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The Influence of Forest Management on Vulnerability of Forests to Severe Weather

Robert H. Beach, Erin O. Sills, Tzu-Ming Liu, and Subhrendu Pattanayak

Robert H. Beach, senior economics, Enviromental, Technology, and Economics, Program, RTI International, Research Triangle Park, NC 27709-2194; **Erin O. Sills**, associate professor, Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695; **Tzu-Ming Liu**, assistant professor, Kainan University, Luchu, Taiwan; **Subhrendu Pattanayak**, associate professor, Duke University, Durham, NC.

Abstract

Excessive wind, ice, and snow regularly cause major disturbances to forests in many parts of the world, significantly impacting both ecological conditions and economic returns to forest landowners. These events cause immediate losses for landowners, and the broken and uprooted trees left in the wake of a storm increase the risk that wildfires, disease, and pest outbreaks will cause secondary damage to the surviving trees. Although weather severity (e.g., windspeed and duration, or form and amount of precipitation) is clearly an important factor in the occurrence and severity of forest damage, site conditions, tree characteristics, and stand characteristics play a major role in determining resistance of a forest stand to wind, ice, and snow loading. However, the relationships between site, tree, and stand characteristics and weather damage are complex and vary spatially and temporally. In this article, we review and synthesize the literature on the risk of forest damages from severe weather—focusing on wind, ice, and snow—and the factors that influence vulnerability. Forest management decisions are found to play an important role in influencing risk associated with severe weather events. The risk of damages can be managed through strategies such as selection of planting site and species, stocking, and selection and timing of silvicultural treatments. Optimal management strategies under endogenous risk vary based on the probability of damage and management objectives.

Keywords: Damage mitigation, ice, natural disturbances, forest policy, risk management, wind.

Introduction

Natural disturbances play an important role in forest stand dynamics and ecology, with effects that are highly dependent on characteristics of the specific disturbance (Foster and Boose 1995). Severe weather events that bring high winds or heavy precipitation or both (e.g., hurricanes and ice, snow, and hailstorms), drought, flooding, lightning strikes, wildfires, and disease and pest outbreaks are a regular feature of forest landscapes. Although these disturbances may serve important ecological functions, they also significantly—and usually negatively—affect economic returns to forest landowners. Wind, ice, and snowstorms affect large areas of forest relatively frequently in some important timber production regions. These storms impact forest landowners by causing the loss of merchantable timber, increased risk of secondary damages to wildlife and from disease and pests in damaged stands, and depressed timber prices in the immediate aftermath of events that cause widespread damage. These risks have led to considerable interest in identifying factors that influence damage levels as well as ways to mitigate damages.

To optimally manage risk, it is necessary to identify and characterize the hazards faced, assess the risk associated with these hazards, identify options to mitigate risk, choose the optimal combination of options given the manager's objectives (e.g., producing amenities or maximizing profitability of timber production), and implement the strategy selected. In the case of forested landscape management, these tasks are complicated by long planning horizons, which lead to substantial uncertainty concerning future prices, production costs, forest policies and regulations, and objectives, in addition to uncertainty regarding severe weather impacts (Wilson and Baker 2001). Spatial and temporal heterogeneity combined with the infrequency of major storms impacting a given area (compared with a human lifespan) make it relatively difficult to learn from previous storms. Damage severity depends on the complex

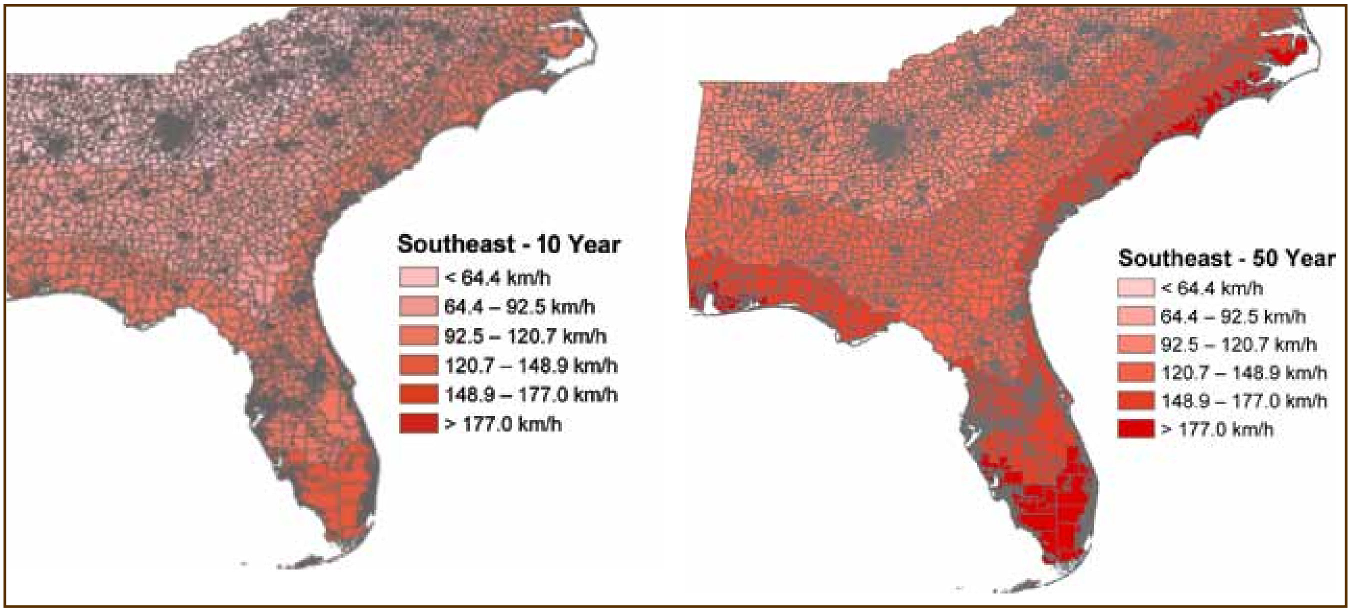

Figure 1—Simulated peak hurricane windspeed associated with hurricanes in the Southeast United States over 10- and 50-year periods using FEMA's HAZUS-MH model. In (a), which is for a 10-year period, only southern Florida and a few coastal census tracts in Alabama, South Carolina, and North Carolina are expected to experience hurricane-force winds (greater than 119 km per hour) within this time-frame. Over a 50-year period, however, the entire region is expected to have winds of at least tropical storm strength, with much higher winds in some coastal areas, as shown in (b). Source: FEMA HAZUS-MH model.

interaction of numerous tree, stand, and site characteristics. For instance, although windspeed is likely to be the most important determinant of timber losses, topography, soil conditions, planting density, species, stand age, the presence of gaps and edges, and other factors determine a stand's resistance to wind loading.

