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Estimating Economic Gains for Landowners Due to Time-Dependent Changes in Biotechnology

John E. Wagner and Thomas P. Holmes

ABSTRACT. This paper presents a model for examining the economic value of biotechnological research given time-dependent changes in biotechnology. Previous papers examined this issue assuming a time-neutral change in biotechnology. However, when analyzing the genetic improvements of increasing a tree's resistance to a pathogen, this assumption is untenable. We derive analytical expressions for the optimal rotation age given non-constant changes in biotechnology. Our model is then implemented using (1) growth and yield simulations, (2) optimal rotation calculations, and (3) survey data on genetic resistance of slash pine (*Pinus elliottii*) to fusiform rust. Non-parametric regression models are used to estimate the economic gain functions which, for the cases considered, averaged about 1% of forestland value per year. FOR. SCI. 45(2):163–170.

Additional Key Words: Research benefits, economic optimal rotation age, fusiform rust, locally weighted regression (LOESS), bootstrap.

Recently, attention has been given to the consequences of the benefits and costs of genetic improvement in forestry. Approaches used to examine this issue have ranged from econometrics (Newman 1990) to optimal control theory (Bhattacharyya and Lyon 1994). In terms of the mathematical programming and optimal control techniques, change in biotechnology has been defined as time-neutral. A time-neutral change in biotechnology implies a uniform proportional rise in the volume of merchantable timber from all age classes forever (Löfgren 1985 and 1988, Bhattacharyya and Lyon 1994). This implies the shape of the production function remain constant, but rotates upward and to the left. We develop a model of time-dependent changes in biotechnology that allow the production function to simultaneously change its shape and rotate upward.

Bhattacharyya and Lyon (1994) provide an excellent summary of the relevant literature concerning the evaluation of biotechnological progress. They state that the major limitation of the existing research is in the use of comparative statics to analyze technological progress. Since biotechnological progress is dynamic in nature, some type of dynamic model is needed. We propose a two-stage model that accounts for past and future additions to knowledge. In addition, the Bhattacharyya and Lyon (1994) model assumes a time-neutral change in biotechnology.

The economic benefits associated with changes in biotechnology can be estimated as the difference between the maximal present value of growth with and without the biotechnological improvements. Löfgren (1988) estimated upper and lower bounds of economic benefits given a time-neutral change in biotechnology. The advantage of these upper and lower bounds is that an explicit gain function does not have to be estimated. If the costs of research are less (greater) than the estimated lower (upper) bound, then the research project should be undertaken (not be undertaken). Only when the costs fall between the upper and lower bound is the decision indeterminate.

The Löfgren model assumes that: (1) the present value function is convex with respect to genetic gain, (2) optimal rotations for future levels of technology are held constant, and (3) the analyst knows the amount of genetic gain with certainty. This paper develops a model for examining time-dependent changes in biotechnology that relaxes these three assumptions. The paper is divided into two sections. The first section develops an optimal rotation model for time-dependent biotechnological changes and derives an analytic ex-

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pression for the optimal rotation age as a flexible function of biotechnology. The second section is an empirical implementation of the model using survey data collected from suppliers of genetically improved seedlings.

The Optimal Rotation Model

The landowner's overall objective is to determine the optimal adoption of biotechnology such that the value of a fixed asset (land) is maximized. A basic model (without biotechnology changes) can be written as:

$$\begin{aligned} &Max_h V(h) \\ &= \left[PQ(h)_e^{-rh} - C \right] . \left[1 + e^{-rh} + (e^{-rh})^2 + (e^{-rh})^3 + \ldots \right] \quad (1) \\ &= \frac{PQ(h)_e^{-rh} - C}{1 - e^{-rh}} \end{aligned}$$

where

V = land expectation value;

P = price;

$Q(h)$ = quantity which is a function of h;

h = stand age;

e = the natural log;

r = the interest rate (0 c r < 1); and

C = regeneration costs.

The solution is to determine the value of h that maximizes Equation (1); this is given by Equation (2):

$$\begin{aligned} P\frac{dQ(H)}{dH} &= rPQ(H) + r\left[\frac{PQ(H)e^{-rH} - C}{1 - e^{rH}} \right] \quad (2) \\ &= rPQ(H) + rV(H) \end{aligned}$$

where H denotes the optimal stand age and $V(H)$ denotes the optimal land expectation value. Equation (2) states that when the value of the marginal product is equal to stand rent (interest value of the stand) plus land rent (interest value of the land), the stand should be cut (Johansson and Löfgren 1985, Bentley and Teeguarden 1965).

The next step is to determine the effects of biotechnological changes on the solution given by Equation (2). Löfgren (1985 and 1988) has solved the effects of a time-neutral biotechnology change on optimal rotation age. A time-neutral change in biotechnology is defined as the percentage change of current annual increment, Q'/Q, and is independent of biotechnological progress (Löfgren 1985). For example, let $Q(h,\Phi(t))$ define the production function as a function of stand age, h, and biotechnology, $\Phi(t)$, as a function of calendar time, t [see Equation (3) for definitions of h and t]. However, if $Q(h,\Phi(t)) = \alpha Q(h)$, where α denotes a biotechnological change, then Q'/Q is only a function of stand age and is independent of biotechnology (Lofgren 1985). Newman et al. (1985) and Hardie et al. (1984) address similar problems. Newman et al. (1985) solves a similar problem of optimal forest rotations with evolving prices. The price changes are, however, defined as time-neutral. Hardie et al. (1984) describe a model allowing for prices and costs to vary with time, but the production function did not allow for biotechnological changes. If change in biotechnology is time-dependent (i.e., $\Phi(t)$ is variable and Q'/Q is a function of $\Phi(t)$), then the formulation of the optimal rotation problem-as given by Equation (1)-must be modified.

