
Market Dynamics and Optimal Timber Salvage After a Natural Catastrophe

Jeffrey P. Prestemon and Thomas P. Holmes

ABSTRACT. Forest-based natural catastrophes are regular features of timber production in the United States, especially from hurricanes, fires, and insect and disease outbreaks. These catastrophes affect timber prices and result in economic transfers. We develop a model of timber market dynamics after such a catastrophe that shows how timber salvage affects the welfare of different market groups and quantifies the impacts of salvage on product markets. A theoretical framework is developed that explores how government spending to mitigate economic losses through salvage is related to the costs of intervention. Using empirical price and quantity parameters derived for Hurricane Hugo as an example, we simulate how alternative levels of salvage would have affected southern pine timber prices and economic surplus. Results show that for this large-scale disturbance, the economic surplus generated by salvage averaged \$6.25 million for each percentage change in the volume of salvaged timber up to the observed salvage rate (-16%). Consumers benefited by an average of \$5.4 million for each percent of the damaged timber that was salvaged, producers of salvaged timber benefited by \$6.4 million for each percent salvaged, and producers of undamaged timber lost an average of \$5.6 million for each percent salvaged. Sawtimber salvage yielded welfare benefits for each cubic meter averaging more than four times those generated by pulpwood. These results therefore have implications for strategic salvage planning following catastrophic damage to forests. *FOR. SCI.* 50(4):495–511.



Key Words: Hurricane Hugo, timber salvage, natural disaster, wildfire, welfare.

HURRICANES, WILDFIRES, AND PEST OUTBREAKS regularly affect forest ecosystems in the United States. Although the average rate of natural disturbance in temperate forests is only about 1% per year (and ranges from -0.5 to -2.0% per year), a given rate of disturbance can be obtained by a regular, low rate of disturbance in most years or by large disturbances that occur only very infrequently (Runkle 1985). Individual tree gaps as found in cove forests of the Southern Appalachian Mountains would be an example of the former disturbance regime (Runkle 1982), whereas large, catastrophic fires as described by Heinselmann (1973) for the pine forests of northern Minnesota are indicative of the latter type of disturbance. Although several studies have investigated the

ecological impacts of natural disturbances on factors such as species diversity (Connell 1978), nutrient cycles (Bormann and Likens 1994), and ecosystem productivity (Sprugel 1985), much less attention has been given to understanding the economic impacts and consequences of large-scale forest disturbances. This lack of study is unfortunate, given preliminary evidence that a single insect epidemic can cause tens of millions of dollars of economic damages (Holmes 1991), and that a single fire season in a given locale can incur hundreds of millions of dollars in economic losses (Butry et al. 2001).

These large-scale forest-based natural catastrophes are true “shocks” to timber markets; they are virtually unforeseeable. However, their risks are well known in general, and

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they serve to dampen investments in timber growing and management (Yin and Newman 1996). Governments intervene after such forest-related catastrophes to help mitigate their economic and social effects. However, little is known about whether the aggregate costs of such interventions outweigh their aggregate benefits. One action that governments as well as corporations and private individuals take to reduce the negative effects of forest-based natural catastrophes is to salvage killed and mortally damaged timber. Timber deteriorates after a forest-based natural catastrophe, and standing and fallen severely damaged and killed timber could encourage secondary damages to neighboring resources and associated values (McIver and Starr 2000). Timber salvage, if done quickly, can recover value from killed and damaged timber, reduce the risks of contagion caused by the same damage agent or new agents, and prepare the site of damage for new timber investments.

In the absence of government assistance to facilitate salvage, the "market" may not salvage a socially optimal level of damaged timber (setting aside for the moment considerations of nontimber values) because of constraints on the mobility of labor and capital and because of the time-dependent nature of salvage activities. Governments have several tools that could be applied to affect the rate of timber salvage. Broadly speaking, these include provision of public goods, tax incentives, direct subsidies for salvage, and tax penalties or fines for not salvaging. Public goods that governments could offer to the private sector include clearing roads on private lands, subsidizing salvage log storage at mills, providing no-cost or low-cost salvage planning services to private landowners, or subsidizing power grid repairs. For example, after Hurricane Hugo, state and local governments facilitated private timber salvage by rapidly clearing and relaxing weight limits on public roads, permitting larger than normal log storage volumes at mills, and providing assistance to private landowners in the planning and coordination of their own salvage (Freeman 1996, Lupold 1996). In the case of Hugo, however, it is not known whether or not government-based salvage incentives were efficient in terms of equating the marginal salvage cost with the marginal benefits obtained.

Indeed, marginal costs and benefits would ideally include expressions of the effects of salvage on ecosystem services and public values. McIver and Starr (2000) summarize research that shows how postfire salvage may negatively affect soil erosion (Potts et al. 1985), soil compaction, and new seedling mortality (Roy 1956, Smith and Wass 1980) and may also unnaturally alter plant and animal species mixes (Greenberg et al. 1994). However, salvage has potentially positive effects as well. Salvage can lower the risks of insect attacks in the zone of forest damage (Amman and Ryan 1991, Saab and Dudley 1998) and positively affect certain animal populations by creating heterogeneous forest structures in an otherwise homogeneous burned area (Blake 1982).

One source of information about the degree to which the public values the attributes of forest management systems is found in the environmental economics literature. This liter-

ature has focused on the structural aspects of forest ecosystems and, to our knowledge, has not considered attributes related to salvage or restoration after a large natural disturbance. Nonetheless, this literature provides some insight into how the public might react to alternative salvage programs. In the United Kingdom, Hanley et al. (1998) found that people prefer forests with organically shaped edges, small-scale felling gaps, and a diverse mix of species. Boxall and McNab (2000) reported that large, straight-edged clearcuts generated large decreases in trip values for both wildlife viewers and hunters in Saskatchewan, Canada. Holmes and Boyle (2003) found that people in Maine prefer selective harvests over clearcuts, prefer leaving snags in the forest after harvest, and prefer forest ecosystems where large areas have been set aside from timber harvest. Taken together, these studies provide evidence that people prefer forest management systems that consider and minimize negative amenity impacts of timber harvests and that tend to mimic natural processes. Using these results to conjecture how the public might value alternative salvage systems, we would hypothesize that the public prefers salvage operations that leave large areas nonsalvaged (i.e., areas with abundant snags providing wildlife habitat) and prefer salvage openings with uneven edges. We stress here, however, that these are hypotheses that bear testing and are far from certain given current knowledge of public preferences.

Incorporating nonmarket values into a parameterized model of optimal salvage when public preferences for salvage attributes are unknown and when salvage impacts are site- and catastrophe-specific and heterogeneous is a great challenge. It bears emphasizing that our efforts to quantify the timber market impacts of salvage excludes these ecological impacts and public preferences, leaving that inclusion for future research.

In addition to the potential nonmarket effects and aggregate timber market benefits of salvage, governments considering devoting resources to facilitate salvage must also grapple with its costs and its distributional consequences. Because timber salvage has different impacts on the owners of damaged and undamaged timber (Holmes 1991), the timber market distributional consequences of salvage could serve as constraints or motivators of government action. Because very little research exists that clarifies how economic transfers are related to levels of timber salvage, acquiring such information could help decisionmakers design a government assistance strategy in the aftermath of a forest-based natural catastrophe. [1]

Finally, because of cost and time constraints, landowners and planners need to develop an operational strategy that prioritizes which stands to salvage. Ideally, salvage should focus first on stands or timber size classes that can yield the highest net returns and then proceed by salvaging progressively lower net value stands. The amount of salvage planned for each successive time interval becomes a balance between timber deterioration, harvest costs, and market prices for each potential timber product. Varying market price sensitivities, then, will affect how to prioritize salvage effort among timber products.

The goals of this research are threefold: (1) develop a theoretical framework for identifying an economically optimal level of government intervention to facilitate salvage that accounts for market forces, (2) derive and quantify how timber salvage affects the welfare of separate market components, using an empirical example, and (3) quantify the relative economic contributions of different salvaged timber products to net economic welfare, given market supply and demand responses. Our empirical example is Hurricane Hugo, and the timber markets analyzed are those for southern pine sawtimber and southern pine pulpwood stumpage, although the framework could be applicable to government decisions in other situations (e.g., salvage effort after catastrophic fires or insect outbreaks).

Holmes (1991) presented a short-run model to estimate changes in timber prices and net economic welfare resulting from catastrophic insect epidemics. The model we present here extends Holmes (1991) and other work on the impacts of timber market shocks (Berck and Bentley 1997) in several ways. First, we introduce a model of market dynamics that includes both short-run and long-run impacts. Second, we focus attention on the linkage between the level of salvage effort and welfare impacts as measured by changes in economic surplus. Third, we frame the salvage decision in the context of government policy. Fourth, by constructing parallel models for sawtimber and pulpwood stumpage, we separately quantify and compare the relative welfare contributions of each product market. Fifth, by calling on published price effects, market price sensitivities, and data on pre- and post-Hugo harvest and inventory levels, hurricane damage, and salvage volumes, we identify an expected value of the salvage discount parameter, enabling a comparison with the product discounts accruing from other forest-based natural catastrophes. Finally, to account for uncertainty in our parameter estimates, we apply a bootstrapping procedure that enables us to calculate confidence bands for welfare impacts and the salvage discount parameter. The bootstraps are further supplemented by sensitivity analyses on timber market supply and demand parameters. This additional modeling highlights market dynamics occurring under market conditions at the extremes of our expectations.

