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Disturbance and coastal forests: A strategic approach to forest management in hurricane impact zones

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Abstract

The Indian Ocean Tsunami focused world attention on societal responses to environmental hazards and the potential of natural systems to moderate disturbance effects. Coastal areas are critical to the welfare of up to 50% of the world's population. Coastal systems in the southern United States are adapted to specific disturbance regimes of tropical cyclones (hurricanes) and fire. In August and September 2005, Hurricanes Katrina and Rita caused what has been termed the most costly natural disaster in U.S. history, including an estimated $2 billion to $3 billion in damage from wind alone. A total of 2.23 million ha of timberland in the coastal states of Texas, Louisiana, Mississippi, and Alabama was damaged. Although financial loss estimates are incomplete, there is little doubt that these hurricanes caused extensive damage and their effects on the landscape will linger for years to come. Crafting a strategy for incorporating large, infrequent disturbances into a managed landscape such as the forested coastal plain of the southern U.S. must balance the desirable with the possible. We advance an adaptive strategy that distinguishes event risk (hurricane occurrence) from vulnerability of coastal forests and outcome risk (hurricane severity). Our strategy focuses on managing the disturbance event, the system after disturbance, and the recovery process, followed by modifying initial conditions to reduce vulnerability. We apply these concepts to a case study of the effects of recent Hurricanes Katrina and Rita on forests of the coastal plain of the northern Gulf of Mexico.
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Keywords: Risk assessment; Loblolly pine; Longleaf pine; Bottomland hardwood forests; Deepwater swamp forests; Disturbance regimes

1. Introduction

A salient feature of coastal systems is their dynamic nature, which makes them vulnerable to natural and anthropogenically induced climate change (Syvitski et al., 2005). Coastal systems in the southeastern United States, for example, are adapted to specific disturbance regimes of sea level rise in the Holocene and tropical cyclone activity (Michener et al., 1997) and would be drastically affected by even modest alteration of these disturbance regimes. The nature of specific changes at local scales will depend upon interactions of altered disturbance regimes and human responses to modification of coastal environments. Tropical cyclones, or hurricanes as they are called in the North Atlantic, are a fact of life in the southern United States. The past 10 hurricane seasons have been the most active on record (Emanuel et al., 2006) and the consensus among climatologists is that greater hurricane activity could persist for another 10–40 years (Goldenberg et al., 2001).

On 29August 2005, Hurricane Katrina hit the Gulf Coast 55 km east of New Orleans after crossing over southern Florida, causing what has been termed the most costly natural disaster in U.S. history. In addition to the wind, storm surge, and flooding damage along the Gulf Coast of Louisiana, Mississippi, and Alabama, levees surrounding the metropolitan area of New Orleans were undermined and collapsed the next day causing extensive flooding damage. One month later, on 24 September 2005, Hurricane Rita made landfall on the southwest coast of Louisiana between Sabine Pass and Johnson's Bayou, damaging forests throughout east Texas. Because forests provide market as well as non-market goods and services, extreme disturbance events such as hurricanes are often followed by attempts to recover value from damaged timber through salvage logging, a practice that is increasingly questioned by the public because of its presumed negative effects on biodiversity (Lindenmayer et al., 2004). Even in a predominantly managed forest landscape such as the coastal plain of the southern United States, such questions are relevant. Our objective in this paper is to focus on the effects of hurricanes on coastal forests as a study in incorporating disturbance into managed forests. Specifically, we will present a conceptual approach to incorporating disturbance into forest