To isolate the effects of a time-dependent change in biotechnology, we hold prices, costs, and interest rates constant. Equation (1) is then modified to reflect a time-dependent change in biotechnology:

$$\begin{aligned} V &= Max_{t_i}\left\{ \sum_{i=1}^{\infty} \left[PQ(t_i - t_{i-1}, \Phi(t_{i-1})) - C \right] e^{-rt_i} \right\} - C \\ &\text{or} \\ V &= Max_{t_i}\left\{ \sum_{i=1}^{\infty} \left[PQ(h_i, \Phi(t_{i-1})) - C \right] e^{-rt_i} \right\} - C \end{aligned} \quad (3)$$

where

h_i = $t_i - t_{i-1}$, the stand age;

t_i, t_{i-1} = calendar time of the ith and $(i-1)$th rotation, respectively;

$Q(h_i,\Phi(t_{i-1}))$ = the harvest quantity as a function of stand age of the ith rotation, h_i, and biotechnology for the regenerated stand, $\Phi(t_{i-1})$ in calendar time t_{i-1}; and

$\Phi(t_{i-1})$ = a time-dependent biotechnology function.

The production function, $Q(h_i,\Phi(t_{i-1}))$, is assumed to be single-valued, continuous, concave, nonnegative, and zero-valued when h_i equals zero. In addition, $\Phi(t)$ is assumed to be continuous with $\Phi(t_{i+1}) \geq \Phi(t_i)$ and $\Phi(t_i)$ converges to a steady state condition; the best genetic gain that can be achieved is 100% resistance to insects and diseases.[1] Consequently, $Q(h_i,\Phi(t_{i-1}))$ would converge to some steady state production function at t_s, $Q(h_s,\Phi(t_s))$, ceteris paribus. Finally, in the theoretical model, we assume the landowner's knowledge concerning $\Phi(t)$ is correct for current and future rotations. Therefore, Equation (3) can be rewritten as:

$$\begin{aligned} V = &Max_{t_i}\left\{ \sum_{i=1}^{k} \left[PQ(h_i, \Phi(t_{i-1})) - C \right] e^{-rt_i} \right\} \\ &+ Max_{t_i}\left\{ \sum_{i=k+1}^{\infty} \left[PQ(h_i, \Phi(t_s)) - C \right] e^{-rt_i} \right\} - C \end{aligned} \quad (4)$$

with

$$t_k \leq t_s < t_{k+1}.$$

[1] Löfgren (1985 and 1988) also address this problem by following a multiplicative time-neutral change in biotechnology with a limit on the potential genetic gain.

The second term of Equation (4) defines the steady state condition as a geometric series. Due to the additive nature of Equation (4), each part can be maximized separately:*

$$V = Max_{t}\left\{\sum_{i=1}^{k}\left[PQ(h_i,\Phi(t_{i-1}))-C\right]e^{-rt_i}\right\}+S(H_S)e^{-rt_k} - C$$

with

$$S(H_S) = Max_{h_s}\left[\frac{PQ(h_S,\Phi(t_S))-C}{e^{rh_S}-1}\right] \quad (5)$$

To determine the optimal calendar time and the stand age of the ith rotation, we solved for the first-order condition of V, given by Equation (5), with respect to t_i:

$$\begin{aligned}\frac{\partial V}{\partial t_i} &= -r\left[PQ(h_i,\Phi(t_{i-1}))-C\right]e^{-rt_i}\\ &+\left[P\frac{\partial Q(h_i,\Phi(t_{i-1}))}{\partial t_i}\right]e^{-rt_i}\\ &+\left[P\frac{\partial Q(h_{i+1},\Phi(t_i))}{\partial t_i}\right]e^{-rt_{i+1}}\\ &+\left[P\frac{\partial Q(h_{i+1}\Phi(t_i))}{\partial\Phi(t_i)}\frac{\partial\Phi(t_i)}{\partial t_i}\right]e^{-rt_{i+1}}\\ &=0\end{aligned} \quad (6)$$

for $t_i < t_k$, and

$$\begin{aligned}\frac{\partial V}{\partial t_k} &= -r\left[PQ(h_k,\Phi(t_{k-1}))-C\right]e^{-rt_k}\\ &+\left[P\frac{\partial Q(h_k,\Phi(t_{k-1}))}{\partial t_k}\right]e^{-rt_k}\\ &-rS(H_S)e^{-rt_k}\\ &=o\end{aligned} \quad (7)$$

for $t_i = t_k$. Equations (6) and (7) can be simplified as:

$$\begin{aligned}P\frac{\partial Q(h_i,\Phi(t_{i-1}))}{\partial t_i} &= r\left[PQ(h_i\Phi(t_{i-1}))-C\right]\\ &-P\left[\frac{\partial Q(h_{i+1},\Phi(t_i))}{\partial t_i}+\frac{\partial Q(h_{i+1},\Phi(t_i))}{\partial\Phi(t_i)}e^{-rh_{i+1}}\right]\end{aligned} \quad (8)$$

$$P\frac{\partial Q(h_k,\Phi(t_{k-1}))}{\partial t_k} = r\left[PQ(h_k,\Phi(t_{k-1}))-C\right]+rS(H_S) \quad (9)$$

respectively, where

$P[\partial Q(h_i, \Phi(t_{i-1})) / \partial t_i] =$
the marginal value product gained from letting the trees grow given the biotechnology at the time the stand was regenerated, t_{i-1};