Theoretical Development

Hurricanes struck the eastern United States 165 times during the past century, many in prime timber growing regions of the South, including Florida, Texas, Louisiana, and North Carolina (Table 1). Hurricanes cost the US economy an estimated \$4.8 billion annually (Pielke and Landsea 1998), and some predict that their frequency will increase over the coming decades in the eastern United States as a result of natural ocean temperature fluctuations (Landsea et al. 1996, Gray et al. 2000, Goldenberg et al. 2001) or human-caused climate forcing (Emanuel 1987, 1995, Royer et al. 1998, Easterling et al. 2000). Because of the empirical significance of hurricanes to timber markets in the South, we develop our theoretical model in the context of

Table 1. Hurricane count by Saffir/Simpson Scale, by state, by year, 1900–1999.^a

Area	Categories					All categories
	12	3	4	5		
Alabama	5	15	0	0		11 ^b
Florida	19	17	17	5	2	60
Georgia	1	4	0	0	0	5
Louisiana	9	5	8	3	1	26
Mississippi	12	5	0	1		9
North Carolina	10	6	10	1	0	27
South Carolina	6	4	2	2	0	14
Texas	12	9	10	6	0	37
Virginia	2	1	1	0	0	4
Connecticut	2	3	3	0	0	8
Delaware	0	0	0	0	0	0
Maine	5	0	0	0	0	5
Maryland	0	1	0	0	0	1
Massachusetts	2	2	2	0	0	6
New Hampshire	1	1	0	0	0	2
New Jersey	1	0	0	0	0	1
New York	3	1	5	0	0	9
Rhode Island	0	2	3	0	0	5
US (Texas to Maine)	61	40	48	14	3	165

Source: US Department of Commerce-National Oceanic and Atmospheric Administration (2000), updated with the assistance of Jack Bevin, Tropical Prediction Center, National Oceanic and Atmospheric Administration.

The sum of state totals by category may be more than the US totals because some hurricanes affected more than one state.

The data for Florida and the US (Texas to Maine) in Categories 4 and 5 reflect an update by US Department of Commerce-National Oceanic and Atmospheric Administration (2002), which reclassified Florida's 1992 Hurricane Andrew as a Category 5 rather than a Category 4.

catastrophic windstorms. However, the theoretical model is applicable to other large-scale forest disturbances.

Large-scale forest-based natural catastrophes have the effect of reducing timber prices for a short period after the catastrophe, as a pulse of salvaged timber[2] enters local markets (Holmes 1991, Yin and Newman 1999, Prestemon and Holmes 2000). Additional longer-run price changes can occur if demand does not completely adjust to the reduced timber inventory levels, resulting in increased scarcity of standing timber (Olson et al. 1988, Berck and Bentley 1997, Prestemon and Holmes 2000). Below, we illustrate these short- and long-run price dynamics in a graphical model. Following that, we describe the market relationships using a structural model of timber supply and demand. The structural model directly leads to an approach for estimating the quantitative linkage between timber salvage effort and impacts on timber producers and consumers.

Graphical Representation

A graphical representation (Figure 1) helps to visualize the southern pine timber market dynamics following Hurricane Hugo, as found by Prestemon and Holmes (2000). Hugo, a Saffir-Simpson Category Four hurricane, struck South Carolina on Sept. 22, 1989. The hurricane is now regarded "as the greatest single forest disaster in the State's history" (Sheffield and Thompson 1992). The storm's winds damaged timber inventories within a swath 50 miles wide from the central South Carolina coast to western North

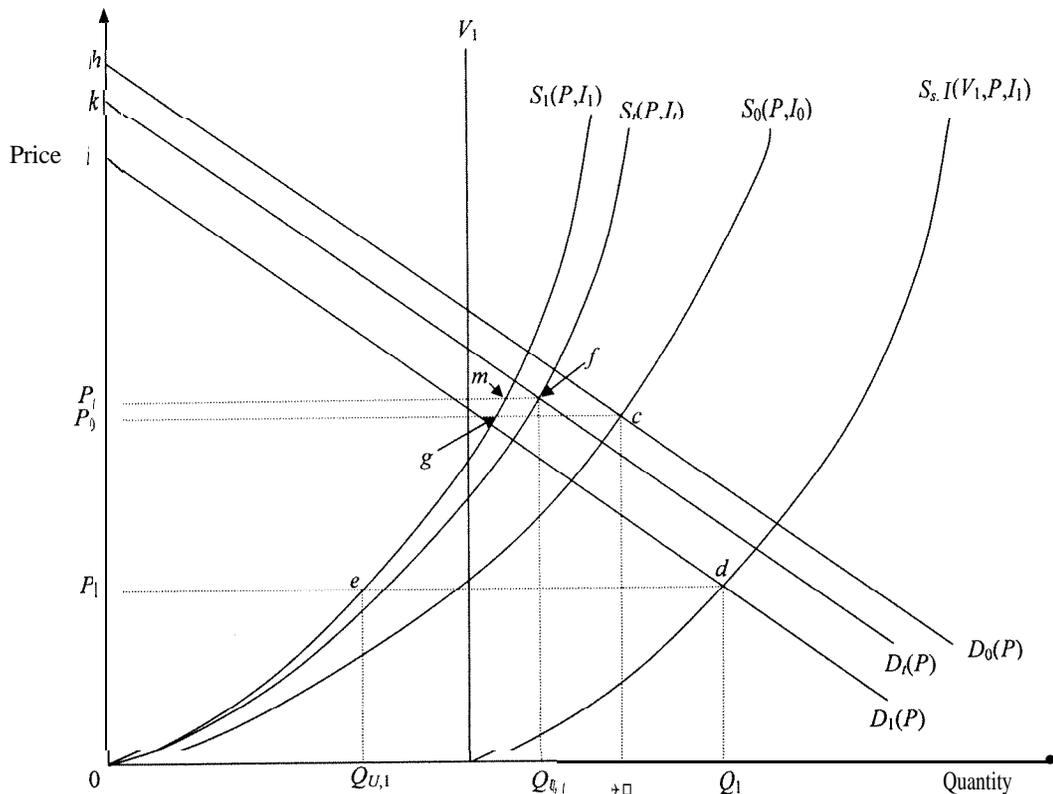


Figure 1. Supply and demand short-run equilibrium for salvage and timber from undamaged stands.

Carolina. Two-thirds of the timberland area within a 23-county area containing the swath was affected. In the damage zone, 21% of the softwood inventory was killed, and a volume equivalent to about 16% of that 21% of killed softwood inventory was salvaged over the next 9 months. Ninety-three percent of the salvaged timber came from private lands (Sheffield and Thompson 1992). Further details of the event can be found in Haymond et al. (1996).

Timber prices in the affected region were observed (Yin and Newman 1999, Prestemon and Holmes 2000) to drop immediately following the hurricane and then recover within a few years. South Carolina's coastal plain and lower Piedmont were directly affected by damaging winds, while southern and western counties (and none of the mountain region of South Carolina-Timber Mart-South Area 1) were not. Standing inventory was severely reduced in the zone, forcing prices upward in a classic response of the timber market to contractions in available supplies, and the wood products (demand) sector exhibited a small contraction (Syme and Saucier 1992). Sawmills and other solidwood product producers were closed in the months and years following the storm, consistent with a backward timber demand shift. In the pulp and paper sector, no such shift was evident, and Syme and Saucier (1992) uncovered evidence that that sector might have even expanded in the hurricane's aftermath.

The price and quantity effects of an inventory loss, a backward demand shift (at least in the solidwood products sector), and a large-scale salvage operation were apparent in the observed quarterly prices uncovered in research reported

by Yin and Newman (1999) and Prestemon and Holmes (2000). Because short-run timber supply is positively related to timber inventory (Binkley 1987), inventory losses force a backward supply shift that can increase prices. Salvage, on the other hand, forces prices down, as local wood demand is saturated. The price path described in Figure 1 illustrates the initial lower price due to the pulse of salvaged timber and then the higher price caused by the inventory loss. Our depiction also includes a small demand contraction consistent with the derived demands of the solidwood products sector. Figure 1 may be a valid representation of timber markets following other catastrophic disturbances such as fires.

In the months and years after the catastrophic disturbance, total supply is shown to first shift out (pulse effect), then shift back to a level below that in effect before the storm (inventory effect), and finally recover to the initial equilibrium over many years as inventory grows back. In the period before the hurricane (period 0), supply was $S_0(P, I_0)$ and derived timber demand was $D_0(P)$, intersecting supply at the equilibrium price (P_0) and quantity (Q_0), point c . When the hurricane struck, undamaged timber inventory was reduced to I_1 , the inventory volume available in the period immediately following the hurricane (period 1). This supply of undamaged timber in period 1 is represented as curve $S_1(P, I_1)$. The difference between S_0 and S_1 is the change in the quantity that would have been supplied to the market if the standing inventory had not been mortally damaged by the hurricane. Some of the inventory lost to the storm entered the timber market as salvage, the quantity V_1 ,

expressed as an undamaged timber equivalent volume (explained below). This volume was added to undamaged timber supplied to the market, $S_{s,1}(V, P, I_1)$, producing a new equilibrium with demand at point $d(Q_1, P_1)$. Owners of inventories of undamaged timber during period 1 harvest the quantity $Q_{U,1}$, defined where S_1 intersects the market price, P_1 .

