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Price and Welfare Effects of Catastrophic Forest Damage From Southern Pine Beetle Epidemics

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ABSTRACT. Southern pine beetle *(Dendroctonus frontalis)* epidemics are periodically responsible for catastrophic levels of mortality to southern yellow pine'forests. Traditional forest damage appraisal techniquesdeveloped for site specific economic analysis are theoretically weak since they do not consider aggregate impacts across ecosystems and related markets. Because the traditional model estimates losses only to producers with damaged forests, it provides misleading information from a distributional standpoint by ignoring impacts on producers with undamaged forests and timber consumers. An economic model of timber supply and demand is introduced and used to develop a new technique for estimating short-run market level impacts of catastrophic forest damages. The null hypothesis that catastrophic disruption of forest ecosystem production has no effect on timber markets is tested using intervention analysis and data on the recent Texas-Louisiana epidemic. Parameter estimates are used to compute short-run changes in economic welfare for producers on damaged forests, producers on undamaged forests, and timber consumers. Principal findings are: (1) changes in social welfare resulting from catastrophic damage to standing timber across forest ecosystems requires market-level analysis, and (2) the net change in economic welfare resulting from insect epidemics is unambiguously negative. FOR. Sci. 37(2):500-516.

ADDITIONAL KEY WORDS. Intervention analysis, impact assessment, time series.

THE SOUTHERN PINE BEETLE (hereafter SPB) is a major pest in southern forests. While the SPB is usually active somewhere in its range every year, epidemics occasionally are responsible for catastrophic levels of timber mortality across broad regions of the South (Price and Doggett 1982). Damage appraisals are useful to forest managers and policymakers who require information on the benefits and costs of forest protection to develop and implement efficient damage control programs.

The traditional damage appraisal technique was developed to assist forest managers determine the optimal level of forest protection. The basic method estimates loss as the difference between the present value of the forest resource with and without damage (Davis 1954, Leuschner et al. 1978, Liebhold et al. 1986). The optimal level of control from a forest manager's point of view is found by minimizing the sum of control cost plus value loss (e.g., see Gorte and Gorte 1979, Herrick 1981).

A fundamental theoretical weakness of the traditional damage appraisal model is that it doesn't consider the depressing effect salvaged timber may have on equilibrium market price and therefore it cannot provide an estimate of the change in economic welfare to producers holding undamaged forests and to timber consumers. From society's viewpoint, ignoring the impact of catastrophic forest

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disturbances on the timber market results in potentially misleading policies from a distributional standpoint.

In a recent paper, Perry and Maghembe (1989) argue that evaluation of forest management strategies must rely on analysis of "system-level properties" and that ". . . questions cannot be answered by focusing on individuals; the answers lie in thinking about ecosystems" (p. 124). While their concern with ecosystem concepts goes far beyond the analysis presented here, our analysis is presented in the same spirit. That is, questions regarding the social costs and benefits of various southern yellow pine management regimes requires information on system-level impacts. Our analysis presents an initial method for evaluating market-level impacts (i.e., net social costs) associated with ecosystem-wide insect epidemics.

Until recently, the welfare effects of price variability in forest products markets has received scant attention. The major exception is provided by Boyd and Hyde (1989) who suggest that, given low administration costs, policies that stabilize timber prices result in positive net social gains. Since government participation in public forest management (on national forests) and private forest protection (via forest pest management programs) influences ecosystem structure as well as timber supply and price, examination of the welfare effects of forest management policies is important.

This paper is organized as follows. First, a new model for assessing timber damage from catastrophic events is derived in the context of timber owner and timber buyer behavior. Second, the damage assessment model is aggregated to the market level. Third, a description of the method used to estimate price shocks and resultant welfare change is provided. Fourth, empirical results are presented. Finally, policy implications of the research are discussed.

THEORETICAL CONSIDERATIONS

LANDOWNER BEHAVIOR

We consider that landowners maximize the present value of their forest holdings subject to a set of difference equations that describe how the forest endowment is changed from one period to another. Our theoretical model is simplified by considering a single pest infestation. Following Reed and Emco (1987) we also assume that once a stand is infested, no further growth occurs. The present value function π^u for undamaged forests is defined as

$$\pi^u = \text{Max}(phg - wz) \tag{1}$$

subject to a set of m biotechnology constraints

$$\begin{aligned} x_{t+1,1} &= (h_{t,1} + \ldots + h_{t,m}) \\ x_{t+1,2} &= x_{t,1} - h_{t,1} \ldots \\ x_{t+1,\alpha+1} &= x_{t,\alpha} - h_{t,\alpha} \ldots \\ x_{t+1,m} &= x_{t,m} - h_{t,m} \end{aligned} \tag{2}$$

For forests with damaged stands, the present value function π^d is written

$$\pi^d = \text{Max}(p^d h^d g^d - wz) \tag{3}$$

which is subject to constraint set (2) and a set of $(m - \alpha)$ biotechnology constraints on the damaged portions of the forest

$$
\begin{aligned}
x_{t+1,1} &= (h_{t,1} + \ldots + h_{t,m}) + (h^d_{t,\alpha} + \ldots + h^d_{t,m}) \ldots \\
x^d_{t+1,\alpha} &= \delta(x_{t,\alpha} - h_{t,\alpha}) + (x^d_{t,\alpha} - h^d_{t,\alpha}) \ldots \\
x^d_{t+1,m} &= \delta(x_{t,m} - h^d_{t,m})
\end{aligned}
\tag{4}
$$

Regarding the π^u and π^d functions, $p = (p_1, p_2, \ldots, p_n)$ is a $(1 \times n)$ vector of discounted timber prices for undamaged forests over the planning horizon and p^d is a $(1 \times n)$ vector representing discounted price of timber for damaged forests. The number of acres harvested from undamaged forests is represented by h, and the number of acres harvested from damaged forests is represented by h^d, which represent $(n \times m)$ matrices of acres harvested by year and age class. The growth function for undamaged forests is represented by $g' = (g_1, \ldots, g_m)$ and the growth function for damaged forests is represented by $g^{d\prime} = (g^d_1, g^d_2, \ldots, g^d_m)$, which represent $(m \times 1)$ vectors of vol/ac by age class.