$r[PQ(h_i,\Phi(t_{i-1})) - Cl =$
the opportunity costs of the net cash flow foregone (harvest revenue minus regeneration costs of the next stand) by not harvesting in period t_i;

$rS(H_s) =$
the opportunity cost of delaying the net discounted cash flow from the steady state condition; and

$P\{[\partial Q(h_{i+1},\Phi(t_i))/\partial t_i][\partial Q(h_{i+1},\Phi(t_i))/\partial\Phi(t_i)][\partial\Phi(t_i)/\partial t_i$
= the marginal value product of putting off regenerating the $i + 1$ rotation (i.e., this denotes a movement along the production function given the biotechnology at t_i) plus the marginal value product of putting off using the biotechnology associated with the $i + 1$ rotation (i.e., this denotes the value of a shift in the production function given the biotechnology at t_i).

The second term on the right-hand side of Equation (8) either increases or decreases the marginal cost of not harvesting the existing stand. This depends on the signs and magnitudes of

$$[\partial Q(h_{i+1},\Phi(t_i))/\partial t_i]$$

and

$$[\partial Q(h_{i+1},\Phi(t_i))/\partial\Phi(t_i)][\partial\Phi(t_i)/\partial t_i 1$$

Increasing (decreasing) the stand age of the existing stand, h_i, will imply a decrease (increase) of the stand age of the next stand, h_{i+1}, causing a decrease (increase) in volume, $Q(h_{i+1},\Phi(t_i))$, ceteris paribus; therefore,

$$[\partial Q(h_{i+1},\Phi(t_i))/\partial t_i] < (>)\ 0.$$

We assume that

$$[\partial\Phi(t_i)/\partial t_i] \geq 0$$

which would imply that

$$[\partial Q(h_{i+1},\Phi(t_i))/\partial\Phi(t_i)] \geq 0$$

therefore,

$$[\partial Q(h_{i+1},\Phi(t_i))/\partial\Phi(t_i)][\partial\Phi(t_i)/\partial t_i] \geq 0$$

However, Equations (8) and (9) imply that optimal

$$T_i = T[P,C,r,Q(H_{i+1},\Phi(T_i)),Q(H_i,\Phi(T_{i-1}))]$$

and optimal $H_i = T_i - T_{i-1}$, for all $T_i \leq T_k$.[3]

2 We followed the technique used by Hardie et al. (1984) for decomposing the model into two stages, one defining the steady state-Equation (4)— and rewriting it in Equation (5).

3 As can be seen from Equations (8) or (9), numerical procedures would be required to solve for the optimal t_i's and h_i's empirically, denoted as T_i and H_i, respectively.

Given the optimal values for T and H, Equation (5) can be expressed as:

$$V(\Phi(T)) = \sum_{i=1}^{k}\left[PQ(H_i,\Phi(T_{i-1})) - C\right]e^{-rT_i} + S(H_S)e^{-rT_k} - C \quad (10)$$

where the optimal land expectation value, $V(\Phi(T))$, is a function of biotechnology.

Genetic gain for tree crop resistance to pathogens is largely based on the process of selecting desirable tree attributes (i.e. resistance) in the field, harvesting seeds, and propagating them in nurseries. Given this process of biotechnological change associated with increases in disease resistance, it is likely that V with respect to $\Phi(T_i)$ will have an arc that is convex (early in the research program when desirable attributes are relatively easy to isolate) followed by an arc that is concave as gains become more difficult to attain. If selection operates by reducing infection from less virulent strains of a pathogen, more virulent strains may persist, evolve, and ultimately counter earlier genetic gains. Nonetheless, the described processes are clearly time-dependent.

We can use the optimal condition described in Equation (10) to determine if V is convex or concave with respect to $\Phi(T_i)$. If V is convex in $\Phi(T_i)$ for $T_i < T_s$, then $\partial^2 V / \partial\Phi(T_i)^2 \geq 0$ and for strict convexity $\partial^2 V/\partial\Phi(T_i)^2 > 0$. If V is concave in $\Phi(T_i)$ for $T_i < T_s$, then $\partial^2 V/\partial\Phi(T_i)^2 \leq 0$ and for strict concavity $\partial^2 V/\partial\Phi(T_i)^2 < 0$. To determine the convexity or concavity of V in Equation (10) with respect to $\Phi(T_i)$, we must first evaluate $\partial V/\partial(T_i)$, which can be simplified by using the Envelope Theorem (Varian 1984):

$$\frac{\partial V}{\partial\Phi(T_i)} = Pe^{-rT_{i+1}}\left[\frac{\partial Q(H_{i+1},\Phi(T_i))}{\partial\Phi(T_i)}\right] \quad (11)$$