The supply of salvage is shown as completely inelastic—owners will accept any price over a stumpage price of zero for timber that has stopped growing or increasing in value due to death or severe injury. This is because the opportunity cost of holding damaged timber rapidly approaches zero in the southern United States. The supply of such stumpage in period 1 is thus the summed volume of damaged material with a residual price greater than zero; its price per unit delivered is greater than the sum of its unit harvest and transport costs. Damaged timber is eventually salvaged or loses all value due to wood decomposition.

At the time of salvage exhaustion, the market reveals the effects of the loss of standing inventory—an increased price relative to the initial equilibrium. Total supply is now $S_t(P, I_t)$ and intersects demand at point $f(P_t, Q_t)$. Between periods $t = 1$ and $t = T$ (where T is the time required for inventory to fully recover), supply shifts outward as timber inventory returns to $I_T = I_0$. Demand can be modeled as shifting outward in step with the recovering inventory, so that at time $t = T$, $D_T(P) = D_0(P)$. Likewise, in period T the quantity harvested returns to its predisturbance equilibrium $Q_T = Q_0$. The regrowth of inventory implies that the kind of “long-run price enhancement” identified by Prestemon and Holmes (2000) will eventually fade away, returning prices and quantities produced per period to levels that would have existed throughout had Hugo not occurred. The time required for the outward shifts of demand and supply would therefore both depend on the speed of inventory recovery.

Consumer and producer (Marshallian) economic surplus (welfare) can be described with the assistance of the graphs as well. These are the areas to the left of the equilibrium point under the demand curve and above the supply curve. The change in consumer surplus in the first period following a catastrophe and during the salvage operations is area $P_1di - P_0ch$, and the change in producer surplus for owners of undamaged timber is $-P_0geP_1$, reflecting the difference between surplus gained at the original price (P_0) and what they gained at the observed price (P_1). After timber salvage is completed, the change in consumer surplus is the area $P_1fk - P_0ch$, and the change in producer surplus for owners of undamaged timber is P_1mgP_0 . Welfare losses experienced by owners of damaged timber during the salvage period are net of the revenues obtained from salvage. The salvage revenues during the periods when salvage is removed amount to a gain equal to the price of salvage that period times the adjusted (see below) quantity. But these owners of salvaged timber also incur a long-run loss, amounting to the timber per period that they could not sell because it was either killed, died, or was salvaged as a consequence of the storm but which would have received the original (pre-Hugo) price. This area is below the old market price line

and between the new and old supply curves (area Ogc in Figure 1).

Calculations of Economic Welfare

The economic effects of salvage on the timber market derive from the linkage between the intensity of salvage effort and the level of timber prices received by timber owners and paid by consumers. To be able to add salvaged timber to undamaged timber (“green timber” in Holmes’ [1991] terminology) to obtain market supply, a measure of “equivalent volume” is required. The equivalent volume is measured by the salvage adjustment parameter (Holmes 1991), $\kappa_t (\geq 1)$, which is calculated as the ratio of the stumpage price of undamaged timber to damaged timber per unit volume. Thus, the greater the amount of product downgrade due to a natural disturbance, and the greater the cost of accessing damaged timber, the higher the value of κ_t .

All damaged stands with a positive stumpage price would be available for harvest, but, as adjusted by κ_t , their price and equivalent volume would be lower than for timber harvested from undamaged timber stands. For example, if $\kappa_t = 1$, then the stumpage price of salvaged timber would be identical to the price of timber removed from undamaged stands. The undamaged timber equivalent volume of salvage would then be identical to its true volume. If $\kappa_t = 2$, then the stumpage price of salvage timber would be half that of timber removed from undamaged stands. Hence, the undamaged timber equivalent volume of salvage would be half that of the physical volume. As might be visualized in Figure 1, lower undamaged equivalent volumes would push V_t toward the y-axis, with the consequence that consumers would benefit less from salvage, undamaged producers would be harmed less, and owners of damaged timber would recover less value from their salvage.

The salvage adjustment parameter is sensitive to time-related decay, the extent of damage caused by the initial catastrophic event, and costs of timber recovery. Hence, it can be expressed as a function of time (t), the severity of the damage agent (S), and government efforts (G) to affect the costs of salvage removal and transport. κ_t therefore includes (1) a timber quality adjustment, accounting for the lower quality of salvage logs relative to undamaged logs (Holmes 1991, Barry et al. 1996), and (2) a harvest cost adjustment, accounting for the (potentially) higher expense of removing and transporting salvable timber from damaged stands (Marsinko et al. 1996). The timber quality adjustment has the effect of increasing κ_t over time because decay (e.g., fungal staining, insect damage) reduces timber quality. The degree of product decay depends on local environmental conditions and the tree species under consideration. The severity of the damage agent indexes how the agent affects the quality of the wood at the instant of the catastrophic event, a function of tree species as well as the event. κ_t would therefore be a positive function of severity, holding species constant. For example, a moderate fire might kill a tree but only slightly reduce timber quality because it *only* kills the cambium and crown through high temperatures. A severe fire can burn into the merchantable part of the wood

itself. A hurricane's high winds create reaction wood and ring shake (Faust et al. 1996a,b), and the proportions of each may depend on species.

The harvest and transport cost adjustment portion of κ_t depends on the type and severity of the damage agent through its effects on harvesting costs as well as the abundance and passability of the local road network. Government efforts that facilitate salvage (clearing of roads, for example) would therefore act to lower κ_t to below its immediate postcatastrophe level in many stands (Lupold 1996). In essence, such efforts act to shift out the salvage supply curve, V_t , shown in Figure 1. Consistent with the above arguments, $\partial\kappa_t(t, S, G)/\partial t \geq 0$, $\partial\kappa_t(t, S, G)/\partial S \geq 0$, and $\partial\kappa_t(t, S, G)/\partial G \leq 0$.

Changes in economic surplus attributable to salvage are divided into effects on the stumpage prices and quantities harvested by owners of undamaged timber, owners of damaged timber, and timber consumers through derived demand. The economic surplus measures described below involve methods described by Just et al. (1982). The approach is partial equilibrium, confining analysis to the timber market alone and not to higher stages of production. Thurman and Easley (1992) confirm the validity of this approach for one resource-based market.

Economic surplus for owners of undamaged timber[3] varies by period because total supply gradually shifts back as available salvable timber (proportion with $\kappa_t < \infty$) is used up. Producer surplus for this group comprises the area to the left of the supply curve for undamaged timber, $S(P, I_1)$, and between the observed market price for the quarter, P_t , and the counterfactual price (the price that would have been observed had the catastrophe not occurred), P_0 :

$$\Delta PS_{U,t} = \int_{P_0}^{P_t} S(P, I_1) dP \quad (1)$$

where I_1 refers to the standing inventory on undamaged stands immediately after the catastrophic disturbance (period 1).

The change in economic surplus for owners of damaged timber each period are losses, net of salvage revenues:

$$\Delta PS_{D,t} = \left\{ \int_0^{P_0} S_t(P, I_t) dP - \int_0^{P_0} S_0(P, I_0) dP \right\} + \{P_t \kappa_t^{-1} [D_t(P_t) - S_t(P_t, I_t)]\} \quad (2)$$

The first term in curly brackets on the right-hand side of Equation 2 is negative and, for each time period t , represents the loss in quantity supplied due to the destruction of standing timber inventory. The second term in curly brackets, quantifying the total value of salvage, is positive during times of salvage and zero afterward. The terms inside the square brackets in Equation 2 quantify the volume of salvage, given a perfectly inelastic salvage supply. In other words, salvage is the difference between the total quantity demanded at the current price, $D_t(P_t)$, and the quantity of

undamaged (or "green") timber harvested at the current price, $S(P_t, I_t)$. This yields the price and quantity combination (P_t, Q_t). Note that as time advances, some of the undamaged timber will be supplied from the land of owners whose stands were damaged, because those stands will be growing back. Hence, the first curly-bracketed term will get progressively smaller (less negative) until inventory recovers. As the second set of curly-bracketed terms in Equation 2 shows, the larger the value of κ_t (i.e., the greater the intensity or severity of the damage), the smaller the benefits available from salvage and the greater net losses experienced by these owners.

The change in economic surplus experienced by consumers each period after the catastrophe, ΔCS_t , is found by subtracting the surplus generated by the counterfactual (original) demand curve from the surplus generated by the current demand curve. These curves are integrated between their price axes (\mathbf{B} , for the counterfactual curve and \mathbf{B}_{t0} for the current curve)[4] and their equilibrium market prices (P_0 and P_t , respectively):

$$\Delta CS_t = \int_{P_t}^{B_{t0}} D_t(P) dP - \int_{P_0}^{B_{t0}} D_0(P) dP \quad (3)$$

During periods immediately following the catastrophic disturbance, including the periods when salvage is sold, ACS, could be positive because $P_t < P_0$ (i.e., consumers are paying a lower price for wood) but could be negative because Q_t could be more or less than Q_0 . After exhaustion of the salvage, ΔCS_t is nonpositive because $P_t \geq P_0$ and $Q_t \leq Q_0$. As inventory volumes return, demand and supply move back, by period T , to attain $P_T = P_0$ and $Q_T = Q_0$ (and $B_{T0} = \mathbf{B}$), so that $\Delta CS_{t=T}$ is zero.