Many studies focus almost exclusively on biophysical properties of forest plots or individual trees to explain differences in damages without explicitly examining the role of landowners' forest management decisions in influencing those properties. However, forest management decisions can change susceptibility to wind damage through effects on tree and stand characteristics such as tree species, tree height, tree diameter, crown area, rooting depth and width, and stand density (Dunham and Cameron 2000, Kerzenmacher and Gardiner 1998, Peltola and others 1999, Peltola and others 2000). Stand age and forest structure may also contribute to vulnerability of forests to high winds (Everham and Brokaw 1996, Francis 2000, Mitchell 1995, Ruel 1995). Silvicultural treatments such as thinning and clearcutting adjacent stands are important as well (Foster 1988, Lohmander and Helles 1987, Mitchell 2000, Wilson and Baker 2001). Similar factors have been related to the degree of ice damage to forests (Bragg and others 2003, Van Dyke 1999), though with different magnitudes and, in some cases, opposite direction of effect. Overlooking the impacts of management decisions on the vulnerability of a stand to weather damages may lead to inefficient decisionmaking by policymakers and private landowners.

In this article, we review and synthesize the literature on the risk of forest damages from severe wind, snow, and ice, the factors influencing the extent of damages in the event of severe weather, alternatives for mitigating weather damages, and policy implications. This type of information can inform forest management decisions and increase the efficiency of policy for managing public forest land as well as public policy that encourages timber stand management and compensates landowners for weather damages.

Severe Weather and Forest Impacts

This section describes characteristics of severe weather storms and selected major events that have taken place in recent years as well as resulting impacts on forests. These impacts include a variety of damages to trees because of excessive loadings by high winds, ice storms, and snow accumulation. In addition to immediate uprooting and stem breakage, heightened tree mortality can continue over time as a result of substantial crown loss. Even trees that recover may have suffered permanent internal damage that reduces wood quality. In addition, damaged stands are more prone to secondary damages from fire, disease, insects, and competing plants.

High Winds

Hurricane-strength winds can cause severe defoliation and directly damage and kill trees through uprooting, breakage and loss of minor and major branches, and stem breakage. Biodiversity is affected through an increase in gaps of broken and uprooted trees and reallocation of light, water, nutrients, and other resources (Nowacki and Kramer 1998). The amenity value of a forest can decrease because of the higher proportion of treefall gaps. Wind damage imposes costs on commercial forestry owing to reduction in timber yields, unscheduled and costly thinnings, and added uncertainty for forestry planning (Quine and others 1995). In addition, broken and uprooted trees left unharvested can lead to additional costs by increasing the probability of disease outbreaks, insect infestations, and wildfires in the remaining growing stock as well as increasing the costs of containment.

Between 1900 and 2005, an average of 1.6 hurricanes per year made landfall between Texas and Maine, with an average of 0.6 major hurricanes (category 3 or above on the Saffer-Simpson scale) annually. In 2004 and 2005 alone, seven major hurricanes had an impact on the United States (Blake and others 2006). Figure 1 shows peak windspeeds associated with hurricanes in the Southeastern United States that are expected in 10-year and 50-year periods based on estimates from the Federal Emergency Management Agency's HAZUS-MH model. Within a 50-year period, the entire Southeast is expected to have winds of at least tropical storm strength.

Hurricanes resulting in the greatest loss of timber from 1900 to 2000 were the Hurricane of 1938 (in New England) and Hurricanes Camille (1969), Frederic (1979), Hugo (1989), Opal (1995), and Fran (1996) (Lutz 2005). For example, Hurricane Hugo swept through South Carolina on September 21, 1989, damaging more than one-third of the State's timberland. The damaged volume of timber was estimated to be 36.8 million m^3 (Remion 1990). More recently, Hurricanes Katrina and Rita damaged more than 2 million ha of forest in the gulf coast States, leading to timber losses of almost $6 billion for affected landowners (though an estimated one-third of these losses may be recovered through salvage efforts) (SAF 2005).

Other regions are also affected by high winds. On average, there are almost 1,000 tornadoes per year in the United States, mostly in the continental interior. Although many are relatively small and weak and cause little damage, a small proportion do considerable damage to forests (see Peterson 2000). Dale and others (2001) estimate that tornado damage in the United States averages $154 million annually. Other windstorms also occasionally result in major damages, such as the July 4, 1999, windstorm that severely impacted approximately 193 000 ha of Minnesota forest (Mattson and Shriner 2001). The hurricane-force winds that affect the coastal Pacific Northwest have a return interval of about 20 years (Wilson 2004).

Ice and Snow Storms

Recurring ice and snow storms are a significant hazard to forests in temperate climates. Snow or ice causes damage when the weight of frozen precipitation exceeds the buckling load of the portion of the tree bearing the load, causing bending or breakage. Bending can result in permanent internal damage without external signs of damage. There are important interactions between winter precipitation and wind because windspeeds required to cause damage are lower for trees loaded with snow and ice, all else equal. Every winter, ice and snow storms affect portions of eastern North America and Europe to some degree, with occasional major events covering millions of hectares and causing millions of dollars in damages. The majority of research on ice and snow damage has been conducted in these regions. Below, we focus on ice storms, recognizing that heavy snow can produce similar damages, particularly in the case of unusually wet snow.

Ice storms require a layer of warm air, with temperatures above freezing, between layers of air that are below freezing. As frozen precipitation falls through the layer of warm air, it melts and reaches the cold lower layer as rain. As the water droplets fall through this cold surface layer, they become supercooled, which means that the water in the droplets is cooled to temperatures below 0 °C without freezing. When this supercooled liquid strikes a cold surface, the impact triggers an almost instant transformation to a smooth thin layer of ice. Although ice storms can result in significant accumulation and major damages when conditions for ice formation are favorable, ice accumulation depends critically on characteristics of the layers of air and the water droplets. Small temporal or spatial differences in air temperature and droplet size frequently result in freezing rain mixed with sleet, snow, or nonfreezing rain, which substantially complicates area-specific forecasting of ice formation and accumulation (Heidorn 2001).

Ice accumulation is one of the most frequent forest disturbances in temperate regions (Irland 2000). However, most ice storms produce minimal ice accumulation and do not result in substantial losses. Some locations in North America experience at least some ice accumulation every 1 to 2 years on average, though most areas have return intervals of 5 years or more (Bragg and others 2003). Ice storms are estimated to occur about every 5 years in Northern New England States (Smith and Musser 1998), while ice storms have been estimated to occur every 6 years in the natural range of loblolly pine (*Pinus taeda* L.) (Shultz 1997) and every 5 to 12 years inland from the Gulf of Mexico (Bragg and others 2003).

Storms resulting in major damages are estimated to have a return time of 20 to 100 years in Northern North America (Van Dyke 1999). Several recent ice storms have caused catastrophic damages over very large areas. For instance, a 1998 ice storm in southeastern Canada and the Northeastern United States damaged over 10 million forested hectares (Irland 1998, Miller-Weeks and others 1999). The Southern United States is less prone to major ice storms, but the region has experienced a number of major events such as the December 2000 ice storms in Arkansas that damaged an estimated 40 percent of the 7.4 million ha of forest in the State (Bragg and others 2003).