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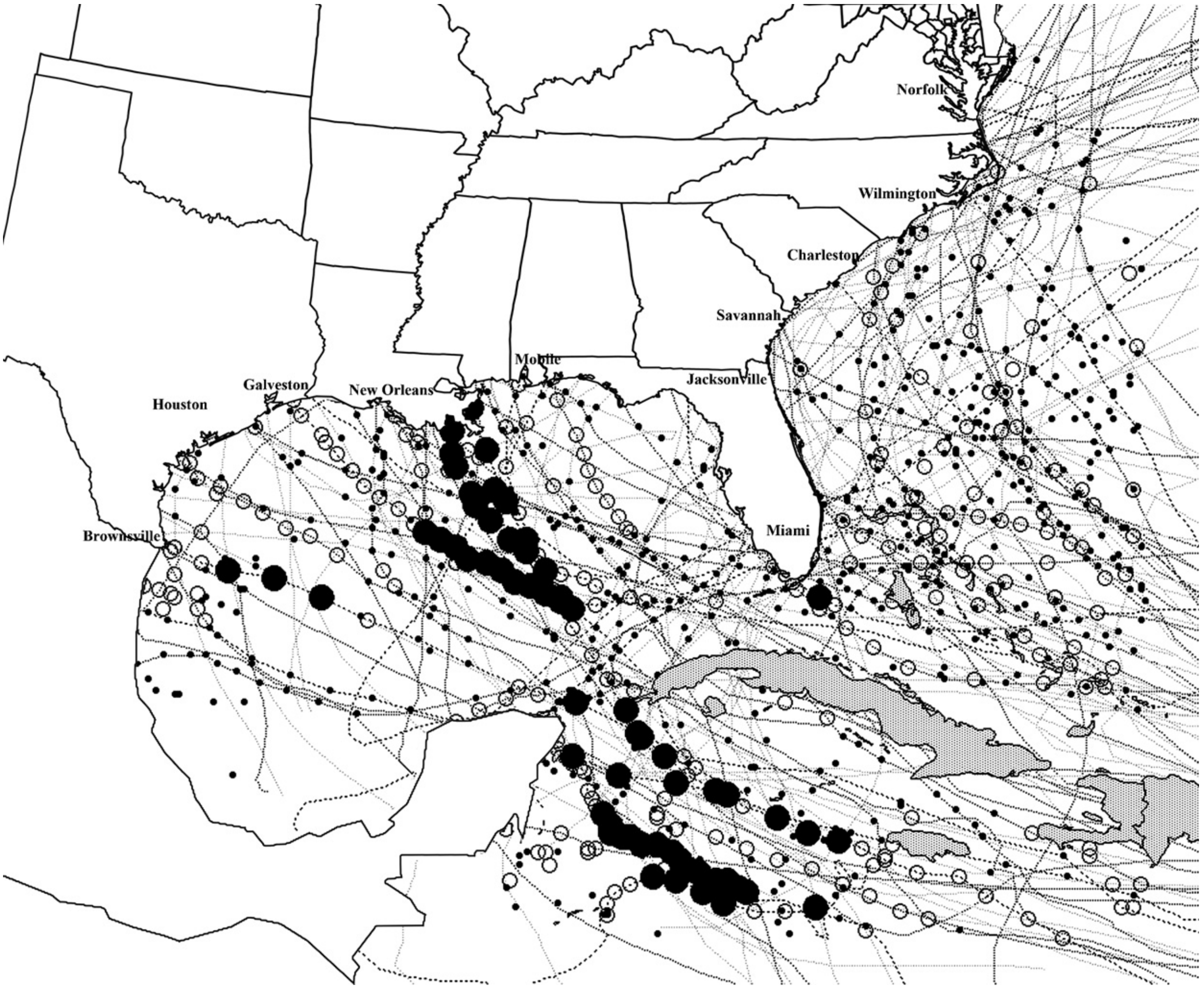

Fig. 1. Major (categories 3–5) hurricanes making landfall in the eastern United States (1851–2005). The circles represent storm intensity during its lifetime (small filled circles are category 3, large open circles are category 4, and large filled circles are category 5). The tracks are for those storms that were categories 3–5 at some point in their lifecycle. The hurricane track map is derived from NOAA's HURDAT data set for 1851–2005, the 'best track' data set (so named as it is the 'best' track and intensity estimates of tropical cyclones as determined in a post-analysis of all available data) for the North Atlantic maintained by the forecasters and researchers at the National Hurricane Center in Miami, Florida. *Source*: Jarvinen et al. (1984).

management and apply these concepts to a case study of the effects of recent Hurricanes Katrina and Rita on coastal forests of the northern Gulf of Mexico, USA.