It is useful to summarize the effect of the severity of the damage agent on various market segments. In general, holding the damaged quantity constant, the greater the size of κ_t : (1) the smaller the price drop for the volume of undamaged timber during the periods of salvage; (2) the smaller the economic surplus losses experienced by owners of undamaged timber; (3) the smaller the surplus gains experienced by consumers; (4) the fewer the benefits accruing to owners of damaged timber; and (5) the lower the total benefits of salvage in the timber market. Considering this, efforts to facilitate salvage will have fewer negative market effects on owners of undamaged timber when the damage severity is great (κ_t far above 1) or the expense of removal is high. When damage is light (κ_t closer to 1) or when removal costs are not much higher than normal harvests, efforts to encourage salvage via government actions will involve larger negative price effects, along with larger distributional effects, as outlined above.

The change in total economic surplus changes for the entire timber market each period following the catastrophic disturbance is the sum of Equations 1, 2, and 3 each period, discounted at a rate r :

$$PVES = \sum_{t=1}^{T-1} (\Delta PS_{U,t} + \Delta PS_{D,t} + \Delta CS_t) e^{-rt} \quad (4)$$

Optimal Government Intervention in Timber Salvage

The value of the change in economic surplus shown in Equation 4 is affected by the observed rate of government spending (G , in dollars) to facilitate salvage, and this effect is transmitted to market participants through the dynamic equilibrium between total supply during the salvage period ($S_{s,t} = S_t(P, I_t) + V_t(G)$) and demand, $D_t(P)$ (Figure 1). Expressing $PVES$ as a function of G , the marginal effect of government expenditure on total surplus in each period is:

$$\frac{dPVES(G)}{dG} = \sum_{t=1}^{T-1} e^{-rt} \left(\begin{array}{l} \left(\frac{\partial S(P, I_t)}{\partial P} \frac{\partial P}{\partial \kappa} \frac{\partial \kappa}{\partial G} \right) \\ - \left(P_t \kappa_t^{-2} \frac{\partial \kappa}{\partial G} [D_t(P_t(\kappa(G))) - S_t(P_t(G), I_t)] \right) \\ + \kappa_t^{-1} P_t \left(\frac{\partial D}{\partial P} \frac{\partial P}{\partial \kappa} \frac{\partial \kappa}{\partial G} - \frac{\partial S(P, I_t)}{\partial P} \frac{\partial P}{\partial \kappa} \frac{\partial \kappa}{\partial G} \right) \\ - \left(D(P_t) \frac{\partial P}{\partial \kappa} \frac{\partial \kappa}{\partial G} \right) \end{array} \right) \quad (5)$$

The first line of terms inside the curly brackets describes how the surplus of owners of undamaged timber is affected by government spending to encourage salvage. Because $\partial S/\partial P > 0$, $\partial P/\partial \kappa > 0$, and $\partial \kappa/\partial G > 0$, this term is negative. In short, greater public spending harms owners of undamaged timber.

The second line of terms inside the curly brackets on the right-hand side of Equation 5 shows that the marginal effect of government expenditures on the producer surplus of owners of damaged timber operates through the salvage adjustment parameter and the quantity of salvage. Here, $P, > 0$, $\kappa > 1$, $D_t - S_t > 0$, and $\partial \kappa/\partial G < 0$, but these elements are preceded by a negative sign. In net, government spending raises the welfare of owners of damaged timber.

The third line of terms inside the curly brackets of Equation 5 describes the impacts of government spending on consumers. This set is preceded by positive elements (P , and κ_t). Inside the first pair of parentheses, $\partial D/\partial P < 0$, $\partial P/\partial \kappa > 0$, and $\partial \kappa/\partial G < 0$, rendering the value represented by the first pair set of terms inside these parentheses positive. For the second set of terms, $\partial S/\partial P > 0$, so the entire second set is negative but preceded by a negative sign. Hence, the value inside the first set of parentheses is positive. The set of terms inside the second pair of parentheses is a negative value. With a negative sign in front, this set of terms adds to consumer welfare. In short, more government spending to facilitate salvage results in greater benefits to consumers.

In summary, if government efforts effectively increase

salvage, then increasing government effort to facilitate salvage decreases the welfare of owners of undamaged timber, increases the welfare of owners of damaged timber, and increases the welfare of consumers. However, the sum of the three terms must be negative, as Holmes (1991) shows. Nevertheless, in circumstances of a highly inelastic demand, the benefits of salvage for owners of damaged timber are small (the price they receive is low), and losses for owners of damaged timber are large (because their quantities harvested as well as prices received are low). However, consumers gain more than the combined losses and gains of producers, due to the excess volume provided at low prices.

If we assume that $\partial \kappa/\partial G < 0$, then in order to identify the optimal rate of government spending to facilitate salvage, the "marginal government expenditure to facilitate salvage with respect to the rate of salvage" function must be defined. Let "global net timber market welfare," or GNW , be the economic surplus changes generated by lost inventories and salvage minus the government cost to facilitate salvage, G . The optimal rate of salvage is defined as the rate of spending where the first derivative of the global net timber market welfare equation, $GNW(G) = PVES(G) - G$, with respect to the rate of government spending equals zero:

$$\frac{\partial GNW(G)}{\partial G} = \frac{\partial PVES(G)}{\partial G} - 1 = 0 \quad (6)$$

Equation 6 summarizes a condition of optimal government expenditure: a dollar of additional government spending must generate an additional dollar of economic surplus at optimality—the marginal welfare benefit equals its marginal cost. This concept is illustrated in Figure 2. The intersection of the marginal present value of economic surplus function, Equation 6, and the marginal salvage facilitation expenditure function define the optimal amount of government expenditure, G^* . Through κ , the publicly optimal rate of salvage is determined. Above that optimal rate, the marginal expenditure involved in obtaining an additional unit of salvage would exceed the additional economic surplus that the additional spending produces.

Determination of the present value of economic surplus requires a method of calculating postcatastrophe market prices under alternative rates of government expenditure to facilitate timber salvage. Because we do not know how κ is related to G in any specific case, we describe here a method for evaluating how economic surplus by producer group and consumers varies directly with κ . We do this by specifying an experimental salvage rate that departs from the observed rate by some factor and then calculating the equilibrium market prices, quantities, and economic surplus measures resulting from the departure. For the moment, assume that the salvage adjustment parameter is invariant to time, so that $\kappa_t = \kappa$ (for all t).^[5] (Knowing how that rate varies with time and government expenditure would not alter the approach that we describe, however.) Next, define a variable, $\bar{\Gamma} \geq 0$, that indexes government spending to facilitate salvage. In this context, $\bar{\Gamma}$ is determined by a political process

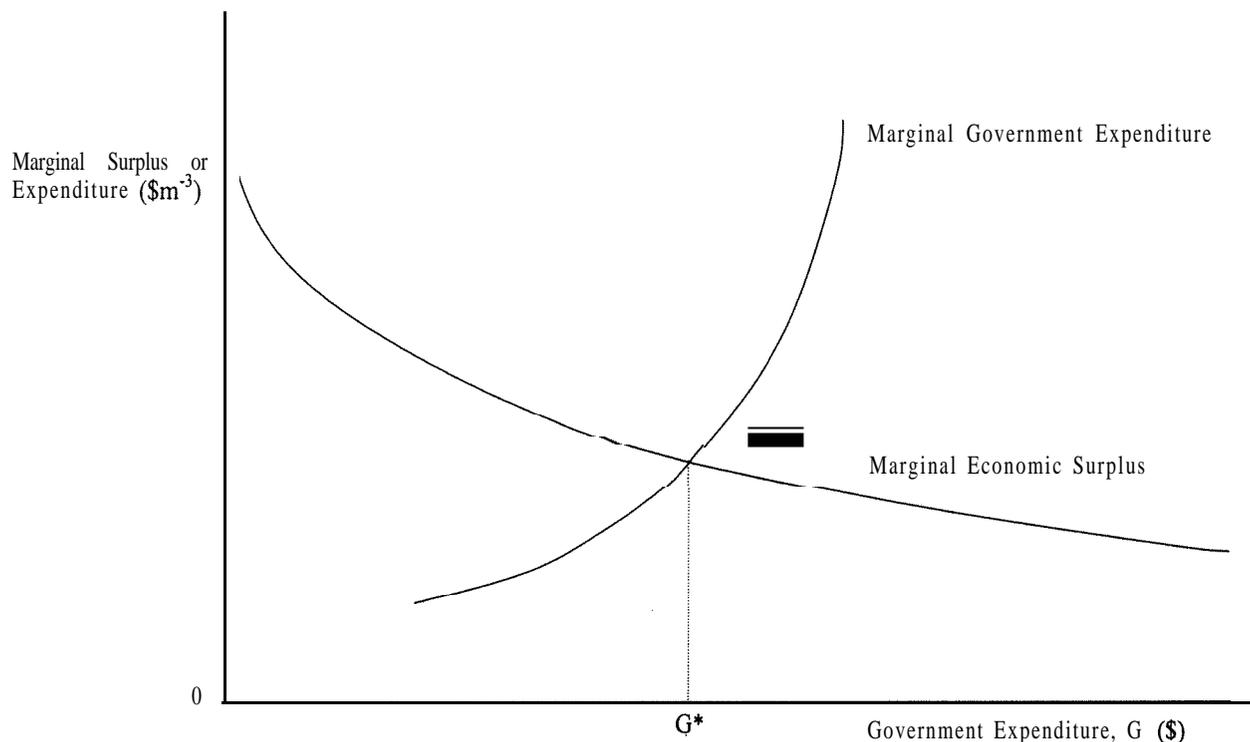


Figure 2. Determination of the optimal rate of government expenditure (effort) to facilitate salvage, G^* , based on the intersection of functions of the marginal government expenditure ($\$m^{-3}$) and the marginal present value of economic surplus ($\$m^{-3}$).

