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## ANALYSIS

# Non-renewability in forest rotations: implications for economic and ecosystem sustainability<sup>☆</sup>

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### Abstract

The forest rotations problem has been considered by generations of economists (Fisher, 1930; Boulding, 1966; 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 non-renewable forest resource and the influence of rotation length and number on forest recovery are reported. 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 with measures of non-timber amenity values and social benefits exhibiting increasing returns to rotation length. © 1999 Elsevier Science B.V. All rights reserved.

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### 1. Introduction

Ecological economics has distinguished itself from traditional economic analysis of the environ-

ment by stressing the essential role of ecosystem services and the maintenance of ecosystem processes. Traditional analysis of renewable resources such as forests, fisheries, and agriculture has long stressed the conditions for steady-state systems of management. The economic study of these natural resources, however, has often overlooked critical intertemporal ecological mechanics related to the timing and impact of disturbing natural systems.

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The study of the regeneration of forests under centuries long harvest sequences is beginning to redefine our understanding of resource renewability. Traditional financial models of the forest resource assume perfect renewability in forest growth following infinite optimal rotations of constant length. Study of forest ecology, however, suggests that rotations 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 non-renewable forest growth specification, leading to the addition of a marginal benefit of recovery in the traditional optimal rotation decision rule.

In this paper, 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. For the ecosystem type examined, the success of early successional species in disturbance–recovery cycles due to short, repetitive rotations have the effect of delaying forest development and entrance into late successional, higher quality, higher return species. Accordingly, an overlooked financial benefit to forest recovery is specified and estimated for a discrete horizon rotations problem. A non-renewable growth specification 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 an economic framework, a clearer management picture results.

## 2. 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 (Faustmann, 1849). Faustmann was concerned with estimating the bare-

land expected profits<sup>1</sup> of a forthcoming forest. Assuming land is to remain in forestry, the problem is to solve for the rotation length ( $T$ ) over an infinite stream of future profits from harvesting a perfectly renewable resource.

Assuming a continuous-time discount factor ( $e^{-\delta t}$ ) and a continuously twice differentiable stand profit function ( $\pi(t)$ ), the infinite horizon profit maximization problem converges to:

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

where:

$$\pi(t) = P Q(t). \quad (2)$$

Stumpage price ( $P$ ) equals net price per unit volume. Natural regeneration is assumed, so replanting costs are assumed zero. In the most general case of the multispecies, multiquality problem,  $P$  represents a matrix of stumpage prices and, likewise,  $Q(t)$  models a matrix of timber volumes across species and quality classes.

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

$$\pi'(t) = \delta \pi(t) + \frac{\delta \pi(t)}{e^{\delta t} - 1} \quad (3)$$

From Eq. (3), a single optimal rotation length ( $T$ ) maximizes net present value ( $\Pi$ ) 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).<sup>2</sup>

<sup>1</sup> 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 aesthetics, biodiversity, or recreation.

<sup>2</sup> If real stumpage prices are assumed to grow at a rate  $r$ , then the Faustmann formula simply becomes:  $\pi'(t) = (\delta - r)\pi(t) + [(\delta - r)\pi(t)]/[e^{(\delta - r)t} - 1]$ . Eqs. (29)–(33) in the empirical analysis introduces price growth.

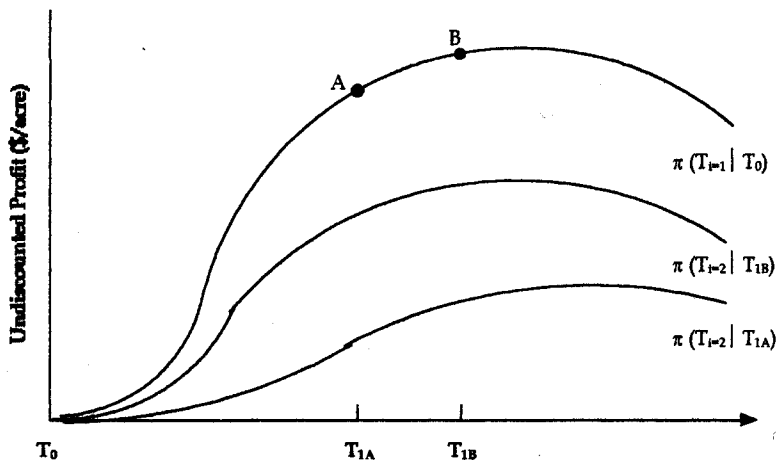


Fig. 1. Cubic forest undiscounted profit functions.