Steven Katovich, USDA Forest Service, Bugwood.org.

Figure 2—Bending and windthrow due to a major windstorm. Illustrated in this picture is wind damage in quaking aspen (*Populus tremuloides*) in Chequamegon National Forest, northern Wisconsin, resulting from a windstorm in July 1999. The majority of damage is in the form of bending and windthrow rather than stem breakage.

Tree Damage and Mortality

Wind can cause severe defoliation and can directly injure and kill trees through obvious damage such as uprooting (see Figure 2), breakage and loss of minor and major branches, and stem breakage (see Figure 3). Trees can be permanently damaged by the bending caused by wind, ice, and snow (see Figures 2 and 4), and compression injuries may be present even in seemingly undamaged trees. Severe bole injuries can lead to sap rot, slower growth, formation of compression wood, unusual growth rings, and intercellular voids between rings (Bragg and others 2003). Winds often carry saltwater inland, and foliage may die on trees that receive salt spray, although most affected trees will grow new leaves and recover (Gresham 2004).

The type of damage suffered tends to differ by tree size. Younger trees are more likely to bend with the wind without suffering serious damage, whereas older trees are more likely to uproot or break. Similarly, saplings and small-diameter trees can become seriously bent by ice accumulation, although these trees often recover. As diameter increases, the proportion of bending to breakage decreases. The majority of ice damage in larger trees is loss of branches and breakage of the main stem within the crown

Ronald F. Billings, Texas Forest Service, Bugwood.org.

Figure 3—Stem breakage from a tornado. Widespread stem breakage is pictured in loblolly pine (*Pinus taeda*) from tornado winds in Texas. The damage appears very similar to that caused by major hurricanes.

USDA Forest Service Archives, Bugwood.org.

Figure 4—Tree bending from ice accumulation. The bending that can result from the weight of ice accumulation brought by a significant ice storm is shown in this picture. Although many of these trees will survive and may appear undamaged after they have straightened themselves, permanent internal damage may be present.

(Van Dyke 1999). Understory trees may be damaged by windthrown trees or broken portions of trees. In addition, tree species differ in their ability to withstand high winds, ice, and snow. Key factors include shape and size of the crown, rooting depth, and wood strength.

Whether a tree recovers from damage depends significantly on crown loss. Hardwood trees are not usually killed by breakage, but those with greater than 75 percent crown loss are likely to die. Conifers broken below the live crown or that have lost a majority of the crown will generally not survive (Van Dyke 1999).

Increased Risk of Secondary Damages

The immediate loss of timber is not the only damage imposed by weather events. Uprooting of trees also causes significant soil turnover and increases risk of soil erosion (Lutz 1940, Lyford and MacLean 1966, Meyers and McSweeney 1995). In addition, the increased number of broken and uprooted trees raises the risk of wildfires as well as disease and pest outbreaks for the surviving trees, whereas newly created canopy gaps provide opportunities for plant invasions. The presence of damage and decay may also increase vulnerability to future wind, ice, and snow (Bragg and others 2003).

Fire hazard may be increased following major storms that result in increased dead tree biomass and low-growing plants (Myers and Van Lear 1998). Federal and State forest resource departments frequently mention the heightened fire risk following major storm events as a key consideration for short-term forest recovery and management. In addition to increased fuel loading, access may be limited by downed trees, which further increases risk (Irland 2000). Myers and Van Lear (1998) examined the historical interaction between hurricanes and fires and concluded that these interactions had a major impact on the composition and structure of ecosystems in the Southern United States, although modern fire suppression efforts may have obscured this relationship in recent years.

Young trees can suffer bark damage following severe bending, which may increase susceptibility to disease. Any wounds permit disease fungi to infect damaged trees. Stain fungi may infect exposed wood within weeks, leading to wood quality degradation. Also, sap rot has been linked to sudden exposure of the stem to intense sunlight following canopy damage (Bragg and others 2003).

Broken and uprooted trees left unharvested also can lead to detrimental insect attacks on the remaining stand (Bakke 1989, Ravn 1985, Schroeder and Eidmann 1993). For example, severe outbreaks of spruce bark beetle (*Ips typographus*) occurred in Norway in 1971–1981, damaging trees equivalent to 5 million cubic meters of timber as an indirect consequence of extensive wind damage (Bakke 1989). Cain and Shelton (1996) reported that an ice storm in southern Arkansas contributed to a southern pine beetle (*Dendroctonus frontalis*) outbreak. Hurricane Hugo caused large areas of loblolly pine (*Pinus taeda*) to be broken or uprooted, and these trees were susceptible to insect infestations (Yates and Miller 1996). Within months of Hurricane Katrina, virtually all of the downed material in De Soto National Forest in Mississippi had been infested by bark beetles and woodborers, and bark beetles (*Ips* engravers) had begun to infest and kill root-sprung trees (Meeker and others 2006).

Gaps resulting from tree fall and defoliation present opportunities for establishment of invasive plants (Burke and Grime 1996, D'Antonio 1993, Davis and others 2000, Hobbs 1989, Hobbs and Huenneke 1992, Réjmánek 1989), which may change forest structure and decrease populations of indigenous species. Increased light levels from large canopy gaps may also encourage the growth of invasive plant species, which could influence forest succession and alter ecosystem function. Snitzer and other (2005) found that mean cover percentage of invasive plants increased by 47.8 percent in high-light canopy gaps created by Hurricane Isabel and by only 4.2 percent in less-damaged forest. Invasive species such as cogongrass (*Imperata cylindrica* (L.) P. Beauv.) can also contribute to heightened wildfire risk (SAF 2005).

Economic Impacts

Because major severe weather events can cause the direct loss of great quantities of timber, large numbers of landowners can suffer revenue losses and the entire forest products sector can be affected. Revenues from salvage operations are generally lower than those from typical harvests because saleable volume is reduced, particularly in cases where there is extensive stem breakage, but also because fungal decay reduces wood quality. At the same time, costs of salvaging damaged stands are usually higher than costs of conventional harvesting. Manley and Wakelin (1989), who took into account the effects of increased costs and reduced revenues, calculated that the discounted net present value of an impacted forest decreases by as much as 11 percent for a 1-percent annual level of damage. Forest landowners also may be affected by depressed timber market prices (at least in the short run) because of the large volume of salvaged timber on the market. Other things being equal, greater production risk unambiguously reduces optimal rotation length and decreases expected returns to forest land and land values, although the effects of price risk are ambiguous (Prestemon and Holmes 2000, Prestemon and others 2001). Prestemon and Holmes (this volume) provide more information on the economic impacts of hurricanes on landowners.