and (or) the managerial decisions of disaster relief government agencies. In our exposition, however, we seek to merely model how prices, quantities, and economic surplus are affected by the rate of timber salvage. (We are forced to leave to others the question of how government spending affects the rate of timber salvage.) Finally, find the price, P , in which the modeled timber supplied to the market (undamaged plus salvage, adjusted by a multiple, $\tilde{\Gamma}$, of the salvage volume) just equals demand. Expressed in terms of exponential supply and demand functions:

$$a_0 \tilde{P}_t^{a_1} I_t^{a_2} + \tilde{\Gamma} \kappa^{-1} (Q_t - Q_{U,t}) = b_0 \tilde{P}_t^{b_1}$$

where $Q_t - Q_{U,t}$ is the observed salvage volume (i.e., with $\tilde{\Gamma} = 1$); a_1 and a_2 are the elasticities of supply with respect to timber price and inventory volume, respectively; b_1 is the elasticity of timber demand with respect to timber price; and a_0 and b_0 are intercepts of these exponential supply and demand functions, respectively (model calibration is described below). By solving Equation 7 at alternative levels of $\tilde{\Gamma}$ and calculating the quantities in Equations 2 and 3, the analyst can describe how changing the amount of salvage would affect timber prices and the aggregate welfare due to a catastrophic disturbance. This description can include the marginal net welfare changes resulting from a marginal change in salvage.

Data

For the empirical example, we used the Hurricane Hugo timber price effects equations estimated by Prestemon and

Holmes (2000), including the short-run negative price effect (containing the effects of timber salvage, inventory reduction, and possible demand reduction) and the long-run positive price effect (containing the effects of the inventory reduction and possible demand reduction). We assembled published estimates of typical harvest volumes, supply and demand sensitivities to inventory and prices, inventory data, and the volume mortally injured or killed outright and salvaged in both southern pine sawtimber and southern pine pulpwood. The economic surpluses of each product were calculated separately. The salvage adjustment parameter for each product was calibrated using observed price departures and observed salvage quantities for each product. The simulation using these assumed values produced average adjustment parameter estimates of 4.35 for sawtimber and 5.26 for pulpwood. These values were similar to those reported by Baumann et al. (1996) and Marsinko et al. (1996).

Supply and Demand Parameters

Supply and demand elasticities with respect to timber price were derived from Newman (1987), whose 95% confidence bands contained point estimates reported by Adams and Haynes (1996) and used by Burch et al. (1996) and Abt et al. (2000). Inventory elasticities were held constant at 1.0, consistent with Adams and Haynes (1996) and Abt et al. (2000). Estimates of these elasticities, reported by Adams and Haynes (1996), differ little from those of Newman (1987), so we contend that the mean estimates and standard error estimates of the elasticities of demand and supply with

respect to prices remain valid today. The assumption of the unitary supply elasticity with respect to inventory elasticity is consistent with economic theory and the literature (Adams and Haynes 1980, Binkley 1987, Abt et al. 2000, Haynes et al. 2001). (Concerns about these assumed levels and standard errors of elasticities are somewhat addressed by a market elasticity sensitivity analysis, reported below.)

Timber Salvage and Loss

Estimates of the absolute timber volume losses and salvage volumes were taken from tables in Sheffield and Thompson (1992). Pre-Hugo quantities were set at the average quarterly harvest quantities, adjusted for pulpwood volumes in the upper stem portion, and recorded in the 1986 South Carolina Forest Inventory and Analysis (FIA) survey (Tansey 1987) for the intersurvey period, 1977-1986: 2.097 million m³ for sawtimber, and 1.308 million m³ for pulpwood. Pre-Hugo equilibrium prices were taken as the average real prices observed for the period 1977-1986, in 1989 dollars, as recorded by Timber Mart-South (The Frank W. Norris Foundation 1977-2001): \$41.15 m⁻³ for sawtimber and \$8.01 m⁻³ for pulpwood. All welfare calculations are expressed in constant 2002 (Jan.-Mar.) dollars based on the price index for all urban consumers (United States Department of Commerce-Bureau of Labor Statistics 2002).

Our analysis was limited to the market surplus changes experienced in the lower Piedmont and coastal plain of South Carolina, corresponding to Timber Mart-South Area 2 (The Frank W. Norris Foundation 1977-2001). Although Hugo affected prices in both of South Carolina's two Timber Mart-South regions (Prestemon and Holmes 2000), only Area 2 experienced inventory losses (Sheffield and Thompson 1992). It is, as well, by far the larger of the two markets and should, therefore, contain the vast majority of the economic effects of Hugo. The larger the size of these effects in Area 1, however, the more that the hurricane's economic impacts are undertallied. Given that Area 1 contains less than 10% of the state's timber, its exclusion does not impair our analysis or the qualitative implications of our findings. Prestemon and Holmes (2000) found no significant price imprints (market shock transmissions, as measured by timber prices) in neighboring states during the large campaign of timber salvage in South Carolina. Hence, consistent with these findings, we do not analyze how the hurricane affected neighboring states' markets.

Model Calibration

Calculations of Equations 1, 2, and 3 required calibration of supply and demand curves based on assumed elasticities, observed average historical prices, average inventory volumes, and average harvest volumes. Parameters a_0 and b_0 shown in Equation 7, the intercepts of the exponential supply ($Q = a_0 P^{a_1} I^{a_2}$) and demand ($Q = b_0 P^{b_1}$) equations, respectively, were identified algebraically by manipulating the supply and demand curves based on the observed average quarterly harvest volume (Q_E) and inventory (I_t). These were obtained from South Carolina's 1987 FIA survey in the 6 years previous to Hurricane Hugo and were summed over the counties found in Timber Mart-South's Area 2

(The Frank W. Norris Foundation 1977-2001) (coastal plain-Piedmont) submarket. The equilibrium price (P_E) was that 1977-1986 real average price obtained from the monthly Timber Mart-South Area 2 proxy price found by applying the approach developed by Prestemon and Pye (2000). Hence, $a_0 = Q_E / (P_E^{a_1} I_0^{a_2})$, and, at time $t = 0$, $b_0 = Q_E / P_E^{b_1}$. The counterfactual price (P_t) shown in Equations 1 through 3 was calculated by subtracting the median price departure (dP_t) found by Prestemon and Holmes (2000) from the price observed in the fourth quarter of 1989 in Timber Mart-South Area 2 (The Frank W. Norris Foundation, 1977-2001): $P_0 = P_{1989:IV} - dP_t$. Subsequent values (periods $t = 1, \dots, T - 1$) of that intercept (say, $b_{0,t}$) were found by changing b_0 between the b_0 effective at period $t = 0$ (b_0) at the same rate as inventory changed, so that $b_{0,t} = b_0 - [(b_0 - b_{0,t})(I_{0,t} - I_t)(I_0 - I_1)^{-1}]$ and where $b_{0,1} = (a_0 P_1^{a_1} I_1^{a_2} + \kappa^{-1} V_1) / P_1^{b_1}$.

As implied by the preceding sentence, our results depend on the regrowth of timber inventories in the affected region. We obtained information on inventories in 1993 from Conner (1993) and in 1999 from the USDA Forest Service (2002). Those inventories were flat between 1989 and 1993, followed by rapid regrowth. Based on these surveys, we conclude that sawtimber inventories should return to pre-Hugo levels by 2011, while pulpwood had already recovered by 2000.

Parameter Uncertainty

Because elasticities and the price effects of Hurricane Hugo on South Carolina sawtimber and pulpwood timber markets used to generate economic surplus results were estimates and therefore uncertain, we used a bootstrap sampling procedure (Davison and Hinckley 1997) to construct confidence bands around each measured category of welfare impact. Bootstrap sampling is based on iterative, random sampling from the distributions of the parameter estimates we used to calculate welfare impacts. Price elasticities were sampled from a normal distribution based on the parameter estimates reported by Newman (1987). We obtained the hurricane price effect equation estimates from three (sawtimber) or four (pulpwood) valid replications reported by Prestemon and Holmes (2000). These replications compared South Carolina prices in Timber Mart-South Area 2 with submarkets from other states, each comparison yielding a pulse equation (from their Tables 4 and 6), with associated parameter estimates and standard errors of those estimates. Each pulse equation had equal probability of being used in the bootstrap. Parameters in the equations selected under the uniform distribution were sampled using a normal distribution. A final source of variation accounted for in the bootstrap was the Hugo inventory shock (timber mortality) and salvage volume estimates reported by Sheffield and Thompson (1992). Standard errors of the shock and salvage volumes were found by implementing an algorithm described by Conner (1993); variations about the estimates were assumed to be normally distributed and hence sampled as such in the bootstraps. Five thousand

bootstrapped estimates of the hurricane's impacts were used in the error band construction.

Discounting was necessary to tally the long-run effects of the hurricane, but the rate of discount is uncertain, so we performed sensitivity analyses around the base rate of discount (6%). The discount rate, however, had little effect on the welfare effects of the catastrophe during the brief "salvage period" because of its brevity and closeness to period $t = 1$. Discounting did affect the overall impact of the disaster, because these effects were distributed well past the limited salvage period.

