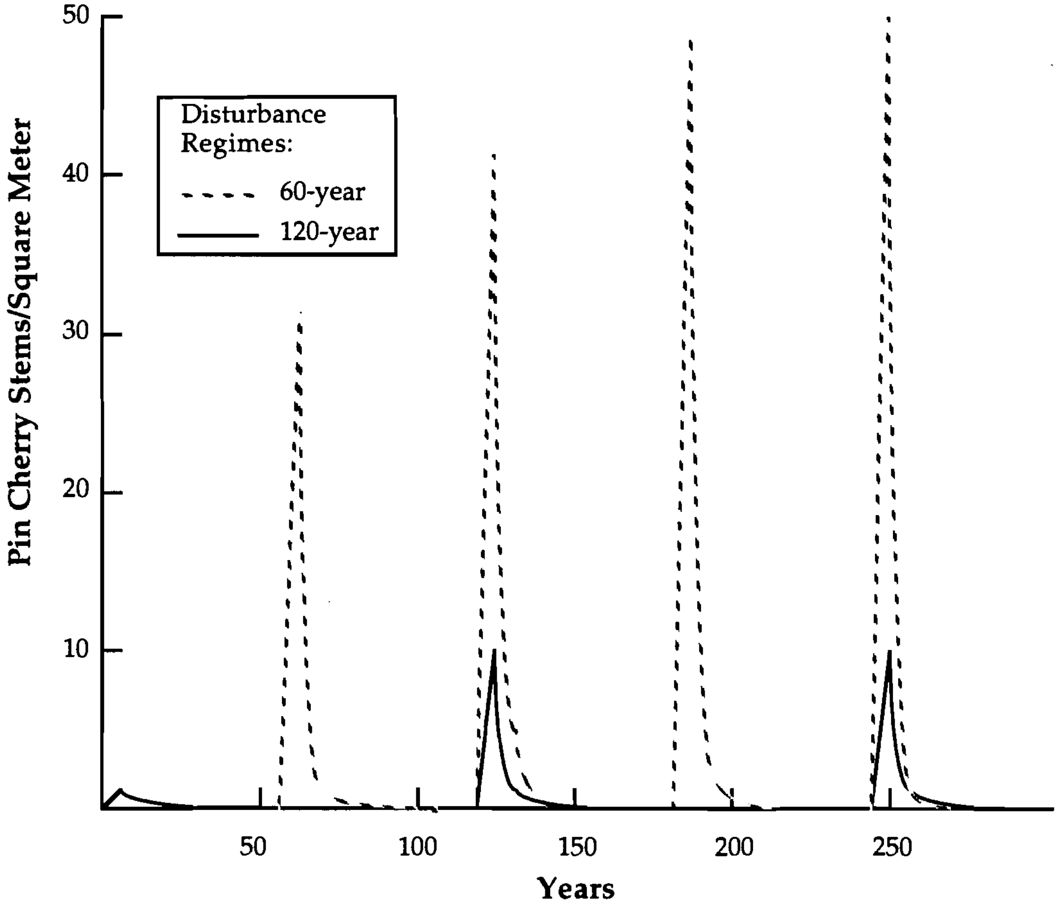

FIGURE C1. PIN CHERRY REBOUND, 60-YEAR AND 120-YEAR DISTURBANCE REGIMES

TABLE C1—DATA FOR PS = $f(T_{i-1}, i-1)$ ESTIMATION

Initial Pioneer Species Density (PS)	Previous Cycle Rotation Length (T_{i-1})	T_{i-1}^2	# of Rotations Before Current (i-1)
100	170	28,900	1
100	170	28,900	2
1000	120	14,400	1
1000	120	14,400	2
3000	60	3,600	1
4200	60	3,600	2
4800	60	3,600	3
5000	60	3,600	4

APPENDIX D:
MULTI-PRODUCT, STOCHASTIC QUALITY MODEL[16]

Species and diameter at breast height (d) are provided for each tree by the ecology model run. When converting diamter to merchantable volume, stems with d < 5 inches are discarded. Softwoods with d < 9 inches are considered softwood pulp (C=6) and hardwoods with d < 11 inches are considered hardwood pulp (C=5). Noncommercial species (S=9) do not reach sawtimber diameters.

Determining the sawtimber classes (C=1,2,3,4) isn't as straight forward. First a species specific site index (si) must be computed from a benchmark index (SI) for the maple-beech-birch class which is in turn modeled as a function of PS.[17] This provides a more accurate growth potential of each species on the site. Defining g as the growth rate of the general class, and g_s as that of the slower or faster growing class, for nine species groups the following model from Hilt et al. (1989) was incorporated. Parameter estimates are tabulated in Table D1.

$$\text{(D1)} \quad si = b_0 + 1.104 \, SI \, (PS) \qquad \text{if } g_s > g$$

$$= \frac{b_0}{1.104} + 0.906 \, SI \, (PS) \qquad \text{if } g_s < g$$

[16] The following procedures and equations were programmed in Visual Basic for Microsoft Excel Macros. A 19 page appendix including the code is available from the author. These procedures were originally developed by the USDA Forest Service and have also been incorporated in the NE-TWIGS forest growth model. See Miner et al. (1988) for a general reference to the TWIGS family of models.