In the constraint set, $x_{t,i}$ represents the number of acres of uninfested timber in year t, age class i and $x^d_{t,i}$ represents the number of acres of infested timber in year t, age class i. The earliest age of pest infestation is represented by α, and the proportion of previously uninfested timber acres infested in year t is represented by δ. Finally, w represents a $(1 \times n)$ vector of discounted input prices and z represents a $(n \times 1)$ vector of nontimber inputs.

For undamaged forests, the optimal cutting program is obtained using Hotelling's lemma to find the gradient of π^u with respect to the anticipated price vector p (Johansson and Lofgren *1985,* p. 129). Given that unexpected forest damage occurs, Hotelling's lemma can be used to find the volume of timber cut from undamaged and damaged forests in year t—find the derivative of π^u and π^d with respect to the appropriate price

$$\partial\pi^u/\partial p_t = h_t g = q^u_t(p_t, w) \tag{5a}$$

$$\partial\pi^d/\partial p^d_t = h^d_t g^d = q^d_t(p^d_t, w, \delta) \tag{5b}$$

where $h_t(h_{t1}, h_{t2}, \ldots, h_{tm})$ is a vector of acres cut by age class from undamaged forests and h^d_t is a similar vector of acres cut by age class from damaged forests. If π^u and π^d are twice differentiable and convex in prices, differentiation of the right-hand side of equations *(5a)* and *(5b)* provides the result that timber supply curves for undamaged and damaged forests slope upwards

$$\partial q^u_t/\partial p_t = \partial^2\pi^u/\partial p^2_t \geq 0 \tag{6a}$$

$$\partial q^d_t/\partial p^d_t = \partial^2\pi^d/\partial p^{d2}_t \geq 0 \tag{6b}$$

From the constraint sets (2) and (4) above, we see that producers holding stands infested by SPB face a set of $(m - \alpha)$ biotechnology constraints not faced by producers with undamaged stands. If we make the simplifying assumptions that (1) older trees are cut first, and (2) older trees are more susceptible to SPB outbreaks, then π^d can be drawn as in Figure 1. The cusp between π^u and π^d represents the price at which SPB infested trees would have been cut even if they had not been infested. At higher prices, the supply curves for undamaged and damaged forests are identical. However, at lower prices, the present value of the optimal cutting plan for damaged forests is less than the present value of undam-

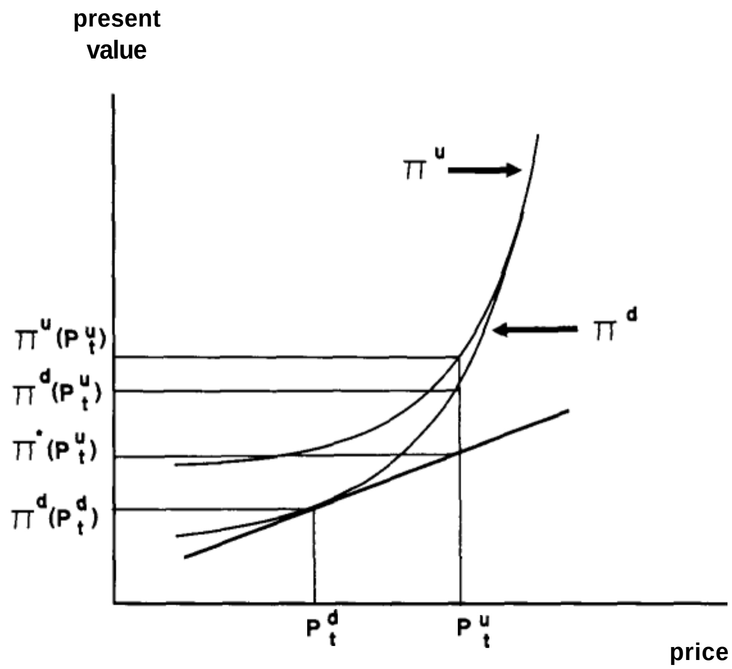

FIGURE 1. Forest damage assessment **using** Hotelling and Le Chatetier principles.

aged forests. Hence, the Le Chatelier-Samuelson relationship (e.g., see Chambers 1988, p. 146–148, 276) suggests that timber supply from damaged forests is less elastic than supply from the forests had they not been infested. Intuitively, if beetle-killed timber isn't cut, it will decay biologically and other undamaged trees may become infested as well—therefore producers with damaged forests are less responsive to price signals than are producers who may profit from delayed harvest. Since the location of the cusp moves up along π^u as the seventy of the outbreak increases, the curvature of π^d (and therefore timber supply) is a function of δ as indicated in Equation (56).