Factors That Influence Vulnerability

The severity of wind, ice, and snow damage depends on the interaction of numerous biological, topographic, stand, tree, and management factors. Before reviewing forest management activities to mitigate damage, we need to know what factors most strongly influence the severity of damage caused by wind, ice, and snow. Many empirical studies have indicated that the susceptibility of forests to damage depends on tree and stand characteristics such as species, height, diameter, crown area, rooting depth and width, stand density, and presence of forest gaps or edges (Dunham and Cameron 2000: Kerzenmacher and Gardiner 1998; Nykänen and others 1997; Peltola and others 1999, 2000; Quine 1995; Solantie 1994; Valinger and others 1993; Zeng and others 2004). However, the statistical significance and even the direction of the effect of individual variables differ across studies. The natural systems involved and the interactions among factors are complex, so these apparent inconsistencies may be a result of nonlinearities in response and the omission of individual variables in some studies.

Weather Severity

The intensity and duration of severe weather events are among the most important determinants of forest damage associated with severe weather. The greater the intensity and duration of loading placed on trees, the higher the likelihood this loading will exceed critical thresholds and cause damage. However, few empirical studies have explicitly incorporated spatially differentiated, quantitative, physical measures of severity or duration or both (e.g., peak wind gusts or ice accumulation). Storm conditions can vary considerably within a relatively small region, so local storm severity must be gauged accurately if researchers are to properly evaluate the impact of local management activities on damages.

Greater windspeed and duration mean that more force is exerted on trees. Thus, the probability of uprooting, stem breakage, or other damages is expected to increase with windspeed and duration. However, forests in areas where strong winds are common may be less susceptible to catastrophic damage because they have developed higher wind resistance in response to greater normal loading. For related reasons, wind direction also influences damage. Storm winds that come from a direction other than the typical prevailing winds may cause greater damage (Ruel 1995). For winds of a given velocity, wind direction affects the loading placed on objects.

Similarly, the greater the accumulation of ice or snow on trees, the greater the likelihood that the trees will suffer structural failure. The National Weather Service declares an ice storm when there is at least 0.6 centimeters of ice accumulation, but minor glazing (0.6 to 1.3 centimeters) may cause little damage (Lemon 1961). Major events may result in accumulations as high as 10 to 20 centimeters (Bragg and others 2003). Depending on weather conditions, ice may remain on trees for some time before melting or being shed. As ice is retained on the trees for longer periods, damages increase (Schultz 1997).

Numerous mechanistic simulation models have been used to simulate the probability of structural failure in response to increased wind and ice, or snow loading or both (Blennow and Sallnäs 2004, Dunham and others 2000, Miller and others 2000, Peltola and others 1999, Talkkari and others 2000). These models generally predict critical windspeeds and ice or snow loading or both required for uprooting and breakage as a function of site, tree, and stand characteristics based on biomechanical properties. Several models incorporate both sources of risk to account for interactions between ice and snow loadings and wind risk (e.g., Miller and others 2000, Talkkari and others 2000).

A few empirical studies have included windspeed or ice and snow accumulation as explanatory variables in their regression models. Ramsey and others (2001) incorporated windspeed and duration to explain the variation in hurricane damage among forest types along the Atchafalaya River basin of Louisiana. Using forest-type distribution from Landsat Thematic Mapper image data, hurricane-impact data from very high-resolution radiometer images, and windspeed and duration calculated from a wind field model, they found that the estimated impact for each forest type was strongly related to the duration and speed of extreme winds from Hurricane Andrew. Proulx and Greene (2001) found higher damage in northern hardwoods associated with greater ice accumulation, but Olthof and others (2004) did not find a direct relationship between ice storm precipitation and forest damage.

Site Conditions

Site conditions are commonly identified as influencing severe weather damage. These are physical properties of a location, such as topography and soil conditions, that cannot typically be directly modified in a particular stand through management actions.

Numerous studies have shown that local topography is a key determinant of risk of wind damage (e.g., Boose and others 2004, Foster and Boose 1992, Kulakowski and Veblen 2002, Quine 1995, Ruel 1995), but the relationship is complex, and specific topographic factors identified as important differ from study to study. Impacts may be increased when there is a barrier behind the stand (Talkkari and others 2000). Stands at higher elevations, on easterly slopes, and near ridges were more likely to suffer wind damage in Colorado (Kulakowski and Veblen 2002). The key issue for topography seems to be its influence on the probability of local windspeeds reaching critical speeds (Quine 1995). In many cases, the topography variables are serving as proxies of local wind intensity in the absence of direct measures of windspeed. Links between topography and ice and snow damages are less studied, but ice damages are increased at greater elevations (Olthof and others 2004, Rhoads and others 2002, Van Dyke 1999) as well as on steep slopes (Proulx and Greene 2001, Van Dyke 1999).

Findings about relationships between soil conditions and wind damage are relatively consistent (Wilson 2004).

Soil saturation is an important factor affecting the probability of windthrow. When hurricanes or other wind storms pass through an area following periods of heavy rainfall, blowdown is more likely (Ruel 1995). Deeper, well-drained soils lower the risk of wind damage. Beese (2001) found wet soil to be one of the largest contributing factors to wind damage. Similarly, damages from ice and snow are greater for wet soils (Van Dyke 1999). Other conditions that prevent establishment of deep roots, such as the presence of boulders, bedrock, or other barriers close to the surface, also increase the probability of uprooting (Rhoads 1999).

Tree Characteristics

A number of studies have focused on relationships between wind, ice, and snow damage and various tree characteristics. Tree characteristics of interest include species, health, age, size, height-to-diameter (H/D) ratio, crown shape, and canopy position.

Conifers tend to be more susceptible than hardwoods to hurricane damage (Foster 1988, Foster and Boose 1992, Jalkanen and Mattila 2000), though there are differences in susceptibility between taxa related to several species characteristics, including crown form, branching, rooting depth, center of gravity, and wood strength. Species susceptibility to hurricane-related damages also varies across types of damage, including breakage, uprooting, exposure to saltwater, and secondary insect and disease damage (Barry and others 1998). In addition, trees planted outside their natural range may be more susceptible to damage.

Differences in susceptibility to ice storms are related to species characteristics such as crown form, crown size, branch thickness, branch angle, root depth, and wood strength. Trees that have an excurrent form (apical dominance) are better able to shed ice and snow than those with decurrent form, and the vase-shaped form of many elms and oaks makes these trees especially vulnerable to ice and snow accumulation (Van Dyke 1999). Trees with branches that are pliable may better withstand ice and snow accumulation because they can shed ice or transfer the force to other parts of the tree, the ground, or neighboring trees. However, wood that is cold, “green,” or less dense has lower resistance to breakage than warm seasoned wood of the same species (Bragg and others 2003).

Root and stem rots, cankers, insect infestation, or any form of prior injury increases the probability of wind damage (Wilson and Baker 2001) and ice damage (Van Dyke 1999) (with the possible exception of defoliating insects or other agents that reduce crown surface area). Trees are likely to break at the point of decay when exposed to excessive loading by wind, ice, and snow. For instance, trees with advanced beech bark disease experienced more ice damage (Rhoads and others 2002). Vine coverage may also increase susceptibility to glaze damage by increasing the surface area available for ice accumulation (Bragg and others 2003). Boose and others (2001) examined hurricanes affecting New England since European settlement in 1620 and found that forest damage from an event was strongly dependent on natural disturbance history. High proportions of compression wood, which can form in response to tree bending in past weather events, may increase storm damage (Dunham and Cameron 2000).