The second derivative, which can also be simplified by using the Envelope Theorem, is given by Equation (12):

$$\begin{aligned}\frac{\partial^2 V}{\partial\Phi(T_i)^2} &= Pe^{-rT_{i+1}}\frac{\partial T_{i+1}}{\partial\Phi(T_i)}\left[\frac{\partial Q(H_{i+1},\Phi(T_i))}{\partial\Phi(T_i)}\right]_I \\ &+ Pe^{-rT_{i+1}}\left[\frac{\partial^2 Q(H_{i+1},\Phi(T_i))}{\partial\Phi(T_i)^2}\right]_I \\ &= Pe^{-rT_{i+1}}\left[\frac{\partial^2 Q(H_{i+1},\Phi(T_i))}{\partial\Phi(T_i)^2}\right]\end{aligned} \quad (12)$$

The sign of $\partial^2 Q(H_{i+1},\Phi(T_i))/\partial\Phi(T_i)^2$ is indeterminate. Nevertheless, Equation (12) shows that V is convex in $\Phi(T_i)$ as long as the gains in the harvestable quantity realized between calendar time T_i and T_{i+1} due to biotechnological change are increasing at an increasing rate. At the inflection point, V will become concave, or the gains in the harvestable quantity realized due to biotechnological change are increasing at a decreasing rate.

We can use a Taylor Series expansion to estimate the economic value of the genetic gain.[4] If V is convex in $\Phi(T_i)$, then Equation (13) can be used to estimate the economic value of the genetic gain:

$$\begin{aligned}V(\Phi(T_{i+1})) - V(\Phi(T_i)) &\geq \left(\frac{\partial V}{\partial\Phi(T_i)}\right)\cdot(\Phi(T_{i+1}) - \Phi(T_i)) \\ &= \left(Pe^{-rT_{i+1}}\left[\frac{\partial Q(H_{i+1}\Phi(T_i))}{\partial\Phi(T_i)}\right]\right)\cdot(\Phi(T_{i+1}) - \Phi(T_i))\end{aligned} \quad (13)$$

where $V(\Phi(T_{i+1})) - V(\Phi(T_i))$ denotes the actual economic value of the genetic gain. The left-hand-side of Equation (13) denotes the optimal land expectation values given $\Phi(T_{i+1})$ and $\Phi(T_i)$ as defined by Equation (10), respectively. The term $\partial V/\partial\Phi(T_i)$ in Equation (13) is the estimated slope (i.e., the tangent) of the present value curve with respect to biotechnology. Conversely, if V is concave in $\Phi(T_i)$, this would imply changing the inequality in Equation (13) to a less than or equal to.

The relationship defined by Equation (13) is similar in form to the lower bound defined by Löfgren (1988). There are four differences. First, Lbfgren's lower bound depends on land expectation value being strictly convex with respect to the time-neutral change in biotechnology. As seen by Equation (12), $V(\Phi(T_i))$ maybe either convex or concave. Second, Lofgren's lower bound is defined for a production function whose shape remains constant and rotates upward. However, $V(\Phi(T_i))$ depends on a production function that can both change shape and/or rotate upward. Third, Lofgren's lower bound is defined given that the genetic progress is known with certainty. Finally, Lofgren's lower bound is defined holding the optimal rotation age constant. As seen by Equation (13), optimal rotation age is allowed to vary over time as seen by Equation (10).

In Equation (13), more wood is (perhaps nonoptimally) produced under the new technology. Because growth and yield models for southern pine stands are available that include fusiform infection parameters, we decided to model $V(\Phi(T))$ explicitly by solving Equation (10) for different levels of fusiform infection. By observing the change in rotation age we are able to estimate directly the change in $V(\Phi(T))$ over time and are not limited to using the tangent estimate. In addition, we were able to estimate statistical upper and lower bounds on the economic value of the genetic gain.

Empirical Analysis

Fusiform rust *(Cronartium quercuum* Berk Miyabe ex Shirai f. sp. *fusiforme)* has long been recognized as the most

[4] Equation (13) defines a first-degree Taylor series polynomial. The larger the degree of the Taylor series polynomial, the better the estimate of the economic value of the genetic gain (Larson et al. 1994). However, the first-degree Taylor series allows a better comparison between our work and Löfgren (1988). In the empirical analysis that follows, we do not limit the estimation of the economic value of the genetic gain to a first-degree Taylor series polynomial.

damaging disease of southern pine forests. The disease occurs in slash pine (*Pinus elliottii*) and loblolly pine (*Pinus taeda*) plantations across the heart of the South (Borders and Bailey 1986, Anderson et al. 1986). Galls on seedlings can cause early mortality. On survivors, areas with cankers are subject to breakage and are unsuitable for solidwood products (Geron and Hafley 1988 and Holley and Veal 1977). The most promising means for reducing damage from this pathogen has been to plant genetically resistant seedlings.

For about 3 decades, the USDA Forest Service, academic institutions, and forest industry have invested in extensive research efforts designed to improve resistance of planted growing stock to fusiform infection. These efforts have included characterizing the basic biology of the disease; identifying resistant genotypes; breeding rust-resistance into orchards and thus planting stock; and developing standardized methods for screening seedlings for rust susceptibility. The fusiform rust research efforts appear to have achieved considerable success-increasing amounts of planted stock have improved genetic resistance, and indeed infection rates in planted southern pine stands appeared to wane in the 1980s.