The economic welfare loss to producers with damaged stands can be derived from their timber supply curves. If the anticipated supply curve for timber from potentially infested stands were known, then the net benefit of timber production could be measured as the area above the supply curve and below the anticipated price. This area is referred to as economic rent or *producer surplus* (e.g., see Just et al. 1982). The welfare loss due to a SPB infestation is computed as the difference between economic rent had timber stands been uninfested and the economic rent given that stands were infested and cut prematurely. This difference is what the traditional model seeks to estimate.

The traditional damage appraisal model essentially simulates the π^u and π^d functions using a stand growth model and assumptions about economic parameters. For the policy analyst concerned with system-level damages, the simulation approach is cumbersome because it requires summation over all individuals in the system and strong assumptions about forest structure. Quicker and fairly precise estimates can be derived using what we call second best and lower bound methods. The "cost" of using these methods is that long-run losses are not measured.

While the traditional model appears to be the best method for estimating long-run losses to individual producers, aggregate long-run losses from bark beetle epidemics are not expected to be very large. Since long-run timber supply is usually modeled as a function of standing inventory (e.g., see Adams and Haynes 1980, Binkley and Dykstra 1987), a marginal reduction in inventory from beetle epidemics is not expected to have a large impact on long-run supply. For example, we have calculated that the recent epidemic killed less than 2.5% of the growing stock in Louisiana and less than 1.5% of the growing stock in Texas. If long-run inventory elasticity is assumed to be about 1, then similar percentage changes in long-run supply are anticipated.

The total welfare impact of a SPB mfestation on landowners with damaged stands is the difference between the present value of the optimal unrestricted cutting plan evaluated at vector p^u and the present value of the optimal restricted cutting plan evaluated where the prices on damaged forests drop to vector p^d: $\Delta\pi = \pi^u(p^u) - \pi^d(p^d)$. This difference can be decomposed into two impacts: (1)the loss due to a drop in price, $\pi^u(p^u) - \pi^u(p^d)$, and (2) the loss of flexibility due to a reduction in the production possibility set, $\pi^u(p^d) - \pi^d(p^d)$.

To see the link between welfare changes and timber supply functions, the total welfare impact can be written

$$\Delta\pi = \sum_{t=i}^{r} \int_{p_t^d}^{p_t*} \frac{d\pi^u}{dp_t} dp_t + \sum_{t=i}^{r} [\pi^u(p_t^d) - \pi^d(p_t^d)]$$

$$= \sum_{t=i}^{Y} \int_{p_t^d}^{p_t*} q_t^u(p,w)dp_t + \sum_{t=i}^{Y} [\pi^u(p_t^d) - \pi^d(p_t^d)] \quad (7)$$

where i is the first year of infestation, r is the number of periods over which timber is salvaged, and p_t^* is pre-epidemic equilibrium price. This formulation assumes that pre-epidemic equilibrium price is anticipated to maintain over the epidemic. The first expression on the right-hand side (r.h.s.) of Equation (7) is the sum of changes in producer surpluses associated with a change in price vectors fromp" to p^d. Of course, this amount underestimates the total welfare impact by the second expression. However, the important point is that welfare impacts associated with a change in price can be derived from cutting decisions over the period of impact even though price changes induce shifts in the future cutting program (for an analogous case see Just et al. 1982, p. 338–341).

The second-best method uses mformation contained in the timber salvage supply curve [Equation (6*b*)] to estimate the short-run welfare loss attributable to pest infestations. In particular, we propose measuring short-run welfare loss as the difference between present value of damaged forests had they captured anticipated prices and the present value under revised prices: $\pi^d(p^u) - \pi^d(p^d)$, where

$$\pi^d(p^u) - \pi^d(p^d) = \sum_{t=i}^{Y} \int_{p_t^d}^{p_t^*} q_t^d(p^d, w, \delta)dp_t \quad (8)$$

The second-best measure underestimates total impact by amount $\pi^u(p^u) - \pi^d(p^u)$.

The lower-bound method (Lofgren 1988) is the quickest method for the policy analyst to use, and it provides an even more conservative estimate of damages. Letting the present value function be convex in prices, the following result is a consequence of the fact that a convex function lies everywhere not below its tangent plane (e.g., see Chambers 1988, p. 308):

$$\pi^d(p^u) - \pi^d(p^d) \geq \frac{d\pi^d}{dp}(p^d)(p^u - p^d) \tag{9}$$

The left-hand side of this expression is the difference between the present value of a salvage-cutting program when the price of salvaged timber equals the anticipated price vector and the present value of a salvage cutting program evaluated at the price vector reflecting salvage prices. This is the value estimated by the second-best method. The right-hand side of the expression says that a lower bound estimate of damages can be evaluated as the gradient of the present value function with respect to price (evaluated at vector p^d) times the difference between the price vectors. On an intuitive level, this method provides a lower bound because the amount of timber cut is held constant at the salvage level which is known from the observed cutting program. Since timber producers could conceivably increase present value by cutting more as the price rises, the right hand side (r.h.s.) of Equation (9) is alower bound.

The gradient of interest on the r.h.s. of Equation (9) is simply the volume of timber salvaged from damaged forests when prices are p^d. Thus, the lower bound on the change in present value is simply the volume of timber salvaged times the difference between anticipated and salvaged timber price. The one-period analog is shown in Figure 1, where the tangent to π^d is shown, and the lower bound damage is $\pi^*(p^u{}_t) - \pi^d(p^d{}_t)$, where $\pi^*(p^u{}_t)$ is present value when salvage volume is priced at $p^u{}_t$.