Stand age and tree size may also contribute to forest vulnerability to high winds. Although age and size are generally correlated, different studies alternately focus on age, height, diameter, or H/D ratio. Many studies indicate that susceptibility to wind damage increases with increasing stand age during the initial decades of forest development (Everham and Brokaw 1996, Francis 2000, Jalkanen and Mattila 2000). Foster (1988) found that conifers’ susceptibility to wind damage increases rapidly after age 15, but hardwood damage increases more gradually with age. Foster and Boose (1992) found wind damage increased approximately linearly with stand height. Ameteis and Burkhart (1996), on the other hand, argued that older, larger trees are stronger and have greater resistance to damage.

Francis (2000) and Greenberg and McNab (1998) also reported increasing uprooting with increasing tree height. Francis (2000) showed that tree height strongly influenced wind damage in San Juan during Hurricane Georges. Other authors suggested that height relative to the height of surrounding trees is the factor that most strongly determines susceptibility to wind damage (Asner and Goldstein 1997, Francis and Gillespie 1993, Hedden and others 1995). Jalkanen and Mattila (2000) and Francis and Gillespie (1993) both showed that the susceptibility of a stand to wind damage was increased by larger mean diameter. Achim and others (2005) found that stem mass was the factor most highly correlated with wind damage. Francis and Gillespie (1993) related gust speed to tree damage in Hurricane Hugo, and their results indicate that the probability of a tree suffering some form of damage increases with increasing tree diameter.

Findings were mixed for ice damage. Bragg and others (2004) found the lowest levels of damage from ice in the oldest plantations. They found that the smallest trees were much more likely to bend severely in response to ice loading, that intermediate-sized trees had both bending and stem breakage, and that the largest trees had little of either but had more crown damage and branch loss. Rhoads and others (2002) found heavy ice damage in intermediate-sized trees that were 24 to 28 years old but little ice damage in younger stands in the affected forest. Proulx and Greene (2001) found that very small trees (3.2 to 9.5 cm in diameter) were more likely to suffer damage, that small and intermediate trees (<17.8 cm in diameter) were more likely to bend or snap, and that large trees were more likely to lose branches. Van Dyke (1999) indicated that older trees may be more susceptible to injury from ice because they have larger crowns, greater likelihood of internal decay, and decreased branch flexibility.

A number of studies have examined H/D ratios rather than either height or diameter individually and have typically found that larger H/D ratios tend to increase the risk of damage from high-wind events (Wilson and Baker 2001), snow (Kato and Nakatani 2000), and ice accumulation (Van Dyke 1999). However, Valinger and Fridman (1997) found that the ratio of the H/D ratio to the upper diameter (measured at 3 or 5 meters) was the best predictor of the probability of snow and wind damage, and that for a given upper diameter, the probability of damage was higher for a site with trees of low H/D.

In addition to looking just at tree height, diameter, or H/D ratio, some studies examine the influence of crown shape and canopy position. Mechanistic models of critical wind, ice, and snow loading generally include crown size and shape because greater crown surface area increases the drag coefficient and potential for loading from accumulation (Peltola and others 1999, Talkkari and others 2000). Empirical observations and models have generally supported this assumption. Foliated trees and trees with large crowns have more surface area for ice and snow accumulation and for wind to act on, increasing vulnerability to damage; however, damage is lowered by greater crown symmetry (Bragg and others 2003, Kato and Nakatani 2000, Van Dyke 1999). Beese (2001) found greater wind damages in trees with larger crowns in montane coastal forests in British Columbia. Hardwoods are less susceptible than conifers to damage from ice or snow storms that occur during the winter months, when the hardwoods do not have foliage. Mitchell (1995) and Ruel (1995) reported that wind damage depends on canopy density and tree position in the canopy. Van Dyke (1999) indicated that dominant trees are more likely to suffer ice damage.

Stand Characteristics

Disturbances that open the canopy may increase the severity of damage from subsequent windstorms (Everham and Brokaw 1996). Stand density, thinning regime, and the presence of edges and gaps each have been found to influence forest damage from severe weather. However, the effects of density on forest damage depend on the interplay of a complex set of factors. Higher densities may lead to greater H/D ratios and trees that are less wind resistant. However, higher stand density may increase the probability of stem bending but decrease the probability of stem breakage because neighboring trees provide support for bending stems (Bragg and others 2004). Wind may move through low-density stands more freely, so that energy is dissipated and wind loadings are lowered. In addition, trees in the interior areas of low-density stands may normally receive higher winds and develop greater wind resistance than those in high-density stands. However, ice damage may be expected to increase at lower stand densities because trees in lower density stands develop larger crowns, and these tend to accumulate more ice and snow (Gardiner and Quine 2000).

It is also possible that bending or breakage of trees results in damage to other trees. When windthrow or breakage occurs in lower density stands, there is less chance that neighboring trees will be damaged (Baker and others 2002). Beese (2001) found that striking of trees by other trees was one of the most common categories of wind damage in their study region.

Recent thinning can increase vulnerability to wind, ice, and snow. Thinning removes structural support of proximate trees, and recently exposed pines tend to have relatively weak stems and ice-accumulating surfaces more concentrated in the crown (Bragg and others 2003). Burner and Ares (2004) found that thinning increases susceptibility to ice damage. Jalkanen and Mattila (2000) suggested that thinning will increase wind damage but decrease snow damage. Peltola and others (1999) simulated critical snow loading for both uprooting and stem breakage for managed and unmanaged stands of Scots pine (*Pinus sylvestris* L.) in southern Finland and concluded that critical snow loading for both uprooting and breakage is lower for unthinned stands than thinned stands.

Proximity to forest edge is highly related to wind (Wilson 2004) and ice storm damage (Olthof and others 2004). Zeng and others (2004) integrated a mechanistic wind damage model and an airflow model with a forest database containing information at the tree, stand, and regional levels and simulated damages for current forest edges and situations where new edges might be created through clearcutting. They found that clearcuttings increased windspeeds at forest edges and increased risk of damage for cases where vulnerable stands remained at the newly created edges. Others have found reduced damage at stand edges, however, especially when the edge has been established for a long time. This is likely due to trees on the edges facing greater wind loading on a normal basis and responding by increasing strength to resist wind loading (Foster 1988).