[17] Site index is a proxy to site quality measured as the height of the dominant canopy species at year 50. Based on eleven JABOWA runs at the PS densities specified above, the following ordinary least squares result was used to predict SI from PS:

$$SI = 54.90197 - 0.00418 \, PS$$

TABLE D1—PARAMETERS FOR SITE INDEX EQUATION (D1)

Height Group	Species included in group (see Table B2 for #'s)	b_0 when $g<g_s$	b_0 when $g>g_s$
Black cherry-poplar-aspen	9		
Elm-ash-cottonwood	4	-1.824	
Maple-beech-birch	1, 2, 3, 7, 8		
Balsam fir-eastern hemlock	5		1.408
R. spruce-tamarack-other hardwoods	6, 9		-0.800

Note: Of the species in the noncommercial grouping (S=9), pin cherry and striped maple were included in the fastest growing class, and mountain maple and chokecherry were included in the slowest growing class with "other hardwoods".
Source: Hilt et al. (1989).

Next a random number is generated and assigned to each stem, and along with d and si, the potential sawtimber class (or tree grade (G_p)) is determined with a generalized logistic regression (GLR) model as estimated by Yaussey (1993). The GLR procedure, parameters, and an example are described in Appendix E.

With G_p assigned by stem, actual tree grades (G_a) are then assigned at current period diameters. Softwoods are either grade 1 or below grade, regardless of current d. Diameter restrictions for hardwoods include 16 inches for grade 1 and 13 inches for grade 2 (Yaussey, 1993). For example, a hardwood with G_p = 1 and d = 15 would be assigned G_a = 2.

With quality classes established, merchantable length (M) is calculated in equation (D2) from si, d, and a new parameter, td (minimum top diameter acceptable). Restrictions on td are 9, 7, and 4 inches for hardwood sawlogs, softwood sawlogs, and pulpwood, respectively. Parameter estimates are tabulated in Table D2.

(D2) $M = a_1\, si^{a2}\, \{1 - \exp[a_3\,(d - td)]\}$

TABLE D2—PARAMETERS FOR MERCHANTABLE LENGTH EQUATION (D2)

#	Species	a_1	a_2	a_3
1	Sugar Maple	21.237	0.182	-0.294
2	Beech	16.430	0.212	-0.328
3	Yellow Birch	18.922	0.176	-0.400
4	White Ash	26.321	0.135	-0.268
5	Balsam Fir	17.394	0.252	-0.326
6	Red Spruce	24.180	0.186	-0.280
7	Paper Birch	18.922	0.176	-0.400
8	Red Maple	22.319	0.149	-0.342
9	Noncommercial	26.129	0.000	-0.493

Source: Yaussy and Dale (1991).

Lastly, within each species and product class, board-feet for sawtimber and cubic feet for pulpwood[18] are estimated from d and M. The following model for merchantable stem volume (Q) is assumed. Parameter estimates for ψ_i for board-feet and cubic feet are tabulated in Table D3.

(D3) $Q = \psi_o + \psi_1 d^{\psi 2} + \psi_3 d^{\psi 4} + M^{\psi 5}$

[18] When prices are introduced, one cord per 70 cubic feet is assumed for pulpwood volume.

TABLE D3—PARAMETERS FOR MERCHANTABLE VOLUME EQUATION (D3)

Species Group	Species # included	Volume Unit	ψ_0	ψ_1	ψ_2	ψ_3	ψ_4	ψ_5
Sugar maple	1	Bd.Ft.	3.73	-0.00182	3.3766	0.0262	2.4291	0.6139
		Cu.Ft.	-0.19	-0.01171	1.8949	0.01340	1.9928	0.6471
Beech	2	Bd.Ft.	-0.84	-0.01207	3.0043	0.0419	2.3951	0.5912
		Cu.Ft.	-0.60	-0.00711	2.2693	0.01399	2.0190	0.6518
Birch species	3, 7	Bd.Ft.	8.23	0.00039	3.0	0.0206	2.2116	0.8019
		Cu.Ft.	-0.27	-0.00675	1.9738	0.01327	1.9967	0.6407
Ash & Aspen species	4	Bd.Ft.	9.20	0.00052	3.0	0.0193	2.2165	0.8043
		Cu.Ft.	0.06	-0.02437	1.5419	0.01299	1.9885	0.6453
Balsam fir	5	Bd.Ft.	-12.29	-0.08212	2.5641	0.1416	2.2657	0.3744
		Cu.Ft.	-0.10	-0.05444	2.1194	0.04821	2.0427	0.3579
Red, white, black spruce	6	Bd.Ft.	-13.03	-0.05197	2.5248	0.1200	2.1999	0.4227
		Cu.Ft.	0.17	-0.06315	2.0654	0.05122	2.0264	0.3508
Soft maple	8	Bd.Ft.	2.84	-0.00557	3.1808	0.0296	2.2606	0.5771
		Cu.Ft.	-0.45	-0.00523	2.2323	0.01338	2.0093	0.6384
Other hardwoods	9	Bd.Ft.	0.03	-0.00196	3.3236	0.0263	2.4162	0.6012
		Cu.Ft.	0.13	-0.00183	2.3600	0.00944	2.0608	0.6516

Source: Scott (1979) and Scott (1981).