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; Forbosh et al., 1996), market structure (e.g. Crabbe and Van Long, 1989), and uneven aged forestry (e.g. Montgomery and Adams, 1995).

All these improvements to the basic Faustmann formula, however, share a strong assumption of perfect growth renewability—a constant growth function ( $Q(T)$ ) across all future planning periods. In contrast, evidence from the study of forest ecology and management indicates a strong relationship between rotation length, rotation frequency, and harvest magnitude in a current management period, with the growth and maintenance of the forest in future periods (e.g. Borman and Likens, 1979; Kimmins, 1987). 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 length ( $T$ ) and rotation number ( $i$ ), given constant technology and harvest magnitude.

Growth in merchantable timber volume is typically modeled using a cubic or exponential form,

consistent with stages for rapid growth, biological maturity, and disease and decay (Clark, 1990). Consider a cubic functional form for undiscounted profit at constant prices:

$$\pi(t) = \beta_1 t + \beta_2 t^2 + \beta_3 t^3. \quad (4)$$

Fig. 1 illustrates three plots of Eq. (4) following a harvest at  $T_0$  assuming different parameter values for  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$ . 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 cycle  $i = 2$ . 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.

To incorporate this interaction between current harvest length and subsequent profit functions consider Eq. (5). The function  $f(T_{i-1}, i-1)$  is added as a variable to the period  $i$  profit function. The level of  $f(T_{i-1}, i-1)$ , or ecological impact, depends on the length of the 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 ( $\beta_1, \beta_2$ , and  $\beta_3$ ) of the stand profit function through an ecological impact represented by the parameters  $\alpha_1, \alpha_2$ , and  $\alpha_3$ :

$$\begin{aligned} \pi(t_i, f(T_{i-1}, i-1)) \\ = (\beta_1 + \alpha_1 f(T_{i-1}, i-1))t_i \\ + (\beta_2 + \alpha_2 f(T_{i-1}, i-1))t_i^2 \\ + (\beta_3 + \alpha_3 f(T_{i-1}, i-1))t_i^3 \end{aligned} \quad (5)$$

where:

$$f(T_0, 0) = \Omega, \quad (6)$$

$$f(T_{i-1}, i-1) \geq \Omega \quad (7)$$

$$\frac{\partial f(T_{i-1}, i-1)}{\partial T_{i-1}} < 0 \quad (8)$$

$$\frac{\partial^2 f(T_{i-1}, i-1)}{\partial T_{i-1}^2} > 0 \quad (9)$$

$$\frac{\partial f(T_{i-1}, i-1)}{\partial (i-1)} > 0 \quad (10)$$

$$\frac{\partial^2 f(T_{i-1}, i-1)}{\partial (i-1)^2} < 0 \quad (11)$$

and:

$$\alpha_1 < 0, \quad (12)$$

$$\alpha_2 < 0, \quad (13)$$

$$\alpha_3 < 0 \quad (14)$$

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

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<sup>2</sup>) 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 ( $\Omega$ ) is assumed which defines the level of  $f()$  following the initial harvest at  $T_0$ . This parameter can be considered a forest health endowment left from the previous land manager. In the case of inheriting a mature forest not previously managed,  $\Omega$  could be considered the ecological effect on forest growth from periodic natural disturbances (e.g. wind storms, fires).

Assuming this non-renewable, rotation length-dependent, stand profit specification over an infinite horizon, the profit maximization problem becomes:

Max

$$\begin{aligned} \Pi = \pi(t_1, f(T_0, 0))e^{-\delta T_1} + \pi(t_2, f(T_1, 1))e^{-\delta T_2} \\ + \pi(t_3, f(T_2, 2))e^{-\delta T_3} + \dots \end{aligned} \quad (15)$$

Under an assumption of perfect renewability,  $f(T_0, 0) = f(T_1, 1) = \dots = f(T_\infty, \infty) = \Omega$ , and the profit maximization problem converges to Eq. (1), from which the usual Faustmann result of a constant rotation length in Eq. (3) is obtained.