Management under Endogenous Risk

The probability of a severe weather event occurring is exogenous to the landowner; that is, landowners are unable to influence this probability through their own actions. However, although these events cannot be prevented, their potential impact can be mitigated through forest management, so the extent of severe weather damages to a particular forest area is partially under the landowner's control. Recognizing this endogeneity of risk and understanding the factors that influence damage patterns are of key importance to efficient forest management. Although there is substantial variation in the empirical findings on the most important factors influencing weather damages, there are some common management recommendations. Landowners can incorporate expectations of severe weather damages into their decisions regarding site selection, species selection, silvicultural treatments, and planning for damage recovery to decrease expected impacts (Bragg and others 2003, Lohmander and Helles 1987, Olofsson and Blennow 2005, Persson 1975, Zeng and others 2004). Another strategy for the forest industry is to diversify spatially to manage risk across total forest holdings thereby avoiding the loss of a large share of their standing timber to a single weather event.

Moore and Quine (2000) presented one example of the ability of forest management to mitigate weather risk. They compared wind risk in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) plantations in Great Britain with that in radiata pine (*Pinus radiata* D. Don) plantations in New Zealand using the FORESTGALES simulation model. They reported that the plantations in New Zealand were at greater risk of damage than those in Great Britain because of differences in management even though the New Zealand plantations were subjected to a less severe wind regime. In Great Britain, silvicultural practices have been adopted to reduce density, conduct more careful site preparation, and reduce thinning. This comparison demonstrates the influence of forest management on the risk of weather damage, but it also demonstrates that mitigation options adopted should reflect the level of risk faced. Managers of plantations in New Zealand have been able to focus on maximizing profit under a less constraining wind risk, and plantations in New Zealand are more profitable than those in Great Britain.

Of course, appropriate response depends on the degree of risk. In cases where the exogenous risk of damages is low, incorporation of weather risk into strategy may result in minimal or no change in optimal forest management.

In contrast, there may be no feasible strategy for reducing damages when the exogenous risk of damages is high other than simply limiting investments and therefore the expected cost of damages. In the intermediate case, where the exogenous risk of damages is significant but there are cost-effective strategies for mitigation, the incorporation of weather risk into decisionmaking may substantially alter optimal forest management practices (Gardiner and Quine 2000).

This implies that any evaluation comparing weather damages on managed and unmanaged sites will be inaccurate if it does not properly account for selection bias. Selection bias arises because the forest management strategies observed reflect decisions made by forest managers based in part on the perceived vulnerability of their stands to weather-related damages and the perceived effectiveness of potential silvicultural actions in those stands. Thus, the value of managing weather risk could be understated if these actions are selectively being undertaken in stands with high expected damages and the outcomes following a storm are compared with those in areas with low expected damages where managers chose to adopt fewer mitigation options. On the other hand, the effectiveness of damage reduction strategies may be overstated if little or no action to reduce impacts is being taken in certain stands because the expected damages in those locations are so large that there are few feasible mitigation options. Thus, careful and systematic program evaluation is needed to account for endogenous selection and to ensure that the effectiveness of damage mitigation options is being assessed after controlling for selection of mitigation options based on perceived baseline risk (Butry 2006).

Damage Mitigation Options

The primary categories of damage mitigation options are site and stand selection, selection and timing of silvicultural treatments, and stand recovery activities. Forest management is unlikely to significantly alter climate, topography, or soils in a given site. However, forest managers establishing a new stand can affect these conditions for forests they manage through site selection. In addition, owners with multiple sites can manage overall risk by selecting a portfolio of sites that offers the desired risk-return profile. Typically, weather risk is not the overriding consideration in the selection of sites for forest investments, but taking the risk of forest damages into account when selecting a site may improve the ability to meet management objectives.

Similarly, among numerous other factors affecting choice of species (e.g., productivity, market forces, objectives of the forest manager), the differential weather risk associated with different species should be taken into account. Some species are more vulnerable to weather damage than others based on crown configuration, rooting, wood strength, and many other factors. In addition, planting trees outside of their natural range may increase their vulnerability to damage (Bragg and others 2003). Selecting a tree species that is less productive or has a lower market price but also provides a reduced risk of severe weather damage may result in a higher expected present value of the stand if the baseline risk of severe weather and the species-to-species difference in expected damages in the event of severe weather are sufficiently large.

The effects of management decisions about stocking, thinning, and pruning on storm damage risk have been identified as key issues in a number of studies. A number of trade-offs are associated with these activities, partly because short-term and long-term effects on risk may differ substantially. For instance, low-density stocking, thinning, or pruning may increase the risk of damage in the short term, but expected damages are reduced farther into the future as trees respond by growing stronger and more resistant to damages. Limited tree-size variation increases susceptibility to developing high H/D ratios in the dominant trees (Wilson 1998). There is typically less variation in tree size in plantations than in naturally regenerated stands, and this may lead to greater H/D ratios of dominant trees, reducing the stability of these trees. To keep H/D ratios down, it is necessary to conduct thinning operations before competition that leads to increased H/D (Wilson and Baker 2001). Similarly, Wilson and Oliver (2000) found that plantation H/D ratios can be lowered by reducing planting density or early thinning to encourage development of strong stems and crowns; later thinning did not appear to be as effective. Also, if the rotation length is reduced sufficiently, the reduction of time at risk of damage may more than offset the increase in expected damages if an event does occur. One of the best defenses against weather damages may be to grow the trees out of vulnerable intermediate sizes as quickly as possible through the application of silvicultural practices such as reduced density and proper thinning and pruning to increase site productivity.

The standard Faustmann equation maximizes discounted net revenue from an infinite series of rotations, accounting for the costs of maintaining land in forest production. The optimal rotation under certainty occurs where the increase in stand value from one additional period of growth is equal to the costs of delaying current and future harvests by one period. Incorporating an exogenous positive probability of damages into the equation unambiguously yields a reduction in optimal rotation length (Martell 1980, Reed 1984, Reed and Errico 1985, Routledge 1980). Under some conditions, increased production risk may also lead to the use of lower intensity production methods such as naturally regenerated stands (Haight and others 1986). Accounting for endogeneity of expected forest damages alters optimal management strategies by explicitly recognizing effects of management decisions on the expected present value of the stand through accounting for changes in expected damages.

Stocking influences, in several ways, damages that result from weather events. Less densely stocked stands may be more vulnerable in the short term because they will have less support from their neighbors. However, less dense stocking increases the growth of individual trees and reduces the time trees require to reach marketable size. In addition, low stand density will result in trees that are more resistant to loading because they are larger and subject to greater loading on a normal basis. One caveat is that low stand density commonly results in trees with larger, less tapered crowns that will tend to accumulate more ice and snow, although their increased strength may offset this effect.

Thinning may result in stronger trees that are more able to withstand wind, ice, and snow (Kato and Nakatani 2000) a few years after thinning but increase the likelihood of damage in the interim. Coates (1997) found that partial cutting doubled the percentage of trees with wind damage in the 2 years after thinning, from 1.1 percent to 2.2 percent but concluded that this increase in damage was too small to warrant changes in management (this increased damage may also be offset by increased tree growth rates that reduce the time spent at risk). Similarly, pruning can increase wind damage if a storm passes through the area soon after the treatment but can reduce damage in the future after trees have strengthened. Pruning was found to result in an increased resistance to snow damage in the short term, though, because the reduced surface area of the crown decreases accumulation. However, to the extent that heavy pruning reduces diameter growth more than height growth, resistance to snow loading may decline in the years after pruning because of increased H/D ratios (Kato and Nakatani 2000).