Before examining aggregate market behavior, we turn to a discussion of log demand and examine how salvaged timber and green timber interact in the timber market. The discussion provides us with a means for partitioning market equilibrium timber volume into damaged and undamaged components, and for deriving the implicit relationship between p_t^* and p_t^d. Then, once we have obtained an estimate of the equilibrium price and volume of damaged timber, derivation of the implicit supply of salvaged timber and changes in economic welfare can be made.

Forest Industry Behavior

We are interested in describing the short-run behavior of timber consumers faced with different qualities or grades of timber inputs. Following Constantino and Haley (1988) we assume that the mill's production function is weakly separable with respect to log grades:

$$Y = F[Q(q^u, q^d), l{:}k] \tag{10}$$

where Y is output, Q is the aggregate log input, q^u and q^d are log inputs from undamaged and damaged forests, respectively, l is labor, and k is (fixed) capital. The aggregate input Q can be thought of as a production function that is independent of k and 1. We make the simplifying assumption that the aggregate input is produced by a linear technology

$$Q(q^u, q^d) = a_1 q^u + a_2 q^d \qquad \text{where } a_1 > a_2 \tag{11}$$

Under a linear technology, logs of various qualities are perfect substitutes in production, and the firm will use whichever is cheaper. The associated cost function for the aggregate input takes the form

$$C(p^u, p^d, Y) = Min\left(\frac{p^u}{a_1}, \frac{p^d}{a_2}\right) Y \tag{12}$$

where p^u is the price of undamaged (green) timber. If both qualities of logs are used, the ratio of equilibrium input prices equals the marginal rate of substitution between qualities. Assuming that the marginal physical product of logs from undamaged and damaged forests remains constant over the insect epidemic, we can write the first-order condition for cost minimization as

$$\frac{p^u}{p^d} = \frac{a_1}{a_2} = \kappa > 1 \tag{13}$$

Equation **(13)** provides two useful results. First, the price of timber from damaged forests is linked to the price of green timber from undamaged forests via the ratio of marginal products ($p^d = p^u/\kappa$). This allows us to treat timber price as a single endogenous variable p^u in the market model. Second, since the aggregate log input is produced by a linear technology, marginal products are identical to average products. By normalizing $a_1 = 1$, and using Equation **(11)**, we see that the aggregate log input minus the log input from undamaged forests times κ equals the log input from damaged forests in damaged forest quality units: $(Q - q^u)\kappa = q^d$. This result will be useful in computing welfare losses to damaged forests.

The wood using a firm's short-run demand curve for timber can be used to estimate the change in economic welfare resulting from a SPB epidemic. The area below the demand curve and above price is referred to as *consumer surplus* (e.g., see Just et al. 1982). If the market equilibrium price of timber falls because of a change in timber supply conditions, then the change in a firm's economic welfare is the consumer surplus after the price change minus the consumer surplus before the price change.

MARKET MODEL

Market supply from damaged forests is the horizontal sum of supply over all firms with damaged forests

$$S^d(p^u, w, \delta, \kappa) \equiv \sum_{i=1}^{n} q_i^d(p^u, w, \delta, \kappa) = Q^d \tag{14}$$

and the market supply from undamaged forests is the horizontal sum over all firms with undamaged forests

$$S^u(p^u, w) \equiv \sum_{i=1}^{m} q_i(p^u, w) = Q^u \tag{15}$$

Aggregate market supply is the sum of supply from damaged and undamaged forests. Since damaged forests contain less usable wood fiber than undamaged forests, Q^d is adjusted to green timber equivalent by dividing through by κ.

For a given market demand curve $D(p^u)$, equilibrium price and quantity are found where the quantity demanded Q_D equals the supply from damaged and undamaged forests; $Q_D = Q^d/\kappa + Q''$. Given $D(p^u)$, a decrease in equilibrium price implies an increase in quantity supplied. If the market demand and supply curves for undamaged forests are known, the quantity supplied from undamaged forests at the new equilibrium price can be computed. The difference between the total equilibrium quantity and the equilibrium quantity supplied from undamaged forests is the quantity supplied from damaged forests (Ovaskainen 1987).

These ideas are illustrated in the four-quadrant diagram shown in Figure 2. Starting with quadrant I, initial equilibrium is found at the intersection of S'' and D. Timber salvage associated with an insect epidemic introduces a new, short-term, source of supply S^d. For simplicity, we assume that salvage supply is perfectly inelastic (corresponding to the lower bound method). The horizontal sum of S^u and S^d results in aggregate supply S^A and a consequent drop in equilibrium price (from P^* to P'). The fall in price causes harvests on undamaged forests to decline by amount $Q^* - Q''$, while total quantity supplied to the market increases by $Q' - Q^*$.