APPENDIX E: GENERALIZED LOGISTIC REGRESSION (GLR) FOR ASSIGNING POTENTIAL TREE GRADES (G_p)

Adapted from Yaussy (1993).

Let G_p = potential tree grade

p_k = probability that G_p equals k

where k = grade 1, 2, 3, or 4 (below grade)

The GLR model takes the form:

(E1) $\ln (p_j/p_4) = f_j$

where j = 1, 2, 3

$f_j = \chi_{j0} + \chi_{j1}(si) + \chi_{j2}(d) + \chi_{j3}(si)(d)$

$\chi_{j1}, \chi_{j2}, \chi_{j3}$ = regression coefficients in Table E1

From (E1) it follows that:

(E2) $p_j = p_4 \bullet \exp(f_j)$

Since the p_i's must sum to 1, the following holds:

$$1 = \sum_{j=1}^{3} p_j + p_4$$

$$= \sum_{j=1}^{3} (p_4 \bullet \exp(f_j)) + p_4$$

$$= p_4 (1 + \sum_{j=1}^{3} \exp(f_j))$$

so

(E3) $p_4 = 1 / (1 + \sum_{j=1}^{3} \exp(f_j))$

TABLE E1—COEFFICIENTS FOR THE GENERALIZED LOGISTIC REGRESSIONS

Species Group	Commercial species included	j	χ_{j0}	χ_{j1}	χ_{j2}	$_{j3}$
Ash	4	1	-1.6880	0.0145	0.0770	-0.00090
		2	3.0552	-0.0235	-0.1620	0.00102
		3	4.3884	-0.0265	-0.2638	0.00155
Beech	2	1	-3.7807	-0.0229	0.0191	0.00023
		2	-4.0959	0.0167	0.1002	-0.00160
		3	0.7484	-0.0173	-0.0890	0.00028
Birch	3, 7	1	-7.2202	0.0313	0.2471	-.00210
		2	-3.5818	0.0285	0.0987	-0.00154
		3	2.9962	-0.0363	-0.2099	0.00205
Hemlock	5, 6	1	0.6158	-0.0033	-0.0057	0.00012
Red Maple	8	1	-4.8396	0.0096	0.1327	-0.00113
		2	-2.2768	0.0144	0.0932	-0.00176
		3	1.9865	-0.0206	-0.1169	0.00052
Sugar Maple	1	1	-4.1101	0.0141	0.1198	-0.00104
		2	-1.1156	0.0062	0.0164	-0.00073
		3	1.7617	-0.0056	-0.0902	-0.00042

Source: Yaussey (1993, p. 7-8, Table 3).

The proportion of trees in one of the four potential tree grade classes (two classes for softwoods) is computed from equations (E2) and (E3). To illustrate how these probabilities are computed and applied, consider an example of a group of sugar maples with DBH (d) of 15 inches and a site index (si) of 60 feet. Using parameter values for sugar maple from Table E1, first compute:

$$\exp(f_1) = \exp(-4.1101 + 0.0141\,(si) + 0.1198\,(d) - 0.00104\,(si)(d))$$
$$= 0.0904$$

$\exp(f_2) \quad = 0.3152$

$\exp(f_3) \quad = 0.7369$

$\Sigma \exp(f_j) \quad = 1.1425$

Next, employing equation (E3), the proportion of trees of this species, diameter, and site index with a G_p equal to below grade is:

$$
\begin{aligned}
p_4 &= (1 + 1.1425)^{-1} \\
&= 0.4667
\end{aligned}
$$

The remaining probabilities for grades 1, 2, and 3 are then computed from equation (E2) as follows:

$$
\begin{aligned}
p_1 &= p_4 \bullet \exp(f_1) \\
&= 0.4667 \bullet 0.0904 \\
&= 0.0422
\end{aligned}
$$

$$p_2 \quad = 0.1471$$

$$p_3 \quad = 0.3439$$

To apply these probabilities, a uniform random number is generated (n) for each sawtimber stem. In this example, for each sugar maple stem with d=15 in a stand with a sugar maple site index of 60, a potential tree grade would be assigned based on cumulative probabilities as follows:

$G_p = 1 \quad$ if $\ 0 \leq n \leq 0.0422$,

$G_p = 2 \quad$ if $\ 0.0422 < n \leq 0.1893$,

$G_p = 3 \quad$ if $\ 0.1893 < n \leq 0.5332$, and

$G_p = 4 \quad$ if $\ 0.5332 < n \leq 1$.

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