2. Conceptual approach

2.1. Strategies for managed landscapes

Strategies for incorporating disturbance regimes into forest management must account for the multiplicity of landownership characteristics, landowner objectives and attitudes toward risk, as well as financial and operational constraints on management. Although it would seem that public ownership and a large contiguous landbase should provide the greatest opportunity to pursue management that emulates coarse-scale natural disturbance processes, statutory constraints often limit the flexibility of public managers to manipulate vegetation over large areas, and therefore constrain efforts to emulate large infrequent disturbances. Small private landowners have few opportunities, by virtue of their limited holdings, to emulate coarse-scale events such as hurricanes. Therefore, crafting a strategy for incorporating hurricane disturbance into a managed landscape must balance what is desirable with what is possible, and managers should be prepared to take advantage of opportunities provided by severe hurricanes to institute changes in composition, structure, or both.

2.2. Risk assessment approach

In order to better understand the risks of damage to coastal forests posed by severe hurricanes, we will distinguish between the risk of a severe hurricane occurring (event risk), the vulnerability of coastal ecosystems, and the significance of an event (outcome risk), which combines event risk and vulnerability (Sarewitz et al., 2003; Pielke et al., 2005). Fig. 1 is a simplistic depiction of event risk for the southern United States that attempts to show both the frequency of hurricane events as well as their intensity with a degree of spatial explicitness. Recent modeling work (Jagger and Elsner, 2006) supports the visual impression that the greatest event risk for severe hurricanes is the Gulf Coast from Texas to Alabama. Event risk seldom can be affected directly by managers but it is important to understand that event risk is dynamic, especially events associated with severe weather such as hurricanes. For example, the southern U.S. likely will experience more frequent and severe hurricanes over the next 30–40 years than occurred over the last 30 years as a consequence of natural climate variability (Goldenberg et al., 2001). Vulnerability is independent of event risk (Pielke et al., 2005) and easier to quantify, as it relates to growing population and wealth in coastal areas and increased value of infrastructure and natural resources (Pielke and Landsea, 1998). For natural ecosystems such as coastal forests, vulnerability to wind-related effects of severe hurricanes is a complex function of stand and site characteristics. Outcome risk takes into account the economic and ecological values that are vulnerable, including both market and non-market values. Outcomes, or effects, are understandably the focus after an event occurs. While managers may desire to minimize outcome risk, it cannot be affected directly. Therefore, the long-term focus of managers should be on ways to reduce vulnerability.

A strategy for reducing outcome risk to coastal forests is to reduce the vulnerability of coastal ecosystems, particularly those areas with higher event risk. For example, Hooper and McAdie (1996) assessed an ecological outcome risk, loss of viable populations of the endangered red-cockaded woodpecker (*Picoides borealis*), using an estimate of event risk (return period for all hurricanes) based on historical records of hurricanes occurring within the boundaries of individual recovery areas for the species. They concluded that vulnerability primarily was a function of distance from the coast. By focusing on vulnerability the conclusions of Hooper and McAdie provided managers a means to indirectly mitigate the outcome risk. Another approach to reducing outcome risk is to seek to avoid damaging events, or at least to minimize the time an asset is vulnerable. At the stand level, one could calculate an encounter probability (Balsillie, 2002) in terms of a return interval in years of a storm of a given magnitude (Fig. 1) and set the rotation length of the overstory (i.e., the design life of the stand) at some interval less than the encounter probability. In another example focused on outcome risk, Haight et al. (1996) used a 6% encounter probability to evaluate pine plantation management in South Carolina under the risk of hurricane damage and found that intensive management was not profitable in the coastal plain under 1992 conditions. This analysis neglected a mitigating factor, namely the availability of government payments for reforestation following a hurricane, which was similar economically to the effect of using other low-cost methods such as natural regeneration (Straka and Baker, 1991).

Our approach is to consider all potential disturbances in an area, the threat matrix, and then assess risks of severe hurricanes within this context. The time following an event can be divided into two general categories of activity, dealing with outcomes (short-term) and managing the recovery (long-term).