Thus, a method for estimating the implicit supply of timber from damaged forests becomes apparent. First, obtain the pre-epidemic equilibrium price (P^*)

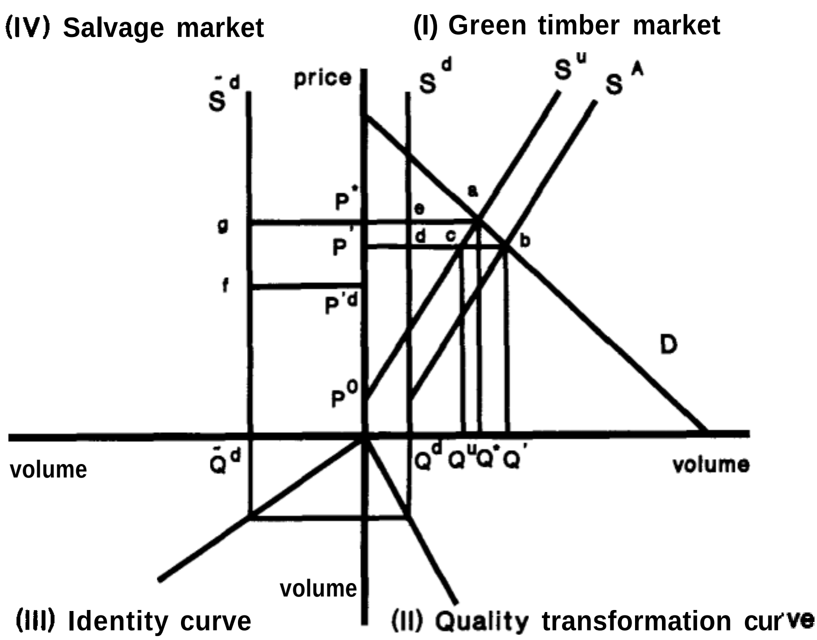

FIGURE 2. Price and welfare effects in green and salvage timber markets.

and quantity (Q^*). Second, estimate the change in the equilibrium green timber price (the estimation method is explained below). Third, estimate the new equilibrium quantity (Q') at the lower price (P'). Fourth, estimate the quantity supplied from undamaged forests (&'') at the new equilibrium price (P'). Fifth, compute the quantity supplied from damaged forests (in green timber equivalents Q^d) by subtracting the quantity supplied from undamaged forests (Q^u) from the total equilibrium quantity (Q'). Sixth, the equilibrium quantity of damaged timber (Q^d) in the implicit salvage market is computed by multiplying the quantity obtained in step five by κ, and the equilibrium price of salvaged timber (P'^d) is computed as the green timber equilibrium price (P') divided by κ. Finally, the equilibrium price and quantity of damaged timber are used to construct the implicit salvage supply curve which is used to estimate lower bound damages.

The analysis is made tractable by assuming that inverse supply and demand functions have constant elasticity forms $P(Q^u) \equiv S^u(Q^u) = a_0(Q^u)^{a1}$, $P(Q^u) \equiv D(Q^u) = b_0(Q^u)^{-b1}$. The elasticity estimates used to compute a, and $-c_1$ are taken from Newman (1987). In particular, the supply and demand elasticities used are 0.55 and -0.57, respectively. The parameters a„ and b, are calibrated to equate inverse supply and demand with the pre-epidemic market price and quantity obtained in step one. While we recognize that other elasticity values could be used, at this stage we are more interested in method development and demonstration than in absolute dollar estimates. Indeed, absolute damage estimates are expected to be sensitive to elasticities used and warrant a detailed analysis beyond the scope of this paper.

WELFARE EFFECTS

As shown in Figure 2, short-run consumer surplus always increases when supply Shifts from S^u to S^A by the area P^*abP'. This says that timber buyers benefit from SPB epidemics when the augmented supply of timber resulting from timber salvage decreases the market price of green timber.

The impact of a SPB epidemic on timber producers is decomposed to illustrate the impact on the two supply subsectors. A drop in green timber price from P^* to P' causes owners of undamaged forests to reduce quantity supplied from Q^* to Q^u and producer surplus declines from P^*aP^0 to $P'cP^0$. The area P^*acP' is equivalent to the amount of money that owners of undamaged forests would be willing to pay to avoid the fall in price. As seen in Figure 2, the welfare loss to producers on undamaged forests is less than the welfare gain to timber consumers by the area *abc.*

The welfare loss to producers on damaged forests is estimated as the difference between producer surplus had salvaged timber captured pre-epidemic green timber price (P^*) and producer surplus under salvage price P'^d. At pre-epidemic prices, economic surplus for producers whose timber is ultimately damaged by SPB is represented by area $P^*g\bar{Q}^d0$ in Quadrant IV. The economic surplus on the quantity of timber salvaged at equilibrium price P'^d is $P'^df\bar{Q}^d0$. The loss in producer surplus is area $P^*gfP'^d$.

The net welfare effect of a SPB epidemic is the sum of producer and consumer effects. Since $Q^d = Q' - Q^u$, visual inspection confirms that area $P^*edP' >$ area *abc.* Area $P^*gfP'^d >$ area P^*edP' for all cases except when $\kappa = 1$ (i.e., there is no timber damage)—the areas are then equal. Therefore an unambiguous loss in net welfare occurs as a result of a SPB epidemic. The amount of loss in net welfare is shown as (area $P^*gfP'^d$ – area *abc*) in Figure 2.

Cut-and-leave is another strategy available for controlling SPB outbreaks. If all SPB outbreaks were treated by cut-and-leave, the supply of damaged timber would be zero, and no impact would occur in the green timber market. Relative to a strategy of cut-and-remove, cut-and-leave benefits timber producers on undamaged forests. However, timber producers on damaged forests would not recover any producer surplus, and timber buyers would not benefit from lower timber prices. In Figure 2, the net welfare loss to society under a program of cut-and-leave is area P^*gQ^d0. As seen, the net loss to society is greater under cut-and-leave than under a program of cut-and-remove.

EMPIRICAL METHODS

Ideally, if sufficient price and quantity information were available for salvage sales, the salvage supply curve could be estimated directly. Unfortunately, these data are not available on a regional basis. Even if these data were available, problems in econometric estimation would arise since there would be little variation in salvage prices over the epidemic. Consequently, we must turn to the green timber market for evidence of a system-level impact and use that evidence to derive the implicit effects in the salvage market using the theory presented above.