Under the assumption of partial non-renewability, however, the selection of the optimal rotation length set ( $T_i$  for  $i = 1, 2, 3, \dots$ ) 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:

$$\text{MBR}_i = \frac{\partial f(T_{i-1}, i-1)}{\partial T_{i-1}} \{\alpha_1 T_i + \alpha_2 T_i^2 + \alpha_3 T_i^3\} > 0 \quad (16)$$

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.

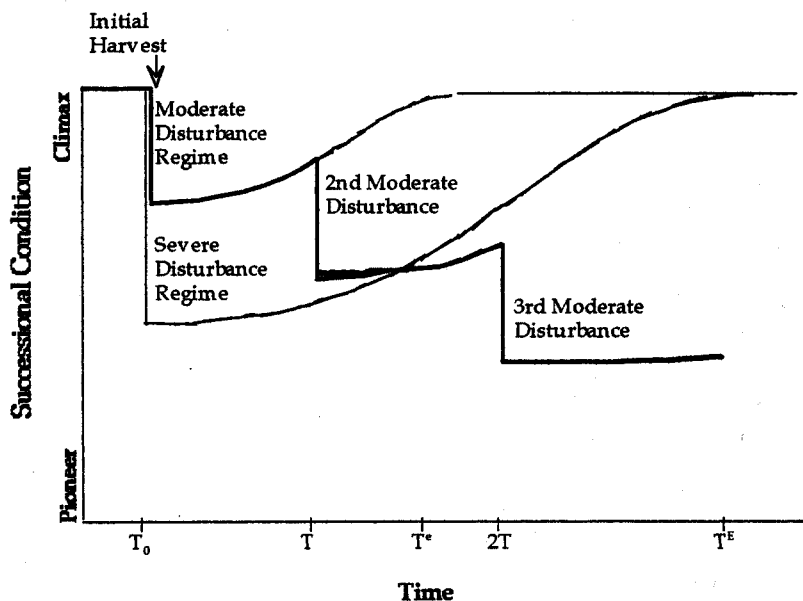


Fig. 2. Kimmins' ecological rotation vs. successional retrogression (Kimmins, 1987).

In the forest ecology literature, Kimmins (1987) 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. Fig. 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, 1987). The vertical axis of Fig. 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  $T^*$ , 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 by grasslands might be represented in Fig. 2 as a path that never rebounds.

While Fig. 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 the next section, 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 deci-

sions, 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 Hartman model after Hartman, 1976). Lastly, the cost and benefits of moving from economic rotations to ecological rotations can be obtained and used for public policy extensions.

### 3. An ecological economic model of the northern hardwood forest

The northern hardwood forest ecosystem is the dominant hardwood component of the larger northern forest of the United States, stretching west to northern Minnesota, east through New England, south into parts of the Pennsylvania Appalachians, and north into Canada. 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. A model was developed to account for forest growth, pioneer species introduction, conversion from biomass to merchantable timber and pulpwood, and stumpage price growth. Development and details of these four components are described in detail in Erickson et al. (1997).

#### 3.1. Growth simulation

The stochastic forest growth simulator JABOWA developed by Christ et al. (1995) was used to model succession and growth following a clear-cut in the northern hardwood forest. The JABOWA model simulates growth of individual trees on small plots at the forest gap level, built on silvical data for the species of the Hubbard Brook Experimental Forest in the White Mountains of New Hampshire. 'Gap' refers to a hole in the forest canopy created by the felling of a tree, naturally or otherwise. 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. Model development, parameters, and forest species characteristics are described in Erickson et al.

(1997). In general, growth algorithms for each species consist of the following components (adapted from Botkin et al., 1972):

$$\Delta d = G(\sigma, L, d_{\max}, h_{\max}) \cdot r(L(I, Z)) \cdot \eta(D, D_{\min}, D_{\max}) \cdot S(A, \theta) \quad (17)$$

$$G() = \sigma L \{1 - [(d \cdot h)/(d_{\max} \cdot h_{\max})]\} \quad (18)$$

$$r() = 1 - e^{-4.64(L-0.05)} \quad \{\text{shade-tolerant}\} \quad (19)$$

$$r() = 2.24 (1 - e^{-1.136(L-0.08)}) \quad \{\text{shade-intolerant}\} \quad (20)$$