The bootstrapped welfare estimates are a function of the set of market assumptions, which are grounded on a few published studies and economic theory. However, a sensitivity analysis that varies supply and demand parameters substantially beyond the point estimates and their error bands illustrates the effects of these maintained assumptions outside the bootstraps. In our results, we therefore present market welfare impacts of the salvage effort and the whole market under inelastic and elastic combinations of supply elasticities with respect to price and inventory and the demand elasticity with respect to the timber price. The sensitivity analysis fixed market parameters at ends of ranges that are plausible, in our judgment—for example, beyond two standard deviations of those reported by Newman (1987) in the case of price elasticities and deviated 25% from those expected from theory in the case of inventory.

Results

Table 2 presents estimates of the present value of changes in economic surplus due to Hugo (*PVES*), given assumed supply and demand elasticities and the base case salvage levels (-16%). Surplus changes are disaggregated by timber product and economic group. Results for owners of damaged timber are further subdivided into the economic surplus gained from salvage and the economic surplus lost because of the loss of damaged inventory.

Several features of the results shown in Table 2 merit discussion, as they illustrate the significance of the hurricane for South Carolina, the magnitude of salvage benefits, and the distributional effects of the posthurricane timber market dynamics. First, total economic surplus changes reported here, averaging -\$1,523 million for the 5,000 bootstraps contained within a wholly negative 95% bootstrapped confidence band, are larger in magnitude than those reported by Burch et al. (1996). Burch et al. examined the surplus changes spread throughout a multistate area, implying that market welfare reductions in South Carolina were partially made up by welfare enhancements in other states (they also did not account for the value obtained from salvage of killed timber). Their analysis relied on an assumption of regional market integration, a finding not entirely supported by results in Prestemon and Holmes (2000). Table 2 shows that salvage generated \$91 million in producer surplus gains for owners of damaged timber, this estimate contained within a wholly positive 95% confidence band. Over 85% of that was generated from sawtimber

Table 2. Means and standard deviations of discounted welfare changes caused by Hurricane Hugo on southern pine timber markets in South Carolina, based on the means of 5,000 bootstrapped market equilibria.

	Producer surplus, owners of damaged timber, gained from salvage		Producer surplus owners of damaged timber, lost from killed timber		Producer surplus changes, owners of undamaged timber, all periods		Consumers surplus changes, all periods		Total surplus changes, producers + consumers, all periods	
	(\$ million, 2002)		(\$ million, 2002)		(\$ million, 2002)		(\$ million, 2002)		(\$ million, 2002)	
Sawtimber	95% lower bound	54	-456	-225	-1,793	-2,105				
	Mean	79*** ^a	-373***	187	-1,029***	-1,136***				
Pulpwood	95% upper bound	108	-297	568	-569	-328				
	95% lower bound	4	-55	-102	-1,822	-1,805				
Total, 6% discount	Mean	12***	-43***	17	-373***	-387**				
	95% upper bound	21	-33	121	-113	-64				
Total, 3% discount	95% lower bound	57	-511	-327	-3,615	-3,910				
	Mean	91***	-416***	204	-1,402***	-1,523**				
Total, 9% discount	95% upper bound	129	-330	689	-682	-392				
	95% lower bound	53	-649	-855	-5,199	-5,870				
Total, 9% discount	Mean	92***	-503***	232	-1,682***	-1,861**				
	95% upper bound	137	-377	1,197	-787	-151				
Total, 9% discount	95% lower bound	51	-454	-281	-3,941	-4,190				
	Mean	90***	-353***	166	-1,178***	-1,275***				
	95% upper bound	134	-265	562	-510	-257				

^a Asterisks indicate that the 90% (*), 95% (**), or 99% (***) confidence intervals about the reported 5,000-bootstrap mean estimate did not contain zero. Distributions of welfare estimates at other confidence bounds are available from the authors on request.

salvage. Third, owners of undamaged sawtimber and pulpwood on average have gained or will gain from the storm \$187 million and \$17 million, respectively. But the backward shift in demand, the large but brief salvage-induced price reduction immediately following the storm, and the significant uncertainty regarding the long-run price enhancement leave these average effects not statistically different from zero based on a 95% (or even a 90%) confidence band. Fourth, consumers lose, in spite of lower prices and higher consumption enjoyed immediately following the event during the salvage period. Sawtimber consumers will lose \$1,029 million and pulpwood consumers have lost \$373 million, both statistically different from zero based on the 95% confidence band. In the end, the lower total production and higher prices (at least for sawtimber) end up causing losses amounting to \$1,136 million in the sawtimber market and \$387 million in the pulpwood market, both nonzero, based on their 95% bootstrapped confidence bands.

Consumer welfare losses were the sum of gains during the time of salvage and subsequent losses, the result of short- and long-run market price dynamics. Consumers gained during the salvage period by consuming more and paying less for timber, compared with the no-Hugo counterfactual. However, consumers lost welfare after the salvage was exhausted, stemming from two sources. The first source was the decline (backward shift) in demand due to lower production possibilities mentioned by Syme and Saucier (1992) (the backward shift from D_0 to D_1 , depicted in Figure 2). The second source of surplus losses by consumers was the combination of the higher price and lower quantities offered because of the contraction in supply experienced until inventory recovered.

Total timber market welfare effects of the catastrophe were sensitive to the assumed discount rate, but the surplus gains from salvage were not. The last two rows of Table 2 report estimates of the welfare impacts of Hugo for the combined sawtimber and pulpwood markets at discount rates of 3 and 9%, respectively. Results are similar in magnitude and effect on different producer and consumer groups as in the 6% case, except that total economic surplus impacts of the hurricane are 22% larger (totaling $-\$1,861$ million) at 3% and 19% smaller ($-\$1,275$ million) at 9%. At lower discount rates, consumer losses experienced in later years loom larger, and these dominate the small gains enjoyed by owners of undamaged timber. At 9%, consumer welfare losses shrink by more than undamaged producer welfare gains do. Surplus gains by owners of salvaged damaged timber were 1% higher at a 3% discount rate and 1% lower at a 9% rate. We can conclude that the discount rate is a trivial concern when evaluating timber market surplus changes caused by salvage.

The bootstrap replications revealed that the hurricane severely damaged salvable timber and created conditions for high salvage removal costs. For each randomly selected set of price elasticities, Hugo mortality and salvage volume, and price effects equation for each product, the supply and demand equilibrium condition was solved to generate a

value of κ that achieved the observed price effect and randomly selected production level.[6] The 95% confidence band for the sawtimber salvage adjustment parameter κ was (3.12, 6.39) while that of pulpwood was (2.72, 14.92), with means and medians of 4.50 and 4.33 for sawtimber and 6.59 and 5.20 for pulpwood, respectively. These are steeper discounts for sawtimber than the plausible levels identified by de Steiguer et al. (1987) for southern pine beetle.[7]

The sensitivity analysis of the effects of market parameter assumptions show that market insensitivities in supply and demand responses led to market welfare losses from the hurricane ranging from the trivially small total (sawtimber plus pulpwood) of \$17 million to six times larger than our bootstrapped average estimate, \$7.5 billion, while salvage benefits varied by an order of magnitude (Table 3). In the latter combination of conditions, consumers would not reduce purchases much in response to the higher timber prices observed in the period between salvage completion and inventory recovery. They would instead buy the expensive timber and face the ensuing large losses compared with the no-Hugo counterfactual. Under these conditions, surplus losses caused by the hurricane would be especially large for consumers in the sawtimber sector. In the pulpwood sector, on the other hand, the sensitivity analysis identified conditions in which consumers (pulpwood buyers) benefited, in total, from the hurricane. This result can be supported by the paper market potential expansion that was identified by Syme and Saucier (1992). Paper mills surveyed had shown a 21% increase in purchases of pulpwood in the years following the storm. Syme and Saucier did not report the primary cause of the expansion. However, we can conjecture that paper mills expanded their capacity in response to the greater availability of low quality sawtimber-sized material in the damage region (supported by findings of Sheffield and Thompson 1992) and (or) in anticipation of a pulse of pulpwood-sized material following the storm as vigorously growing younger stands grew as a result of Hugo's natural thinning and landowners' tree-planting after the storm. That consumers (indeed, the pulpwood market in total) during the years of salvage and inventory recovery could have benefited from the storm appears counterintuitive. It can be understood by accepting the possibility that damaged sawtimber-sized materials can move into the pulpwood sector as a result of storm injury.

The sensitivity analysis revealed effects of market supply and demand parameter elasticities on the benefits of salvage that were opposite those of the aggregate market in the long run. With inelastic demand and supply, salvage surplus gains were \$14 million for sawtimber and \$3 million for pulpwood; with elastic parameters, salvage gains were \$130 million and \$39 million for sawtimber and pulpwood, respectively. This result is obtained by understanding that the quantity of timber salvaged (unadjusted for the salvage discount) is known. Under a combination of inelastic supply and demand conditions, owners of undamaged timber would have reduced their output little in response to the lower market price of timber during the salvage period. But

Table 3. Economic surplus changes from a no-Hugo counterfactual, given price elastic and price inelastic demand and supply and low and high inventory elasticities of supply (6% discount rate).