Thus, in areas that receive severe weather very frequently, managers may be less willing to conduct thinning or pruning because of the high probability that a storm will occur during the period when the stand is more vulnerable. In addition to removing support for remaining trees, thinning operations often cause minor damage to individual trees, and the damage sites can serve as entry points for insects and disease that then become established and infest the stand (Lohmander and Helles 1987). However, there is a reduced probability of trees damaging their neighbors following thinning because the spacing between trees is increased (Bragg and others 2003). In addition, identifying and removing trees most vulnerable to damage during thinning operations may be advantageous. Cameron and Dunham (1999) found that trees that were damaged by wind and snow had significantly more compression wood than did undamaged trees, and Dunham and Cameron (2000) therefore recommended preferentially removing trees likely to contain compression wood.

Because of the complexity of the interactions between various factors affecting expected forest damages, the relative costs and benefits of a particular action will vary spatially and temporally. Thus, optimal management strategies regarding planting density and whether, when, and how intensely thinning and pruning should be conducted need to be determined on a site-specific basis.

If a plan for stand recovery is formulated before a damaging event takes place, this can help mitigate the damage. Salvage efforts after ice storms should concentrate on minimizing economic losses from damage to timber. Timber subject to losing the greatest value to degradation in the short term should be salvaged first, although timber of all ages and sizes may require some remediation to lessen fire danger and insect outbreaks. Salvage of severely damaged pine is more time sensitive than salvage of severely damaged hardwoods because pine is more susceptible to infestation by bark beetles and wood borers, but downed hardwoods should also be salvaged as soon as possible to avoid degradation (Van Dyke 1999). Remedial actions following hurricanes, such as staking saplings upright, are not clearly effective and are feasible only on small areas. In one study, saplings left in a leaning position did not lose measurably more growth than those staked upright, and many righted themselves (Gresham 2004), although it is important to recognize that bent trees may have permanent internal damage. In some cases, severely bent trees will not fully recover and may die or grow at greatly reduced rates. Managers may wish to explore selective harvesting of damaged trees.

Optimal Thinning and Rotation Decisions

As an illustrative example of the implications of treating weather damage risk as endogenous, we examine optimal thinning and rotation decisions. The implications of production risk for optimal rotations have been examined in several previous studies, including Martell (1980), Routledge (1980), Reed (1984), and Reed and Errico (1985), all of which evaluated changes in optimal rotation length under the exogenous risk of forest fires. Each found that optimal rotation age unambiguously declined where production risk was assumed to exist. Thorsen and Helles (1998) modifed these earlier models to treat risk as endogenous, focusing on the timing and intensity of thinning activities to influence the risk of damage. Thinning is one of the silvicultural practices that is most frequently mentioned in the literature as playing an important role in damage risk and as being readily applied.

Thinning offers the benefit of immediate income, and it promotes faster diameter growth of remaining trees, which increases net price received and reduces the risk of windthrow. Thinning also reduces the remaining volume that could potentially be damaged by storms. However, thinnings are costly because of fixed costs of thinning operations and increased risk of storm damage for several years after thinning. These dynamics are complex, but important to consider in determining optimal forest management strategies.

Thorsen and Helles (1998) examined an even-aged forest stand managed to maximize expected present value. They modeled the selection of an optimal thinning strategy and optimal rotation age (at which time the stand is clearcut), taking into account the stand growth function, net timber price, and risk of severe weather damage. Stand density, age, site, tree, and stand characteristics, including time since thinning and thinning intensity, all affect the risk of damage. The damage risk functions describe how the stand's stability is impacted by current and past stand management decisions. The less the risk functions are affected by management decisions, the more resistant the stand is to disturbances such as thinning, and the less important it is to consider the implications of management decisions for weather damage risk. Thorsen and Helles (1998) used numerical optimization procedures to determine optimal management in the case of Norway spruce (*Picea abies* L. Karst.), which they identified as one of the species most often suffering from health or windthrow problems that necessitate salvage harvest of entire stands. Based on their assumptions regarding growth, risk dynamics, storm probability, and other variables, they found that optimal rotation age is reduced from 74 years under no risk to 69 years if storm risk is treated as exogenous, but 71 years when risk is assumed to be endogenous. In addition, the optimal number of thinnings increases from 10 to 11 between the case of no risk and exogenous risk. When risk is considered to be endogenous, the optimal number of thinnings increases to 18, but the intensity of each thinning is reduced. In addition, they found that incorporating endogeneity in determining optimal management increases expected present value of the stand.

The findings of this study are dependent on the growth, risk, and other dynamic relationships assumed. Optimal management will differ across stands depending on baseline damage risk, effects of thinning on growth rates and damage risk, prices and costs, and other variables (Straka and Baker 1991). In addition, this example assumes profit-maximizing behavior, which may be appropriate for forest industry but not for many nonindustrial private forest (NIPF) landowners or public forest managers. NIPF landowners and public forest mangers are expected to consider the amenity value of standing forests, which would add an additional term measuring amenity value to the optimal control problem discussed above. This term would depend on site, tree, and stand characteristics. Nevertheless, treating severe weather risk as endogenous may enable both private and public managers to reduce damage risk while increasing the expected present value of their stands.

Policy Implications

To the extent that weather damage risk is endogenous, private and public forest managers may be able to improve ecological and economic returns by allowing for the effects of their decisions on risk. However, this does not tell us whether any particular strategy should be adopted in the case of any specific stand. Options to be adopted depend on managers' objectives and the cost of the option relative to the reduction in risk provided. Many key factors interact in a very complex manner to influence weather risk, making it vital to consider case-specific conditions in making decisions regarding mitigation of weather risk. It is important to consider joint risk of different types of weather events, which may reinforce or contradict each other.

Policy implications are expected to differ among forest industry, NIPF landowners, and public forest managers because these groups have different objectives. Forest industry managers are expected to be profit maximizing, whereas NIPF landowners likely have more varied objectives and value nontimber amenities of standing forests more highly. Damage mitigation options that would be optimal for forest industry may be less suitable for NIPF lands or vice versa, depending on the joint effects of the strategies on damage risk, expected present value, and stand amenity values. Similarly, public land managers are expected to take various nontimber objectives into account. The presence of endogenous storm risk may be an opportunity for the public sector to provide incentives for private landowners to take actions to mitigate storm damage, especially where private inaction could result in secondary insect and disease infestations or other conditions that could have negative effects on neighboring properties.