Data

An extensive study on the evaluation of fusiform rust research (Pye et al. 1997) provided the data used in the empirical analysis to estimate $\Phi(T)$ and $V(\Phi T)$). Merchantable yield functions were computed for ten levels of initial fusiform rust infection given three site classes, two species, and four stumpage utilization levels-poor, pulp, sawtimber, and full. The initial yields for slash pine were estimated using the University of Georgia GAPPS model (Burgan et al. 1989) and for loblolly pine using the North Carolina State University Loblolly Yield Model (Hafley and Smith 1989).[5] The computer routines for estimating the merchantable yields given the four utilization levels were developed by Pye et al. (1997). In addition, the level of biotechnology at any point in time can not be stated with certainty. During any particular year, seedlings from different seed orchards represent different vintages that are being planted. Consequently, to assess the estimated gains associated with the different vintages, a survey of both loblolly and slash pine seed and seedling producers was undertaken. Producers were surveyed for estimates of historic and expected production and gain in fusiform resistance for seedlings they produced for 5 yr increments between 1970 and 2020 (Pye et al. 1997). Gain was defined in the questionnaire as "the relative reduction in your infection rates which would have occurred had nonresistant seedlings been planted instead".[6] Surveys were returned from 14 producers that provided 154 total observations on genetic gain (see Table 1).

Table 1. Estimated gain in rust resistance for slash pine.[1]

Date	Mean gain % (SD)
1970	1 .O (0.029)
1975	5.0 (0.106)
1980	14.0 (0.168)
1985	27.0 (0.179)
1990	39.0 (0.180)
1995	43.0 (0.154)
2000	47.0 (0.167)
2005	54.0 (0.186)
2010	60.0 (0.176)
2015	61.0 (0.190)
2020	64.0 (0.190)

1 These data are taken from a study by Pye et al. (1997).

Stumpage prices were computed using 1992 average prices for the southern states and sub-state regions where fusiform rust is prevalent. Product prices were weighted by removal rates to compute a weighted average price per cubic foot for pulpwood, chip-n-saw and sawtimber. The following prices were used in the analysis: (1) pulpwood = \$1 1.31/m^3, (2) chip-n-saw = \$23.32/m^3, and average sawtimber = \$33.21/m^3 (sawtimber prices were adjusted to reflect value as a function of log length as determined in the merchandising routine). Regeneration costs were based on cost trends published by Belli et al. (1993). With seedling costs included, regeneration costs were \$343.33/ha for low quality sites and \$486.59/ha for high quality sites.

For the empirical analysis, we chose the following initial stand characteristics: (1) the species selected was slash pine; (2) the site classes selected were low (site index = 15.24 mat stand age 25) and high (site index = 21.34 m); (3) the initial fusiform rust infection level was 70% in 1970; and (4) the stumpage utilization level was defined as sawtimber. The primary reason for this choice was the reported gains in resistance for slash pine; Table 1 shows that rapid gains were attained during the 1980s. Gains were anticipated to be relatively strong through the end of the century but then taper off after the millennium.

Robust Locally Weighted Regression

Because of the generality of our optimization model with respect to changes in biotechnology, we did not want to arbitrarily impose a functional form on the relationship between V and $\Phi(T_i)$. Our modeling requirements were for a flexible, smooth, and continuous function. The theory and methods of nonparametric smoothing techniques have advanced rapidly over the past decade (Härdle 1990), and we chose a nonparametric regression technique that both smoothes the data and is robust to potential outliers. The locally weighted regression function (LOESS) compromises between a global assumption of functional form and purely local averaging by using a weighted least squares algorithm (Cleveland 1979 and Cleveland et al. 1988).[7] The smoothing procedure accommodates data of the form:

$$y_i = g(x_i) + \varepsilon_i \qquad (14)$$

where g is a smooth function and the ε_i's arerandom variables with mean 0 and a constant scale.

5 The location of cankers or galls on the bole or stem of the surviving trees affect how trees can be utilized. A canker or gall on the bole reduces scaled volume that can be sawn into dimension lumber. The yield tables and yield functions are programmed to reflect this.

6 Gains in resistance are expressed in percentage terms, where 0% gain indicates no improvement in resistance over nonresistance-selected stock, and 100% indicates total immunity to infection. Thus, if genetically resistant seedlings with a 50% gain in resistance are planted in an area that normally experiences 30% infection rates [0.30(1.00 – 0.50)* 100 =] 15% of the resistant seedlings should become infected.

7 The LOESS algorithm in Mathcad (Mathsoft 1995) was used to fit the models.

Local regression refers to a "k-nearest-neighbor" (*k-NN*) type neighborhood. The *k-NN's* are specified by the user as a proportion α of the n data points to be used at each point of the estimation. For each value of x_i, the n points are ranked according to the absolute value of their distance from x_i, and the $k = \alpha n$ nearest points are identified. Let $d = |x_i - x_k|$ be the (maximum) distance from x_i to the kth nearest neighbor x_k. A weighted least-squares linear regression is fit to the αn points. The weights $w_m(x_i)$ decrease as the distance from x_i increases:

$$w_m(x_i) = W(d^{-1}(x_m - x_i)) \quad (15)$$

where d^{-1} is the inverse of d, and $(x_m - x_i)$ is the distance of the mth observation from x_i, $m = 1, \ldots, k$, and Wis the tri-cube weight function $W(u) = (1 - u^3)^3$. Thus, points close to (far from) x_i play a large (small) role in the determination of the fitted y_i values. Increasing the neighborhood of points influencing the fitted values increases the overall smoothness of the smoothed points.