3. Coastal forest ecosystems of the northern Gulf of Mexico, USA

The coast of the northern Gulf of Mexico is an arc from peninsular Florida on the east to the southern tip of Texas on the west (Fig. 2). The extensive coastal plain extends landward to uplands (Piedmont, Appalachian Mountains, and Ouachita Highlands) and to the beginning of the more arid area of Texas. The coastal plain is punctuated by several major estuaries and the Mississippi River, which has built several deltas that extend Louisiana into the Gulf of Mexico. Along the coast, barrier

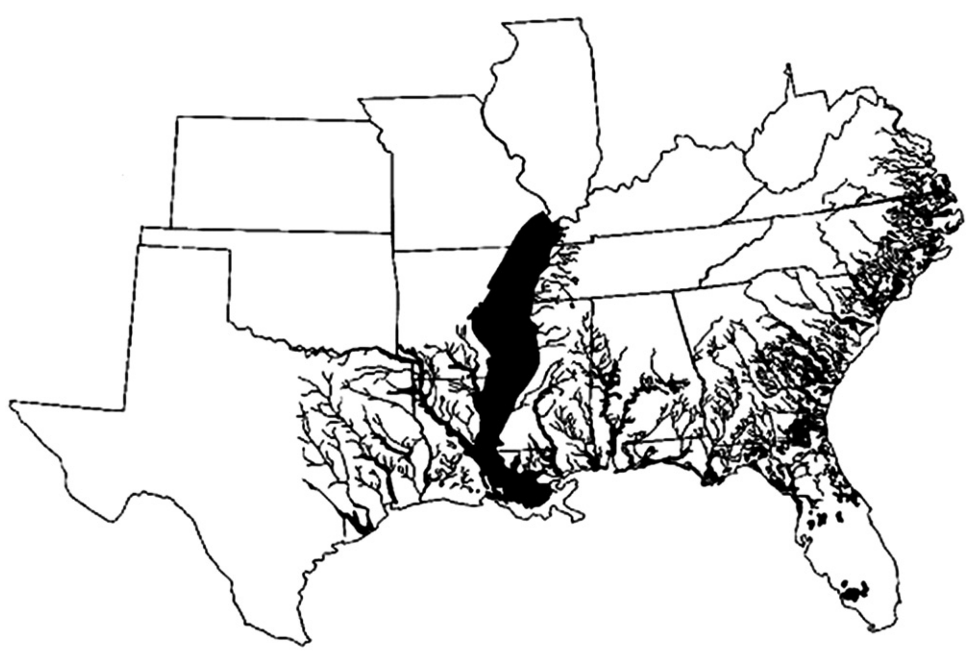

Fig. 2. Distribution of major riverine forest ecosystems in the southern United States. *Source*: Putnam et al. (1960).

islands and marsh ecosystems are important habitat but are not considered in the following descriptions.

3.1. Coastal plain forests

Coastal Plain forests in the South are predominantly pine in the uplands and hardwoods in the floodplains of major and minor rivers (Fig. 2). The dominant species include longleaf (*Pinus palustris*), loblolly (*P. taeda*), slash (*P. elliottii*), pond (*P. serotina*), sand (*P. clausa*), and shortleaf pines (*P. echinata*). Periodic fire has shaped these ecosystems (Meyers and van Lear, 1998), as the several pine species differ in their tolerance of fire, requirements for soil aeration, and ability to withstand drought. Longleaf pine forests, adapted to groundfires on a 2- to 5-year interval, predominated before European settlement; mixed hardwood forests were confined to narrow strips between the pine and floodplain forests (Batista and Platt, 1997). Historically loblolly pine was a component of mixed hardwoods stands along streams and ponds of the coastal plain, where flooding was not excessive but where it was moist enough to limit fire frequency (Schultz, 1997). Today, plantations of predominantly loblolly pine occupy most of the pine sites in the coastal plain, especially on forest industry land where plantations are managed intensively (Duryea and Dougherty, 1991; Conner and Hartsell, 2002; Stanturf et al., 2003).

Deepwater swamps dominated by baldcypress and water tupelo (*Taxodium distichum* and *Nyssa aquatica*) are found along rivers and streams of the coastal plain and throughout the Lower Mississippi Alluvial Valley (Conner and Buford, 1998). Cypress-tupelo swamps nearest the coast have been severely impacted by subsidence and saltwater intrusion as a result of oil and gas development in Louisiana (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 1998). Riverine or bottomland hardwood forests are extensive in the coastal plain, especially along major rivers (Fig. 2) and characteristically are rich in species (Meadows and Stanturf, 1997; Kellison et al., 1998). In aggregate, most of the remaining bottomland hardwood forests are in the floodplains of minor rivers (Hodges, 1998). The primary natural disturbance affecting these riparian and wetland forests, in addition to river dynamics, is wind. Hurricanes in particular can defoliate and overturn trees, and affect the bottomland forests more because of the shallow rooting of many species. In deepwater swamps, cypress especially can withstand hurricane force winds and windthrow is rare (Conner and Buford, 1998). Breakage is mostly confined to defective and hollow stems. After Hurricane Hugo, Putz and Sharitz (1991) reported that previously damaged stems were more susceptible to new damage than were undamaged stems.