	Demand price sensitivity	Supply price sensitivity	Supply inventory sensitivity	Producer surplus, owners of damaged timber, generated from salvage (\$ million, 2002)	Producer surplus, owners of damaged timber, lost from killed timber (\$ million, 2002)	Producer surplus changes, owners of undamaged timber, all periods (\$ million, 2002)	Consumers surplus, all periods (\$ million, 2002)	Total surplus changes, producers, all periods (\$ million, 2002)
	Low ($E = -0.1$) High ($\epsilon = -1$)	Low ($\epsilon = +0.1$) High ($\epsilon = +1$)	Low ($\epsilon = +0.75$) High ($\epsilon = +1.25$)					
Sawtimber	Low	Low	Low	14	-424	256	11,014	-4,167
	Low	Low	High	13	-679	280	-6,450	-6,837
	Low	High	Low	63	-205	204	-2,687	-2,626
	Low	High	High	57	-328	190	-4,919	-5,000
	High	Low	Low	97	-424	219	-497	-605
	High	Low	High	89	-679	203	-735	-1,122
	High	High	Low	142	-205	202	-363	-224
	High	High	High	130	-328	184	-581	-595
Pulpwood	Low	Low	Low	3	-35	54	-395	-373
	Low	Low	High	3	-57	45	-701	-710
	Low	High	Low	16	-19	66	94	158
	Low	High	High	15	-30	59	-255	-211
	High	Low	Low	25	-35	62	-14.5	-94
	High	Low	High	23	-57	56	-264	-243
	High	High	Low	42	-19	68	115	207
	High	High	High	39	-30	61	-20	50

in order for that market price and undamaged timber production quantity to be observed, a large salvage discount parameter κ (on the order of 20) would have been required. The opposite results are obtained with elastic market responses.

Nonmarginal changes in the salvage rate reveal the magnitude of the opposing trends in welfare among affected market groups (Figure 3). Equations 1, 2, 3, and 7 were used to evaluate the effects of varying $\tilde{\Gamma}$ from 0 to 2 (i.e., so that the observed salvage quantities ranged from 0 to about 32% of killed timber inventories). The price effects of such variations are tallied in Tables 4 and 5, and the welfare differences that they embody and illustrated in Figure 3 were generated for a 6% discount rate and relative to the median price effects resulting from Hugo (i.e., with $\tilde{\Gamma} = 1$), as reported by Prestemon and Holmes (2000). Total combined economic losses experienced by timber producers and consumers under Hugo would have been about \$1,262 million had no salvage been done, while losses would have been \$1,085 million if the amount of timber salvaged could have been doubled.[8] At low salvage levels, prices received by owners of undamaged sawtimber and pulpwood stumpage would have been higher because Hugo's inventory losses would have immediately registered in the South Carolina market in the form of higher sawtimber and pulpwood prices. With smaller salvage volumes, however, timber consumers would not have benefited from the lower prices, and owners of damaged timber would have reaped less value by salvaging some of their damaged timber. At higher than observed salvage rates, the lower prices would have yielded smaller total losses for timber consumers and owners of damaged timber but fewer total gains for owners of undamaged timber. For example, at a doubled salvage rate, sawtimber prices would have dropped by 80% more than at the observed rate.

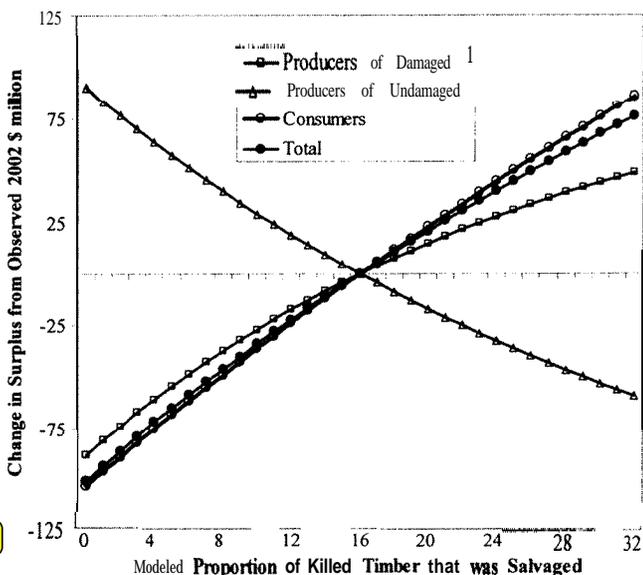


Figure 3. Modeled changes (departures from observed levels) in economic surplus experienced by southern pine sawtimber and pulpwood producers and their consumers, in 2002 dollars, under varying rates of timber salvage.

Varying salvage levels from the observed rate reveal that sawtimber salvage creates marginal benefits in the timber market that were four times larger than those generated by pulpwood salvage. Figure 4 illustrates these marginal benefits per unadjusted unit of salvage (i.e., salvage price, not adjusted for quality or cost), for a 6% discount rate and base levels of supply and demand elasticities, the median price effects (pulse) equations of Prestemon and Holmes (2000), and reported inventory, mortality, and salvage volumes from Sheffield and Thompson (1992) in 2002 dollars per cubic meter of sawtimber ($4.53 \text{ m}^3 \text{ mbf}^{-1}$) and pulpwood ($0.0283 \text{ m}^3 \text{ ft}^{-3}$). The first 1% of salvaged killed timber yielded $\$11.7 \text{ m}^{-3}$ for sawtimber and $\$2.75 \text{ m}^{-3}$ for pulpwood, averaging $\$7.3 \text{ m}^{-3}$ and yielding $\$7.2$ million of net benefits in southern pine timber markets. At the observed salvage rate ($\sim 16\%$), the marginal economic surplus generated was $\$9.0 \text{ m}^{-3}$ for sawtimber and $\$1.8 \text{ m}^{-3}$ for pulpwood, and the two combined yielded about $\$6.3 \text{ m}^{-3}$ on average. The marginal benefits curve decreased at a decreasing rate, implying that the marginal benefits of salvage, in terms of aggregate timber market welfare, would remain positive through rates of postdisaster salvage harvesting that exceed even the 32% shown.

Summary and Conclusions

The short-run effects of timber salvage on timber markets have been previously investigated (Holmes 1991), but no systematic effort has been made to quantify the market dynamics of short- and long-term welfare impacts. Modeling results reported here show that southern pine timber salvage reduced timber market welfare losses caused by Hurricane Hugo on the South Carolina coastal plain and lower Piedmont by about 9%, or by \$100 million, at median price effects and assumed market responses to prices. Modeling shows that losses would have been \$110 million smaller than those of the observed rate if salvage could have been doubled. However, our analysis did not show whether the observed rate of salvage was optimal from the standpoint of public intervention—no public expenditure information was available on how much governments spent to facilitate salvage. In other words, we do not know whether the costs incurred by governments in facilitating the observed salvage rate were greater than or less than \$100 million. Alternatively, if governments need to spend nothing to directly encourage salvage (e.g., because the forest-based catastrophe does not affect the transportation infrastructure), then it might be optimal to salvage all timber with a nonzero stumpage price (although this would cause higher benefits transfers). From the perspective of aggregate timber market welfare and given these specific conditions, timber market losses from a catastrophe are minimized only when most killed or dying timber is salvaged.

On the other hand, the welfare impacts of the hurricane and its associated salvage reported here refer specifically and perhaps narrowly to the timber market. Our analysis ignores external costs and benefits of salvage, including how salvage may affect ecosystem and public values. Inclusion of these factors in the optimization calculations

Table 4. Southern pine sawtimber: Price departures ($\$m^{-3}$, in 2002 dollars), at alternative rates of timber salvage, compared with a no-Hugo counter-factual.

Quarter, following Hugo	Salvage percent				
	0	10	16.69 (Observed)	20	30
1989:IV	3.53	-5.99	-10.47	-13.03	-18.17
1990:I	3.53	-2.24	-5.39	-7.12	-11.22
1990:II	3.53	0.08	-1.96	-3.05	-5.89
1990:III	3.53	1.49	0.22	-0.44	-2.26
1990:IV	3.53	2.33	1.56	1.17	0.04
1991:I	3.53	2.83	2.37	2.14	1.46
1991:II	3.53	3.12	2.85	2.71	2.31
1991:III	3.53	3.29	3.13	3.05	2.81
1991:IV	3.53	3.39	3.30	3.25	3.11
1992:I	3.53	3.45	3.39	3.37	3.28

could affect the preferred level and nature of government intervention into the timber market. This difference should be kept in mind when evaluating our results. Indeed, the optimal salvage rate for Hugo, from a public policy standpoint, might have been less or more than that observed. Although a complete treatment of those costs and benefits is beyond the scope of this article, ongoing and new research into these effects could enhance public decisionmaking in the period of crisis and concern following a forest-based natural catastrophe.

Understanding the net economic gains from timber salvage requires an assessment of the salvage discount parameter. In fact, one reason that we could not identify an optimal government expenditure level to facilitate salvage was that we lacked a salvage adjustment function, $\kappa(t, s, G)$. Additionally, identifying exactly how particular government actions following a forest-based natural catastrophe affect the salvage rate could be challenging. Government actions following large-scale disasters that affect forests also affect many other parts of society; parsing effects of actions on the timber sector would be required. In any case, no research could be identified that quantifies this function. Knowledge developed from such research could enable better government and private sector salvage decisionmaking, leading to smaller negative economic impacts from these kinds of disasters.

Table 5. Southern pine pulpwood: Price departures ($\$m^{-3}$, in 2002 dollars), at alternative rates of timber salvage, compared with a no-Hugo counterfactual.