Fitted values for each target value are estimated using a second-order polynomial for the defined neighborhood using weighted least squares.[8] Thus, the $\beta(x_i)$'s are chosen to minimize[9]

$$\Sigma_m w_m(x_i)(y_m - \beta_0 - \beta_1 x_m)^2 \quad (16)$$

Fitted values for (y_i, x_i) are computed from the β vector that minimizes Equation (16), and regression residuals are computed. The model is "robustified" by using computed residuals to reweight values in the neighborhood of the target values. New weighted least square values are estimated, and the procedure reiterated to estimate robust locally weighted regression fitted values. In general, outliers have small robustness weights and do not play a large role in the estimation of fitted values.

Bootstrap Confidence Intervals

The local nature of the LOESS algorithm produces estimates that have small bias but are highly variable. Value function estimates are based on LOESS fitted values and, consequently, are also highly variable. To evaluate variation in the statistic of interest (the increase in stand value with respect to changes in biotechnology), we use the bootstrap technique.

Bootstrapping involves resampling the data with replacement many times to generate an empirical estimate of the entire sampling distribution of a statistic (Efron and Tibshirani 1993 and Mooney and Duval 1993). Similarly, a parametric bootstrap resamples from a parametric description of the data to estimate the sampling distribution of a statistic. For our analysis, we use a parametric bootstrap technique to compute estimates of mean gain and 95% confidence intervals using the following steps:

1. Compute the mean and standard deviation of genetic gain for each point in time using the survey data.
2. Make random draws from normal gain distributions described in step 1 to create a bootstrap data set b.
3. Use the bootstrap data b in step 2 to estimate fitted values of gain Φ^b_t versus time t using the LOESS procedure.
4. Given the level of initial infection I at time t (I^b_t), compute infection at time $t + 1$ (I^b_{t+1}) using Φ^b_t.
5. Using I^b_t and I^b_{t+1}, estimate V^b_t and V^b_{t+1} using LOESS fitted values relating infection and optimal economic value.
6. Subtract $(V^b_{t+1}) - (V^b_t)$ to obtain a bootstrap estimate of the economic value of genetic gain.
7. Repeat steps 2 through 6 "B" times. For this study, the number of bootstrap replications $B = 100$.

Mean gain was estimated as the mean of the vector of bootstrap values. Confidence intervals were estimated using the percentile method (Efron and Tibshirani 1993). That is, for the ordered vector of bootstrap replications $(V^b_{t+1}) - (V^b_t)$, the α percent confidence intervals are the values of (V^b_{t+1})-(V^b_t) between the $B^*\alpha/2$ replication and the $B^*(1 - \alpha/2)$ replication. For example, if $B = 100$, then $\alpha = 10\%$ corresponds to the values between the 5th and 95th ordered observations. The study by Pye et al. (1997) provided estimates of $V(\Phi(T_i))$ used in step 5 above and reported in Table 2.

Results

We estimated the mean and 90% confidence bands for $V(\Phi(T_i)) - V(\Phi(T_{i+1}))$ for T_i equal to 1991 and T_{i+1} equal to 1996 (Table 3). We chose 1991 as the starting point because it was the closest to a known historic data point. Given the nature of the research, a 5 yr interval was a tenable assumption. As shown in Table 3, the estimated mean percent gain in rust resistance, $\Phi(1991) = 36.7$ and $\Phi(1996) = 44.4$, translated into an initial infection level at stand age 5 of 44.3% and 38.9%. respectively. The average gain in economic value per hectare due to a reduction in infection over this 5 yr period

Table 2. Land Expectation Value (LEV) for slash pine given an initial percent infection.[1]

LEV[2] ($/ha)		Initial infection
Low SI	High SI	level at age 5 (%)
422.37	2516.93	90
555.75	2892.37	80
721.24	3178.89	70
837.33	3522.22	60
995.41	3853.20	50
1094.21	4181.71	40
1207.83	4542.33	30
1331.33	4846.14	20
1449.89	5179.59	10
1341.21	4520.10	0

1 These data are taken from a study by Pye et al. (1997).
2 1 ha = 2.47 acr. Low Site Index = 15.24 m at stand age 25 and High Site Index = 21.34 m at stand age 25.

8 As α increases, the tit becomes smoother. Because we use quadratic fitting, as $\alpha \to 1$, the fitted values $g(x_i)$ tend to a quadratic function. The goal is to choose α as large as possible to minimize the variability in the fitted values without distorting the pattern in the data (Cleveland 1979).

9 Note that (βx_i) values are estimated for each target x_i.

was $67/ha on low quality sites and $190/ha on high quality sites; this translates in to approximately 1.00% annual gain in land value on low and high quality sites. The lower and upper bound estimates of gain in economic value were $10/ha and $130/ha for low quality sites (which translate into annual gains in land value of 0.19% and 2.59%) and $27/ha and $372/ha for high quality sites (which translates into annual gains in land value of 0.13% and 1.90%).