Private Forest Management Decisions

For forest industry, management of weather risk should be selected to maximize expected profitability, assuming risk neutrality. Under risk neutrality, firms are interested in maximizing the expected value of profits without regard for variability, whereas risk-averse firms would be willing to accept lower expected returns in exchange for reduced variability of profits. Decisionmaking under risk aversion could be analyzed using similar methods but would have to account for risk tolerance. One strategy when operating under risk is to reduce rotation age. Accounting for damage risk reduces the optimal rotation age relative to that obtained by solution of the standard Faustmann equation under certainty (Gardiner and Quine 2000, Haight and others 1996). However, if risk is truly endogenous, then managers may be able to alter practices to mitigate risk and potentially even increase expected present value of a stand, as described in "Optimal Thinning and Rotation Decisions." Selective removal of specific high-risk trees when thinning, as well as adjustment of thinning timing and intensity could reduce risk of storm damage. However, it must be possible to identify and remove these trees cost effectively. Heavily damaged or dead trees are obvious candidates for removal, but it may be worth selectively removing those trees with features that increase their risk, such as large, asymmetric crowns, and trees that have been heavily bent.

Numerous other management strategies, including site selection, species selection, and planting density, could be modified to mitigate risk and should be adopted if they offer expected benefits exceeding their costs. Each of these strategies and combinations could be examined through empirical simulations using a model similar to that described in "Optional Thinning and Rotation Decisions."

To optimally incorporate these strategies into forest management practices, it is necessary to understand the implications of each for the dynamic risk of storm damage in the event of a storm at different points in time, forest growth rates, and stand value.

For NIPF landowners, behavior may be more complex because the perceived impacts on aesthetics, wildlife, and other nontimber amenities provided by standing forests are a more important part of their management objectives. These landowners are likely to have substantially different optimal management policies as a result, probably tending toward fewer thinnings and increased rotation age relative to land managed by the forest industry, although this may vary depending on the primary objectives of particular NIPF landowners.

Public Policy and Forest Stand Management— Management of public lands to mitigate weather risk also is likely to differ from the profit-maximizing forest industry case. Wilson and Baker (2001) argued that managing stands to allow greater future flexibility may be more important in the case of public lands than in that of private lands because objectives of public land management are more likely to change over time with shifting political pressures. It is important to develop stands that are capable of producing multiple outputs, from timber to older forest habitat, when future objectives are uncertain. Like NIPF landowners, public land managers are likely to consider aesthetics, wildlife, recreation, and other nontimber products in determining optimal forest management strategies.

In addition, the presence of endogenous forest risk and the extensive losses that could result from a major event could lead public agencies to become involved in providing incentives for improved private forest management, especially to avoid secondary impacts such as insect and disease infestations that may negatively affect neighbors. Private landowners will not fully account for the damages that may result on neighbors' lands and may underinvest in storm damage mitigation relative to the socially optimal level. This negative externality may be an argument for government intervention to correct this market failure through subsidies of mitigation practices, by establishing penalties for not following recommended practices, or by establishing regulations requiring specific practices. However, it is important to construct such programs with care to ensure that they result in net increases in forest investment and improvements in forest health and do not simply offset private investment that would occur in the absence of the policy.

In Switzerland, short-term damage resulting from storm Lothar was similar across cantons (states) even though different cantons employed significantly different forest protection measures (Bisang and Zimmerman 2006). More expensive measures adopted in some cantons were not much more effective in preserving forests and preventing forest damages than much less expensive options. In addition, forest owners' salvage decisions appeared to be independent of the financial incentives provided by cantons. Forest owners spent more of their private resources in cantons that provided minimal financial support, and their marketing of salvaged timber was less successful in these cantons than in those that provided greater public resources. Thus, the varying strategies for public involvement in providing financial incentives for forest management had important distributional effects for forest owners and government spending but not for forest health (Bisang and Zimmerman 2006).

Conclusions

Our review characterizes primary influences on damage risk as site, tree, or stand characteristics, each of which is influenced by forest management decisions. Findings about key factors differ from study to study, and this indicates both the complexity of storm damage and the substantial variation in data and methods used to conduct analyses. A few studies simultaneously incorporate many of the factors identified in the literature as having an important influence on damages; most focus on only a few variables and do not necessarily report statistical significance. Thus, it is unclear just how broadly applicable the findings of many studies are. This review reveals a need for additional empirical research to better quantify the effects of various factors influencing the risk of forest damages, particularly in the case of complex stands that are unlikely to be captured adequately through standard mechanistic models. Future studies should place greater emphasis on empirical analyses that examine the effects of variables believed to affect damages and their interactions simultaneously. Another important issue is the need for more systematic program evaluation that accounts for endogenous selection of damage mitigation options to better identify the effects of management actions while controlling for differences in underlying conditions.

Our review indicates that some general management practices are likely to affect risk and that forest managers must consider the influence of their management decisions on the extent of weather damages. Site and species selection, as well as choice and timing of silvicultural treatments, affect expected damages. In the event of damage, the effectiveness of management plans for storm recovery is another key determinant of economic impacts and secondary damages, although management planning for storm recovery is not a focus of this chapter. Thus, optimal stand management where damage risk is treated as endogenous is likely to differ from management where risk is treated as completely exogenous. Treating risk as endogenous results in more frequent, less intense thinnings and a longer rotation age than when risk is treated as exogenous, though both cases have shorter optimal rotation ages than when there is assumed to be no weather risk (Thorsen and Helles 1998). This finding depends on a number of assumptions regarding the change in expected damages associated with thinning, however, and may differ across stands depending on their baseline risk of damage, effects of thinning on tree growth rates, timber price, thinning costs, and other variables. Developing better parameterizations of these relationships is an important area for additional research to better understand optimal decisionmaking under endogenous risk for a variety of climate and forest characteristics.

Management practices should be selected on the basis of the risk faced and management objectives. In the case of the forest industry, risk-neutral firms should undertake damage mitigation measures only if the increase in the expected present value of the stand exceeds the cost of the mitigation option. For NIPF landowners, management decisions under endogenous risk are generally expected to be more complex because of objectives other than profit maximization. Thinning regime and rotation age have implications for nontimber amenities provided by forests. Therefore, to the extent that NIPF landowners have objectives that include the production of such amenities, management by NIPF landowners will differ from management where the goal is profit maximization. Incorporating the nontimber amenities provided by standing forest will probably tend to reduce the optimal number of thinnings and increase rotation age, although this may vary depending on the primary objectives of particular NIPF landowners (Foster and Orwig 2006). Similarly, the implications for public land management under endogenous risk are expected to differ from the profit-maximizing case based on the varied objectives of public agencies managing forest land.

Recognition of the endogenous nature of forest damages and the large potential losses could induce public agencies to provide incentives for private landowners to engage in improved management practices. This is particularly true when damages may lead to secondary impacts such as insect infestation or forest fires that could spread to neighbors' land. Landowners do not fully account for impacts on neighbors or invest at socially optimal levels in damage mitigation and stand recovery measures, and this provides a rationale for potential government intervention. However, it is important to construct such programs with care to ensure that they result in net increases in forest investment and improvements in forest health rather than simply offsetting private investment.

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