where:

$$L = I e^{-kZ} \quad (21)$$

$$\eta() = \frac{4(D - D_{\min})(D_{\max} - D)}{(D_{\max} - D_{\min})^2} \quad (22)$$

$$S() = 1 - A/\theta \quad (23)$$

Eq. (17) 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 Eq. (1). The function  $G$  represents a growth rate equation for each species under optimal conditions, depending on a solar energy utilization factor ( $\sigma$ ), 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 ( $Z$ )). The function  $\eta$  accounts for the effect of temperature on photosynthetic rates, and depends on the number of growing degree-days ( $D$ ) and species specific minimum and maximum values of  $D$  for which growth is possible. Lastly,  $S$  is a dynamic soil quality index dependent on total basal area ( $A$ ) on the plot and maximum basal area ( $\theta$ ) under optimal growing conditions.

Stochastic dynamics of stand growth enter the model through stem birth and death subroutines. Each year, individual trees competing for light become established on the forest floor, grow, or

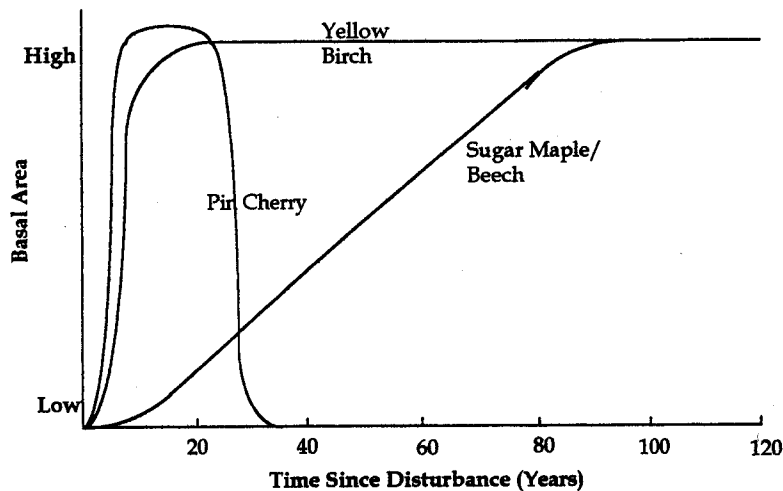


Fig. 3. Northern hardwood succession following clear-cut.

die. Species characteristics and chance determine the dynamics of these birth–growth–death cycles. New saplings randomly enter the plot within limits imposed by their relative shade tolerance and degree-day and soil moisture requirements. 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. Given this stochasticity, simulation data vary widely with each model run.<sup>3</sup>

### 3.2. 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 Fig. 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 run-off and limiting soil and nutrient loss (Marks, 1974). However, their initial density will also influence stand biomass accumulation and growth of commercial species (Wilson and Jenson, 1954; Marquis, 1969; Mou et al., 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 (1998) 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 with a Kimmins' ecological rotation). Rotations at 60-year intervals (closer to a Faustmann economic rotation) result in increasing pioneer species densities toward a carrying capacity asymptote.

<sup>3</sup> Data specific to defining equations in the remainder of this section can be obtained from the authors, and are based on ten runs (ten 100 m<sup>2</sup> plots). This builds an approximately 1/4 acre plot, which is subsequently expanded to a full acre by assuming each tree represents four trees per acre.

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 Fig. 2. The following ordinary least squares model was estimated to capture the hypothesis of a rotation-dependent ecological impact function proposed in Eq. (5). Estimation is based on data from the soil seed bank dynamic modeling results of Tierney and Fahey (1998). Ecological assumptions and research results are reported in Erickson et al. (1997).

$$PS = f(T_{i-1}, i-1) = 100 = \Omega \quad (24)$$

for  $T_i > 140$  years

$$PS = 7342.27 - 89.18 T_{i-1} + 0.25 T_{i-1}^2 + 550(i-1) \quad (25)$$

for  $T_i \leq 140$  years<sup>4</sup>

### 3.3. Multiproduct, stochastic quality model

The third model component converts biomass 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. Stand profit is represented as<sup>5</sup>:

$$\Pi(t, PS) = \left\{ \sum_{S=1}^9 \sum_{C=1}^6 Q_{S,C}[d, M, PS] \right\} \cdot \mathbf{P}_t \quad (26)$$