The estimated derivatives of the value function showed that $V(\Phi(1991))$ was concave. In fact, diminishing marginal gains were observed throughout the 1990s as would be expected in a mature research program.[10] Our results are therefore more conservative than they would have been if we used the exponentially improving biotechnology model discussed by Liifgren.[11] Löfgren's method is not affected in a major way, however, by the assumption that rotation ages are held constant. For our analysis, rotation ages varied between 24 and 25 years for low quality sites and between 23 and 24 years for high quality sites.

Summary

This paper presented a model for examining the economic value to the landowner of biotechnological research given time-dependent changes in biotechnology. Previous papers examined this issue assuming a time-neutral change in biotechnology. A time-neutral change in biotechnology implies a constant proportional rise in the volume of merchantable timber from all age classes forever. This assertion was not tenable when dealing with genetic improvements such as increases in a tree's resistance to a pathogen. In this case, the best genetic gain that can be achieved is 100% resistance and the change in biotechnology would be time-dependent.

We derived analytical expressions for the economic gains due to biotechnological research when rotation ages optimally adjust. The necessary conditions given by Equations (6) through (9) determine the optimal timing of adopting new biotechnology by comparing the additional benefits of letting the existing stand grow given the old biotechnology versus the opportunity cost of cutting the stand and then planting using newer biotechnology. Examining land expectation values (LEVs) using a comparative static "with versus without" analysis will demonstrate whether or not LEV is increasing by adopting the newer biotechnology; however, it is not known if the timing of the adoption is optimal or maximizes the value of the land asset. The theoretical model presented here solves this more general problem by dynamically linking rotation ages. However, we note that in our empirical model the dynamic linkages had little influence on optimal timing (generally, rotation ages changed by less than 1 yr). Therefore, for most users of this model, comparative static analysis will yield quicker and reasonably precise empirical estimates.

The analytical model was implemented using growth and yield simulations, a merchandising simulator, and survey data of historical and anticipated gains. Nonparametric regression techniques were used to estimate flexible relationships between genetic gain, fusiform infection, and economic value. Confidence intervals were estimated using the bootstrap technique. We found that the economic value of genetic progress due to fusiform rust research translated into about a 1% increase in forestland value per year during the early 1990s for slash pine sites.

The advantage of our approach is that it provides the analyst with a very general theoretical and empirical model for making precise estimates of the economic gain for many different time-paths of genetic progress. Empirical methodology was introduced for estimating confidence intervals to reflect uncertainty regarding historical and anticipated rates of biotechnological progress. We note that confidence intervals get much wider after the year 2000 and, in fact, include zero. This is due to the combined effect of increasing uncertainty in the gain estimates provided by survey respondents and a negative second derivative of economic gain with respect to time. It is apparently becoming increasingly difficult for seed and seedling suppliers to identify and select improved genetic stock given the significant gains that have already been made.

Because rotation ages are relatively short for the species considered here, the economic benefits of genetic improvements are realized quickly relative to slower growing species with longer rotation ages. To evaluate the sensitivity of economic gains to changes in the biotechnology, we computed the "value elasticity of genetic progress," which is defined as the percentage change in the value of forestland resulting from the percentage change in Φ. For slow growing timber species in Sweden (*Pinus sylvestris* and *Picea abies*) Löfgren reports a value elasticity of about 0.011. For slash pine grown in the study area, the value elasticity was 0.30 for stands with low site index and 0.22 for stands with a high site index. These higher elasticity values and consequent quicker payback periods reflect the shorter rotation ages in the South.

The results of this study suggest that rust resistant seeds and seedlings confer economic benefits to timber producers with perfect information regarding fusiform infection rates and the rate of genetic gain. This suggests that an opportunity may exist for seedling producers to charge a premium for resistant stock. However, our results show that the economic gain associated with different vintages of resistant stock are highly variable. Because fusiform rust hazard information and market segregation by vintage are not costless, seedlings of different vintages may not be perfectly targeted to specific sites, and economic gain may be less than our estimated mean levels. Until these various sources of uncertainty are resolved, it is unlikely that a market premium for resistant stock will develop.

The result that the rates of economic gain due to genetic progress are slowing down should not be taken as an indication that the fusiform rust problem is about to be solved once and for all. New, undetected, or especially virulent strains of this pathogen may "reset the clock" with respect to the

[10] The mean economic gain from 1991 to mid-1993 was $116 ($37) on high quality sites (low quality sites); from mid-1993 to 1996 the mean gain was $74 ($30); from 1996 to mid-1998 the mean gain was $62 ($25).

[11] In particular, Löfgren assumed that trees planted at time t will grow according to $g(t) = g(0)e^{at}$ whdre $0 < a < r$ and r is the interest rate.