To test hypotheses regarding equilibrium price, we would like to have time series data on both stumpage price and the amount of timber salvaged. In such a case, a causality test such as discussed by Buongiorno et at. (1985) could be used. Unfortunately, monthly or even quarterly timber salvage data are not available at the market level. Consequently, we use a less informative model which allows us to test the general hypothesis that a fall in stumpage price coincides with the period of intense salvage activity. Such a model is described below.

INTERVENTION ANALYSIS

A technique for analyzing the impact of a known intervention on a given response variable in the presence of dependent noise structure is known as *intervention analysis.* This model was introduced by Box and Tiao (1975), who demonstrated its use by analyzing the impact of public policy on the output of economic and environmental systems. Intervention analysis falls within a general class of models known as transfer function–noise models.

In general, the transfer function–noise model is written as follows

$$Y_t = f(\xi_t) + N_t \qquad (16)$$

where

Y_t = dependent variable at time t
f = transfer function
ξ_t = event at time t
N_t = noise at time t

The noise term is modeled as a mixed autoregressive moving average **(ARMA)** process which, in our case, describes the stochastic price generating process

$$N_t = [\theta(B)/\phi(B)]\eta_t \tag{17}$$

where

B = backshift operator

η = white noise

θ = moving average polynomial

ϕ = autoregressive polynomial

While the event term ξ_t in the transfer function could be any exogenous time series, impact analysis restricts ξ_t to be an indicator variable that takes the value 1 and 0 to indicate the occurrence or nonoccurrence of an event. It is analogous to a dummy variable in standard regression analysis.

The indicator variable ξ_t can represent a step $S_t^{(T)}$ where

$$\begin{aligned} S_t^{(T)} &= 0,\ t < T \\ &= 1,\ t \geq T \end{aligned} \tag{18}$$

or a pulse $P_t^{(T)}$ where

$$\begin{aligned} P_t^{(T)} &= 0,\ t \neq T \\ &= 1,\ t = T \end{aligned} \tag{19}$$

The general form of the transfer function is

$$f(\xi_t) = [\omega(B)/\delta(B)]\xi_t \tag{20}$$

where ω and δ are transfer function parameters. The functional form (20) is very flexible for modeling dynamic adjustment of system output to known interventions. For example, a "zero order" transfer function $f(\xi_t) \equiv \omega_0 B S_t^{(T)}$ represents an abrupt change of amount ω_0 in the output variable in period t + 1 in response to a step input in period t (it is implied that $\delta = 1$). Other dynamic responses to step and pulse inputs (say, where the denominator has more than one term) are discussed in Box and Tiao (1975).

The general model-building strategy follows the usual Box-Jenkins method of model identification, estimation, and diagnostic checking. First, specify a tentative model of change describing what is expected to occur given knowledge about the intervention. Next, analyze the data based on that model. Finally, perform diagnostic checks to test the adequacy of the model. If the checks indicate that the model is inadequate, iterate the procedure using an appropriately modified model.

Diagnostic checking of the full model is typically performed using the portmanteau (i.e. Box-Pierce Q) statistic to test the hypothesis that the model residuals are not white noise (Pindyck and Rubinfeld 1981). For an ARMA(p,q) model, the Q-statistic is approximately χ^2 distributed with $k - q - p$ degrees of freedom, where k is the number of lags in the residual autocorrelation function, and p and q are the orders of the autoregressive and moving average parameters, respectively.

DATA ANALYSIS

East Texas and west Louisiana were chosen for analysis. Loblolly pine *(Pinus taeda* L.) and shortleaf pine *(Pinus echinata* Mill.) are common to this region. During 1984–1986, forests in this region experienced the most damaging SPB epidemic on record. While salvage volume by month is not available, it is clear that salvage activity was moderate in 1984, intense in 1985, and declined substantially in 1986 (Dogett, et al. forthcoming). Due to climatic and biological factors, control operations are generally performed from May through December with the largest proportion of spots controlled from July to September (Billings 1980). Based on this *a priori* information, it is reasonable expect a "step" increase in timber supply, of the form represented in Equation (18), during the spring of 1985. Since SPB-killed trees remain usable as sawlogs for only a few months along the Gulf Coast (Levi 1981), we expect a "reverse step" from summer to fall 1986 as salvage activity ends and the market moves towards its pre-epidemic equilibrium. The general form of the equations to be estimated is therefore a compound transfer function–noise model

$$Y_t = f(\xi_t) + f(\xi_{t+r}) + N_t \tag{21}$$

where r is the number of periods (months) over which salvage is conducted.

Monthly southern yellow pine sawtimber stumpage price time series for Texas (market region 2) and Louisiana (market region 1) were obtained from Timber Mart South (TMS). To capture the price impact over an entire SPB population cycle (about 7 years), prices used for analysis are for January 1980 (when SPB activity was endemic throughout the Gulf Coast region) through December 1987 (the last month that monthly prices were reported in TMS). While more recent (i.e., quarterly) data could have been included in the analysis, many observations would have been lost by converting monthly to quarterly prices. Thus, 96 observations were used for analysis. Prices were deflated (1982 = 100) using the all commodity producer price index. Prices used in the analysis are shown in Figures **3** and **4.**

RESULTS AND DISCUSSION

A plot of the autocorrelation function for each time series showed that the sample autocorrelations did not rapidly approach zero as the number of lags increased, indicating that the original series were nonstationary. Indeed, both price series exhibit a downward trend—a fact that we note for future research. Further, no peaks were observed in the sample autocorrelation function at regular intervals (such as 12 months) indicating that seasonality was not present in the data. **A** first difference of each series yielded autocorrelation functions that dropped off rapidly-consequently, the stationary first-difference series were used for model building.