Quarter, following Hugo	Salvage percent				
	0	10	15.39 (Observed)	20	30
1989:IV	1.77	-1.04	-2.16	-2.75	-3.82
1990:I	1.77	-0.01	-0.86	-1.34	-2.34
1990:II	1.77	0.67	0.10	-0.25	-1.03
1990:III	1.77	1.11	0.74	0.51	-0.04
1990:IV	1.77	1.37	1.14	1.00	0.64
1991:I	1.77	1.53	1.39	1.30	1.08
1991:II	1.77	1.63	1.54	1.49	1.35
1991:III	1.77	1.68	1.63	1.60	1.52
1991:IV	1.77	1.72	1.69	1.67	1.62
1992:I	1.77	1.74	1.72	1.71	1.68

However, some knowledge was gained in our treatment of the salvage adjustment parameter, particularly its likely magnitude: three times larger than that found for southern pine beetle damages. Additional research on the salvage adjustment parameter would focus on other forest-based natural catastrophes. In the case of wildfire, physical wood damage is often far less severe, perhaps comparable to that deriving from beetle kills. Harvest cost differences following fire and insect mortality are probably small compared with the undamaged condition. The smaller the discount, the greater the net timber market benefits from salvage, so salvage could generate net percentage gains for consumers and producers that are larger than those found here. Nevertheless, with each disaster, a careful assessment of the salvage discount parameter is required to correctly quantify the costs and benefits of timber salvage and to develop a salvage plan that meets public objectives.

Our modeling emphasizes the importance of concentrating timber salvage on damaged stands with higher value materials. In the case of Hugo, sawtimber salvage would have been more profitable than pulpwood salvage, even if salvage removal and transport costs averaged $\$8 m^{-3}$ higher for sawtimber than for pulpwood. After other kinds of

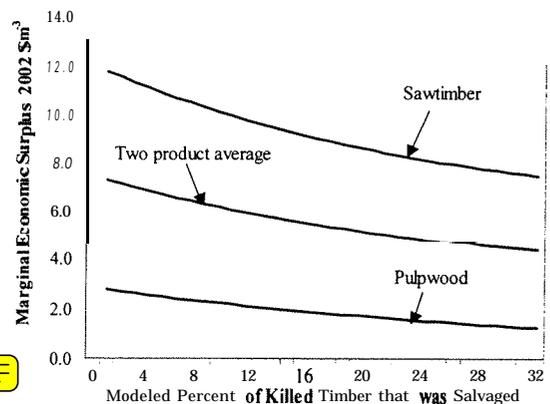


Figure 4. The marginal present value of economic surplus (in 2002 dollars) in the southern pine sawtimber and pulpwood timber markets of South Carolina with respect to the rate of timber salvage.

forest-based natural catastrophes or in markets with different product prices and different supply and demand parameters, the differences in unit benefits among products would not be the same, so this \$8 m⁻³ difference should not be used as a rule of thumb. A substantial amount of pulpwood volume is removed in the process of sawtimber harvesting (as a “come-along” volume), because its marginal harvest cost at that stage is low, so the prioritization of salvage effort must consider this as a constraint to such targeting. However, our findings highlight the importance of developing a plan for salvage that prioritizes stands based at least in part on the net value of materials that could be obtained from each potential salvage site. Significant timber market gains might have been obtained by shifting resources from salvage of pulpwood to sawtimber dominated stands.

We have provided a framework for understanding the optimal rate of public expenditure to facilitate timber salvage after a large-scale forest-based natural catastrophe, and we have begun to describe the context of the political economy of timber salvage following such events. The model framed the salvage process as purely timber-related and characterized government interventions as actions that could affect salvage rates, probably on private lands. A further development of the model would explicitly recognize that some government action could include salvage of timber on public lands. It also could incorporate in that model some expression of how nontimber and nonmarket values are affected by that public salvage. That is an area worthy of additional research.

Using the theoretical construct described in this article, we were able to quantify how salvage tended to benefit owners of damaged timber and consumers but harmed owners of undamaged timber. Consistent with this, the higher the rate of salvage, the greater the wealth transfers from owners of undamaged timber to owners of damaged timber and to consumers. If government efforts are effective in increasing the quantity of salvage entering timber markets, then these efforts accentuate these transfers. Nevertheless, after such disasters affecting forests, emergency response is time- and cash-constrained. Timber salvage decisions are set in the context of decisions regarding public health, housing, and other immediate concerns following the catastrophe. Distributional and equity considerations regarding the expenditure of public funds could affect this decision calculus.

Endnotes

[1] Lupold (1996) describes how government spending that directly aided the salvage effort was several orders of magnitude smaller than the potential value gained from salvage, \$100 million, which he reported was for the targeted salvage volume. However, this did not include expenditures related to salvage of hurricane-damaged timber on government-owned lands. In the case of Hugo, nearly all of the government salvage came from the Francis Marion National Forest. In the model presented in this article, we do not explicitly account for salvage of public timber and instead assume that salvage decisions therein are affected in the same way that salvage decisions are set on private lands-based on whether the timber has a nonzero stumpage price. Obviously, the decision process for public timber salvage is likely to be different from this, perhaps including consideration of nontimber and nonmarket values affected by salvage in the forests on these public lands.

- [2] We refer to damaged timber as timber that is severely enough damaged that it will lose all value due to its recent immediate death or because it has sustained injuries and/or sustained physical wood injuries so great as to leave it no longer increasing in value over time. Damaged inventory thus includes both killed and such severely damaged timber. Undamaged inventory is that portion of the inventory (volume) that was not damaged by the event. Undamaged timber is synonymous with “green” timber: it is timber not significantly physically affected by the damage agent. After the salvage period ends, all remaining timber inventory and harvested volume are undamaged and green in every sense.
- [3] Clearly, some owners of damaged timber also hold undamaged timber, so as is made clear in the subsequent paragraphs, they are benefited and harmed in ways that are opposite in time through opposing timber price and quantity effects. This reality, however, does not affect our seemingly abstract results. Similarly, consumers (mills) are also timberland owners and are also affected on the supply side, but calculations are unchanged.
- [4] Referring to Figure 1, B_{00} corresponds to point h and B_{10} to point k . B_{10} , the intercept of the demand curve in the first period following the storm, would correspond to point i in Figure 1.
- [5] The larger the elasticity of the salvage adjustment parameter with respect to time, the greater the incentive to salvage more quickly. Because greater volumes of salvage would accentuate the price depression caused by salvage, an optimal salvage path (V_1, V_2, \dots, V_{t+j}), where j is the last period of salvage harvest, should exist. Identifying this time path is beyond the scope of this article.
- [6] This adjustment parameter estimate was made by setting demand equal to total supply for each randomly selected values of elasticities, inventory volumes, salvage volumes, and price effects: $D_t(P_t) = S_t(P_t, I_t) + \hat{\kappa}^{-1}V_t$, where $\hat{\kappa} = V_t/[D_t(P_t) - S_t(P_t, I_t)]$ and V_t is the unadjusted salvage volume for the period, D_t is the undamaged-equivalent volume (quantity) of timber demanded at price P_t , and S_t is the undamaged timber supplied at price P_t , and inventory volume I_t for that period.
- [7] These authors calculated the parameter to range from 1.5 to 2.0.
- [8] Note that the welfare effects of Hugo at base elasticities and volumes of inventory, mortality, and salvage based on the median price effects of Prestemon and Holmes (2000) are different from the average effects identified by the bootstrapping simulation (reported in Table 2). This difference occurs principally because the median price effects were only one possible set of price effects considered; other replicates of the price effects found by Prestemon and Holmes were sampled in the simulation. The salient feature of the results shown in Figure 3 is the magnitude of the difference in the welfare generated by the observed versus simulated salvage rates.

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An error on the reported percentage of damaged timber salvaged following Hurricane Hugo was carried erroneously throughout the article. The correct value is 37%. This did not affect any of the welfare analyses, but it did affect how the costs and benefits of timber salvage were expressed for each percentage change in timber salvaged in several instances in the text. Additionally, it required rescaling of the horizontal axes of two figures and the subheadings of two tables.

Lines 10 through 15 of the Abstract on p. 495 should read: "... surplus. Results show that, for this large-scale disturbance, the economic surplus generated by salvage averaged \$2.8 million for each percentage change in the volume of salvaged timber up to the observed salvage rate (~37%). Consumers benefited by an average of \$2.9 million for each percent of the damaged timber that was salvaged, producers of salvaged timber benefited by \$2.3 million for each percent salvaged, and producers of undamaged timber lost an average of \$2.4 million for each percent salvaged. . . ."

The horizontal axis numbers in Figures 3 (p. 507) and 4 (p. 508) should appear as: 0, 9, 19, 28, 37, 47, 56, 65, 75.

The subheadings on the salvage percent in Table 4 (p. 508) should be: 0, 22, 36.54 (Observed), 44, 66.

The subheadings on the salvage percent in Table 5 (p. 508) should be: 0, 25, 37.78 (Observed), 49, 74.

Line 4 in the first column on p. 498 should read: "... and a volume equivalent to about 37% of that 21% of killed. . . ."

Line 4 of the Results on p. 504 should read: "... salvage levels (~37%). Surplus changes are disaggregated. . . ."

Line 10 in column 1 on p. 507 should read: "... the observed salvage quantities ranged from 0 to about 74%. . . ."

Lines 13–18 in column 2 on p. 507 should read: "... yielded 12.3 m^{-3} for sawtimber and 2.85 m^{-3} for pulpwood, averaging 7.6 m^{-3} and yielding \$3.3 million of net benefits in southern pine timber markets. At the observed salvage rate (~37%), the marginal economic surplus generated was 9.3 m^{-3} for sawtimber and 1.9 m^{-3} for pulpwood, and the two combined yielded about 5.7 m^{-3}"

Line 23 in column 2 on p. 507 should read: "... vesting that exceed even the 74% shown."