Profit [ $\pi(t, PS)$ ] is defined at a year following a clear-cut and before the next ( $t = 0, 1, 2, \dots, T$ ), given initial pioneer species density (PS). Pioneer species density influences profitability through in-

roducing significant competition for light and other resources in the JABOWA model during early stand development. As in Eq. (1), total stand profit (US\$/acre) is the product of a price matrix ( $\mathbf{P}_t$ ) and merchantable volume ( $Q$ ) for eight commercial species ( $S = 1-8$ ) and a non-commercial species group ( $S = 9$ ) in each product category ( $C = 1-6$ ). Product categories are comprised of grade 1-3 timber ( $C = 1-3$ ), below grade sawtimber ( $C = 4$ ), and hardwood ( $C = 5$ ) and softwood ( $C = 6$ ) pulp. To assign quality classes, a random number is generated and assigned to each stem and compared with class probability limits as estimated by a generalized logistic regression (GLR) model developed by Yaussy (1993). The GLR procedure, parameters, and an example are described in Erickson et al. (1997). 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 Eq. (25) based on the previous period's rotation length ( $T_{i-1}$ ) and number ( $i-1$ ). PS influences diameter growth through the dynamics of the forest growth simulator, as well as 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 Erickson et al. (1997).

### 3.4. 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 stems per 100 m<sup>2</sup>. Volume within each species, product class, and year was then converted to profit by multiplying a net price matrix of 1995 stumpage 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.

<sup>4</sup> All parameters are significant at  $\alpha = 0.10$ ;  $R^2 = 0.98$ ;  $F = 65.05$ .

<sup>5</sup> The timber/pulpwood component of the model was programmed in Visual Basic for Microsoft Excel Macros. A 19-page appendix including the code is available from the authors. 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.



Table 1  
Initial sawtimber stumpage and pulpwood prices ( $P_0$ )<sup>a</sup>

Species	Below grade	Grade 3	Grade 2	Grade 1	Pulp
	(US\$/thousand board feet)				(US\$/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
Non-commercial	–	–	–	–	7

<sup>a</sup> 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.

This specification results in a  $264 \times 6$  explanatory variable matrix. The following cubic model was fitted<sup>6</sup>:

$$\pi(t, PS) = (\beta_1 + \alpha_1 PS)t + (\beta_2 + \alpha_2 PS^2)t^2 + (\beta_3 + \alpha_3 PS)t^3 \quad (27)$$

$$\begin{aligned} \pi(t, PS) &= (7.718 - 0.0025PS)t \\ &+ (0.219 + 1.52 \times 10^{-9}PS^2)t^2 \\ &- (0.00082 + 1.40 \times 10^{-8}PS)t^3. \end{aligned} \quad (28)$$

Fig. 4 plots  $\pi()$  at some illustrative PS values. Here  $\pi()$  represents stand profit at 1995 prices. Price growth is taken up separately in Section 3.5.

### 3.5. Price growth ( $P$ )

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

<sup>6</sup> Assessment:  $\alpha_1$ ,  $\beta_2$ ,  $\alpha_2$ , and  $\beta_3$  all significant at  $\alpha < 0.005$ ;  $\beta_1$  and  $\alpha_3$  significant at  $\alpha = 0.073$  and  $0.209$ , respectively;  $R^2 = 0.58$ ;  $F = 59.19$ .

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 foot restrictions on removals in the Northwestern United States, 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, Fig. 5 plots a representative model run. Here prices are assumed

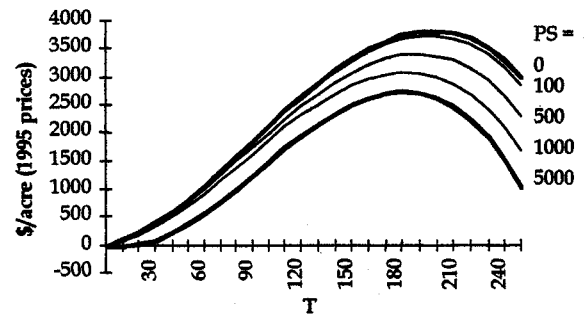


Fig. 4.  $\pi(T, PS)$  at five initial pioneer species (PS) densities.