Parameter estimates and test statistics for the price impact assessment models are shown in Table 1. The Q-statistics indicate that the specified models are statistically adequate. The t-statistics indicate that the step-decrease variables (ω_1) were significant at the 0.05 level or higher and the step-increase variables (ω_2) were significant at the 0.10 level or higher. In both market regions, the noise

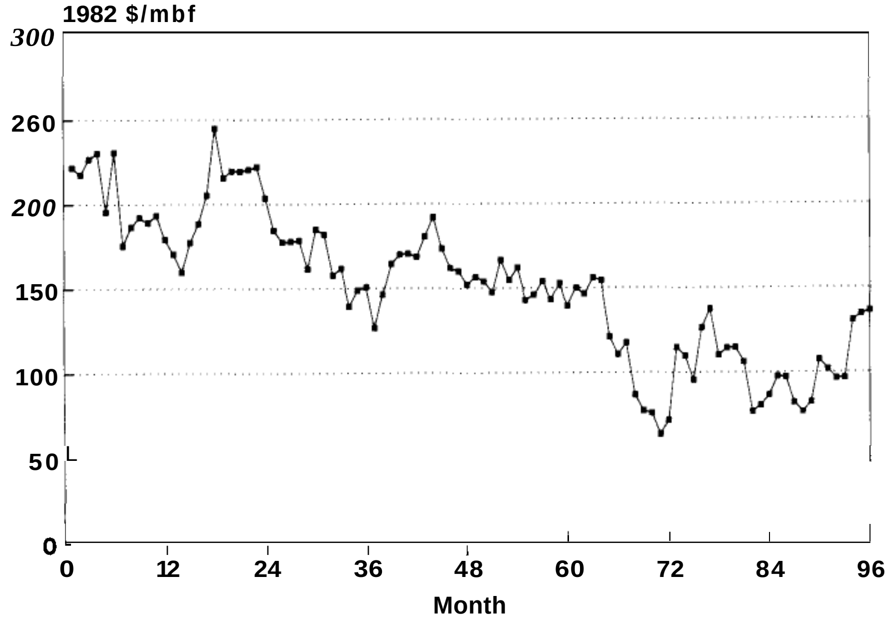

FIGURE 3. Pine sawtimber stumpage price, Texas region 2, 1980–1987. (Data source: Timber Mart South.)

term was modeled as a first-order autoregressive process (ϕ_1) which was found to be significant at the 0.05 level.

Iterative testing suggested that a compound zero-order transfer function was the best-fitting model—the price shock both occurred and remitted abruptly. The

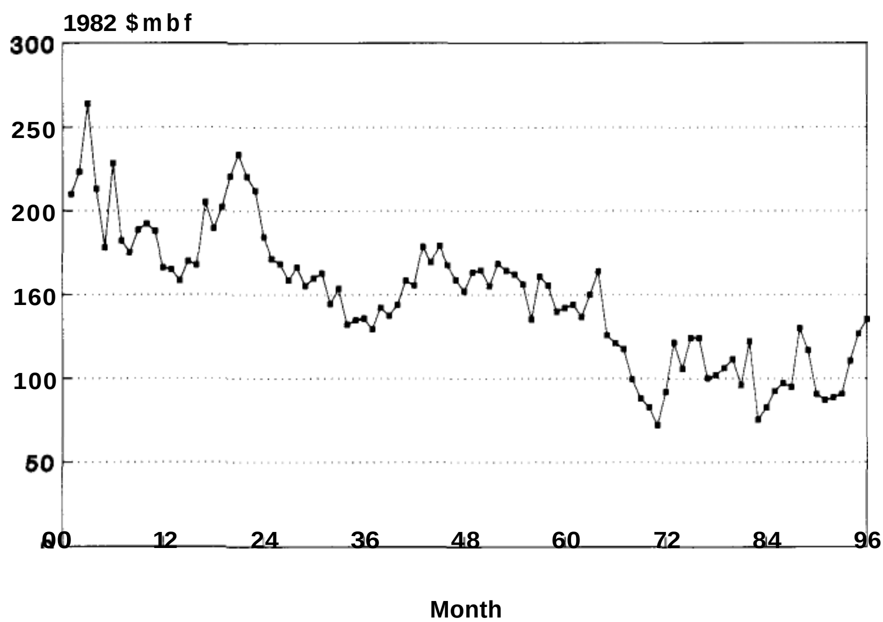

FIGURE 4. Pine sawtimber stumpage price, Louisiana region 1, 1980-1987. (Data source: Timber Mart South.)

TABLE 1.

Estimates of sawtimber stumpage price step changes and autoregressive noise parameter.