3.2. Population and land use

Coastal areas sustain a variety of natural resource-based activities including forestry, capture fisheries, and aquaculture; recreation and tourism are increasingly important. Transportation historically has been important in coastal areas and increasingly, the necessary infrastructure requires dredging that impacts natural resources. In some coastal areas such as the Gulf of Mexico, extracting fossil fuels (petroleum and natural gas) has caused coastal subsidence and erosion, as well as saltwater intrusion, resulting in many direct and indirect impacts on other resources (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 1998).

Population growth in the southern US since World War II has been high; the coastal states of Florida, Alabama, Mississippi, Louisiana, and Texas increased 164% between 1950 and 2000 (Hobbs and Stoops, 2002). The greatest change in population in these coastal states over the last half of the 20th Century was in Texas (170%) and Florida (477%). The combined market value of coastal areas generally is underestimated; the value of infrastructure development is increasing (Pielke and Landsea, 1998) but the insured value represents only a fraction of the total value (Mills et al., 2005).

4. Hurricanes and forest ecosystems

4.1. Nature of tropical cyclones

Tropical cyclones are low-pressure systems originating in the tropics (or sometimes the subtropics). These storm systems develop over the tropical or subtropical ocean in relatively homogenous masses of very warm humid air. The circulation of a tropical cyclone is sustained by the release of latent heat as water evaporates from the ocean surface. The homogenous environment allows the storm to develop a symmetric circulation, concentrating large amounts of energy in a relatively small area. Tropical cyclones in the North Atlantic progress through a series of stages: tropical disturbance, tropical depression, tropical storm, and hurricane. Tropical disturbances begin as poorly organized areas of convection and transition to tropical depressions as the development of a rotary circulation organizes the convection. As the strength of the rotary circulation increases beyond $17\ m\ s^{-1}$ (39 mph) the system becomes a tropical storm. Further intensification (winds greater than $33\ m\ s^{-1}$ or 74 mph) and development of a pronounced rotary circulation transitions the storm to hurricane status. Hurricane intensity is rated on the Saffir-Simpson scale based on maximum sustained winds (Table 1).

Hurricanes making landfall in North America can begin as tropical disturbances anywhere in the tropics of the North Atlantic Ocean from the coast of West Africa, the Caribbean Sea or the Gulf of Mexico. Most storms develop between 10° and 20° north latitude as tropical disturbances embedded in easterly waves off the coast of West Africa and slowly move westward or northwestward across the North Atlantic Ocean. Prolonged exposure to warm tropical waters provides the energy for these disturbances to develop into tropical storms and hurricanes. As a storm continues its westward path to the Caribbean or Greater Antilles regions, it may move toward the Gulf of Mexico or curve to the right of its path and accelerate up the Atlantic Seaboard. Those storms reaching the Gulf of Mexico may continue on to the coast of Texas or Mexico or

Table 1
Saffir-Simpson hurricane intensity scale (Moran and Morgan, 1989)[a]

Category	Central pressure		Wind speed		Storm surge		Damage
	mb	in	km h^{-1}	mi h^{-1}	m	ft	
1	≥980	≥28.94	119–154	74–95	1–2	4–5	Minimal
2	965–970	28.50–28.91	155–178	96–110	2–3	6–8	Moderate
3	945–964	27.91–28.47	179–210	111–130	3–4	9–12	Extensive
4	920–944	27.17–27.88	211–250	131–155	4–6	13–18	Extreme
5	<920	<27.17	>250	>155	>6	>18	Catastrophic

[a] Units are given in SI and English for ease of comparison: mb, millibars; in, inches; km, kilometers; mi, miles; m, meters; ft, feet.

curve north toward the coastal regions of Louisiana, Mississippi, Alabama, and Florida (Fig. 1).