Table 3. Mean gains and 90% confidence bounds for fusiform rust research benefits.[1]

Gain [$V(\Phi)$]	Genetic gain (%) (Φ)	Infection (%)	Economic value: Low SI	Economic value: High SI
Mean			($)	
T_i = 1991	36.7	44.3	1057	4083
T_{i+1} = 1996	44.4	38.9	1124	4273
Gain	7.7	-5.4	67	190
Lower bound[2]				
T_i = 1991	40.3	41.8	1089	4184
T_{i+1} = 1996	41.4	41.0	1100	4211
Gain	1.1	-0.8	10	27
Upper bound[2]				
T_i = 1991	31.3	48.1	1003	3925
T_{i+1} = 1996	45.7	38.0	1133	4298
Gain	14.4	-10.1	130	372

[1] The initial stand characteristics were: (1) slash pine stand, (2) the initial fusiform rust infection level is 70% in 1970, and (3) the stumpage utilization level was defined as sawtimber. The Low Site Index = 15.24 m at stand age 25 and the High Site Index = 21.34 m at stand age 25.

[2] The lower and upper bounds were computed using B = 100 bootstrap replications.

economic benefits of genetic progress. If a more virulent fusiform rust strain does come along, then research would be needed to maintain the economic gains that are illustrated in Table 3. This situation would not affect the analytical model described by Equations (3) through (13) nor would it alter the methodology used in the empirical analysis. However, the empirical analysis could be used to illustrate the impact on economic gains if a more virulent strain infected the stands given no more fusiform rust research or a continued fusiform rust research program.

Literature Cited

ANDERSON, R.L., J.P. MCCLURE, N.C. COST, AND R.J. UHLER. 1986. Estimating fusiform rust losses in five southeastern states. South. J. App. For. 10:237–240.

BENTLEY, W.R. AND D.E. TEEGUARDEN. 1965. Financial maturity: Atheoretical review. For. Sci. 11(1):76–87.

BELLI, M.L., T.J. STRAKA, M. DUBOIS AND W.F. WATSON. 1993. Costs and cost trends for forestry practices in the South. For. Farm. 29th Man. Ed. 52(3):25-31.

BHATTACHARYYA, A., AND K.S. LYON. 1994. Biotechnical progress in forestry: An optimal control analysis. For. Sci. 40(1):120–141.

BORDERS, B.E., AND R.L. BAILEY. 1986. Fusiform rust prediction models for site-prepared slash and loblolly pine plantations in the southeast. South. J. App. For. 10:145–151.

BURGAN, T.M., R.L. BAILEY, AND J. BROOKS. 1989. Georgia pine plantation simulator, vers. 3.0. Sch. of For. Resour., Univ. of Georgia, Athens, GA.

CLEVELAND, W.S. 1979. Robust locally weighted regression and smoothing scatterplots. J. Am. Stat. Assoc. 74(368):829–836.

CLEVELAND, W.S., S.J. DEVLIN, AND E. GROSSE. 1988. Regression by local fitting-methods, properties, and computational algorithms. J. Econ. 37:87–1 14.

EFRON, B., AND R.J. TIBSHIRANI. 1993. An introduction to the bootstrap. Chapman & Hall, New York.

GERON, CD., AND W.L. HAFLEY. 1988. Impact of fusiform rust on product yields of loblolly pine plantations. South. J. Appl. For. 12(4):226–231.

HAFLEY, W.L., AND W.D. SMITH. 1989. North Carolina State University managed pine plantation growth and yield simulator. North Carolina State Univ. Sch. of For. Resour., Raleigh, NC.

HARDIE, LW., J.N. DABERKOW, AND K.E. MCCONNELL. 1984. A timber harvesting model with variable rotation lengths. For. Sci. 30(2):51 l-523.

HÄRDLE, W. 1990. Applied nonparametric regression. Cambridge University Press, Cambridge.

HOLLEY, D.L., AND M.A. VEAL. 1977. Economic impact of fusiform rust. P. 39-50 *in* Management of fusiform rust in southern pines, Dinus, R.J., and R.A. Schmidt (eds). South. For. Disease and Insect Res. Counc., Gainesville, FL.

JOHANSSON, P-O., AND K-G LÖFGREN. 1985. The economics of forestry and natural resources. Basil Blackwell, Ltd., United Kingdom.

LARSON, R.E., R.P. HOSTETLER, AND B.H. EDWARDS. 1994. Calculus with analytic geometry. D.C. Heath, Lexington MA.

LÖFGREN, K-G. 1985. Effects on the socially optimal rotation period in forestry of biotechnological improvements in the growth function. For. Ecol. Manage. 10(3):233–249.

LÖFGREN, K-G. 1988. On the economic value of genetic progress in forestry. For. Sci. 34(3):708–723.

MATHSOFT. 1995. Mathcad user's guide. Cambridge, MA.

MOONEY, C.Z., AND R.D. DUVAL. 1993. Bootstrapping-a nonparametric approach to statistical inference. Sage Publications, Newbury Park, CA.

NEWMAN, D.H., C.B. GILBERT, AND W.F. HYDE. 1985. The optimal forest rotation with evolving prices. Land Econ. 61(4):347–353.

NEWMAN, D.H. 1990. Shifting southern softwood stumpage supply: Implications for welfare estimation from technical change. For. Sci. 36(3):705–718.

PYE, J.M., J.E. WAGNER, T.P. HOLMES, AM) F.W. CUBBAGE. 1997. Positive returns from investment in fusiform rust research. USDA For. Serv. South. Res. Sta. Res. Pap. SRS-4.

VARIAN, H.R. 1984. Microeconomic analysis. Ed. 2. W.W. Norton, New York.