State	Constant	Step decrease (ω_1)	Step increase (ω_2)	Autoregression (Φ_1)	Q (k = 24)
Texas	−0.78	−34.82	26.12	−0.23	20.1
	(- 0.58)	(- 2.26)	(1.69)	(- 2.22)	
Louisiana	− 1.14	−34.52	33.20	−0.23	19.3
	(−0.79)	(- 2.08)	(2.01)	(- 2.30)	

Note: t statistics in parentheses.

step decrease in price for the best-fit model was found to occur during the sixty-fifth month of the series, or in May 1985. This corresponds with our *a priori* hypothesis. The final model suggests that the market adjusted toward the pre-epidemic equilibrium via an abrupt upward shift in price 25 months and 23 months after the abrupt decrease in price in Texas and Louisiana, respectively. While the timing of the upward shift is somewhat later than we expected, it may be explained by the hypothesis that SPB outbreaks in neighboring states kept timber prices low in the study area. The spatial diffusion of price impacts is a subject for further study.

The point estimates of ω_1 indicate that southern yellow pine sawtimber stumpage prices fell by $34.82 in Texas and $34.52 in Louisiana. The welfare effects of price change on timber producers and consumers in Texas and Louisiana are given in Table 2. All dollar figures shown are for the estimated period of impact. Since salvage timber prices are generally not reported, we based our analysis on assumed ratios of green to salvage timber price κ. Our assumption regarding κ are based on a study by de Steiguer, Hedden, and Pye (1987) which indicates salvage prices are typically one-half to three-quarters of green timber prices.

TABLE 2.

Welfare effects of SPB epidemic for given changes in green and salvage sawtimber prices.

Impact/State	APS (undamaged)	APS (damaged)	APS (net)	ACS	ΔNW
TEXAS	....		($1,000)	....	....
(1) κ = 1.33					
Δp = -$35/mbf	−67,631.2	−38,937.6	−106,568.8	74,838.4	−31,730.4
(2) κ = 2.00					
Δp = -$35/mbf	−67,631.2	−85,363.2	−152,994.4	74,838.4	-78,156.0
LOUISIANA					
(1) κ = 1.33					
Δp = -$35/mbf	−29,668.8	− 12,165.1	−41,833.9	32,088.0	−9,745.9
(2) κ = 2.00					
Δp = -$35/mbf	-29,668.8	−26,818.6	−56,487.4	32,088.0	−24,399.4

Note: κ = (green timber price)/salvage timber price. PS is producer surplus, CS is consumer surplus, *NW* is net welfare, and A denotes change.

Estimates of net welfare loss in Texas ranged from **$31.7** million to **$78.2** million and from **$9.7** million to **$24.4** million in Louisiana. Damages over the two-state area therefore ranged from **$41.5** million to **$102.6** million. It is interesting to note that Boyd and Hyde **(1989)** found that a total reduction in stochastic price variation would cause an annual gain in social welfare of about **$4** million per year (p. **111).** It is clear that the social welfare impacts of a large SPB epidemic are about an order of magnitude higher than social welfare impacts arising from stochastic price variation.

Two other points are worth noting in Table **2.** First, the loss in economic welfare to producers on undamaged forests for the two-state area was nearly **$100** million. This loss is due to the unexpected drop in price and the volume of timber committed to harvest. **A** strategy of prevention, rather than control, would clearly benefit all timber producers in SPB outbreak areas. Second, the loss in economic welfare on damaged forests always exceeds the change in net social welfare. Consequently, traditional damage appraisal methods tend to systematically overestimate net social damage by failing to consider change in market equilibrium conditions.

Some insight into the reliability of our damage estimates can occur by comparing our intermediate estimates of the amount of timber salvaged (corresponding to the estimated price drop) with exogenously obtained estimates of timber salvage volume (Doggett, et al. forthcoming). We estimate that about **449.3** mmbf of timber were salvaged in Texas throughout the epidemic, which compares favorably with the amount reported, **479.3** mmbf. Our estimate of the volume salvaged in Louisiana, about **138.2** mmbf, is much more conservative than the volume reported, **632.4** mmbf. The difference between our estimates and those reported may be explained in part by the fact that our estimates do not account for salvaged timber exported to neighboring market areas, and are therefore expected to be somewhat conservative.

CONCLUSIONS

The traditional forest damage appraisal model provides a measure of producer's willingness-to-pay to avoid forest damage but is theoretically correct only if a single producer's output is affected and the output of the producer is too small to affect the market price. Because this approach only estimates loss to producers with damaged forests, it can be misleading from a distributional standpoint if equilibrium market prices are affected by catastrophic forest damage. If the aggregate effect of a cut-and-remove damage control strategy is a reduction in stumpage price, then the traditional approach alone is incapable of estimating welfare change to timber users and producers with undamaged forests.

This paper introduces a market model for estimating aggregate forest damage. The model depends on the policy analyst's ability to quantify change in equilibrium market price resulting from salvage activity. Intervention analysis was introduced to accomplish this goal. While this empirical method does not unambiguously demonstrate causality, it is a reasonable method given the types of data that are available.

The market model introduced here is short-run in nature. By itself, this approach is useful for evaluating the impact of catastrophic events that have a large impact on current markets but negligible impacts on long-run markets. Southern pine beetle epidemics are such a case, where salvage activity represents a large percentage of current harvest, but a marginal percentage of standing inventory. The model would need to be combined with compatible long-run simulation models to compute total effects of disturbances that have large impacts on the standing inventory, such as Hurricane Hugo or perhaps the chronic forest decline as experienced in European forests. Of course, the short-run impacts associated with salvage or sanitation cutting could be estimated using the methods presented here.

A major advantage of the damage assessment model presented here is that it allows the policy analyst to conduct a fairly quick and theoretically sound analysis of large-scale forest damages. Such a method should be useful in evaluating the social costs and benefits of whole forest ecosystems subject to catastrophic losses.

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