While hurricanes are a danger to marine shipping, the greatest damage occurs when a storm makes landfall and moves inland. Damage comes from three primary features of the hurricane: rainfall, storm surge, and winds. Tropical storms and hurricanes bring torrential rains and frequently cause extensive flooding well after making landfall. In 1998 Hurricane Mitch killed over 11,000 people in Central America as heavy rains were funneled into small valleys by the mountainous terrain (Emanuel et al., 2006). Storm surge, a rise in sea level due to low pressure in the center of the storm, causes extensive coastal damage when its arrival coincides with high tide. As storm surge is linked with the low pressure of the hurricane, it is therefore also linked to the strong winds that make up the circulation about the storm's center. Wind is the feature of hurricanes that is linked to a vast majority of a hurricane's damage, both directly and indirectly through waves and storm surge. The strongest winds occur in a semicircle to the right of the storm's path a short distance from the center. As the storm continues inland and is cut off from its oceanic energy source, it rapidly loses energy and weakens. Tornadoes frequently occur embedded within the rain bands that spiral out from the eye of the hurricane. While short-lived and less intense than tornadoes in the Midwestern U.S., they add to the spatial variability of storm effects on the landscape.

4.2. Hurricane effects on coastal forests

As a hurricane makes landfall its energy is transferred directly to the impacted coastal system over a large area by high velocity winds, with effects extending inland hundreds of km in severe events (categories 3–5 on the Saffir-Simpson scale; Table 1). Hurricane Hugo struck the coast just north of Charleston, South Carolina in 1989 and did extensive damage 325 km inland (Janiskee, 1990). At the coast and for some distance upstream in estuaries and coastal rivers, direct and indirect effects are felt due to high water from the storm surge, especially if landfall coincides with local high tide. Elevated precipitation usually accompanies hurricanes, especially those that move slowly along a coast, continually drawing moisture from the ocean to feed torrential rains.

4.2.1. Wind effects

Hurricane force winds, frontal squall lines, and associated tornadoes create a complex pattern of damage at a range of spatial scales (Brokaw and Walker, 1991; Tanner et al., 1991; Boose et al., 1994; Walker, 1995) from the individual tree and stand to the landscape (Brokaw and Walker, 1991). Abrasion is the most common form of damage, as leaves and small branches are stripped and crowns become streamlined by wind, entrained soil particles, and blowing debris (Brokaw and Walker, 1991). Large branches may break off and cause damage to understory trees (Frangi and Lugo, 1991). Wind induces trees to sway, with pulsating gusts and changes of wind direction affecting the transfer of energy from the wind to the tree crown (Ennos, 1997; Drouineau et al., 2000; Peterson, 2000). General responses of trees to mechanical stress within the windfield of a hurricane include swaying, twisting, and rocking. Branch movement may dampen the swaying and help transfer energy from the crown through the bole to the root system (Drouineau et al., 2000). Individual stems may bend, break, tip (full or partial uprooting), or remain standing with root system intact or broken loose from soil contact.

Predicting damage is difficult because of variation within the windfield due to distance and position relative to the center of the storm, wind speed, direction, and duration of gusts. Differential response of stems add to the difficulty because of species' differences in crown and root system configurations, stem and branch wood density, as well as species' differences in the ability to refoliate. Topography influences exposure to wind; soil texture, stoniness, root-impeding horizons, and moisture condition affect anchorage. Stem and stand conditions also affect response to hurricane winds. For example, tree height and taper and stand density influence the likelihood of stem breakage versus uprooting (Brokaw and Walker, 1991; Peterson, 2000). These factors all affect tree mortality (Walker, 1995); estimates of mortality following a hurricane vary from 2% (Hurricane David, 1979 in Dominica; Lugo et al., 1983) to 95% (Hurricane Betsy, 1956 in Puerto Rico; Wadsworth and Englerth, 1959). Estimates of mortality following a hurricane are sensitive to timing of a damage survey and may be too high if made before the trees have refoliated or too low if made during vigorous re-sprouting or before standing trees with root systems severed by rocking have died (Walker, 1995).

4.2.2. Storm surge

Less studied effects of hurricanes than wind damage include storm surge, the wedge of water pushed ashore by a hurricane. Also called storm tide, hurricane tide, or tidal wave, the storm surge can reach heights greater than 5 m at the coast. The mechanical stress of the storm surge affects forests in the

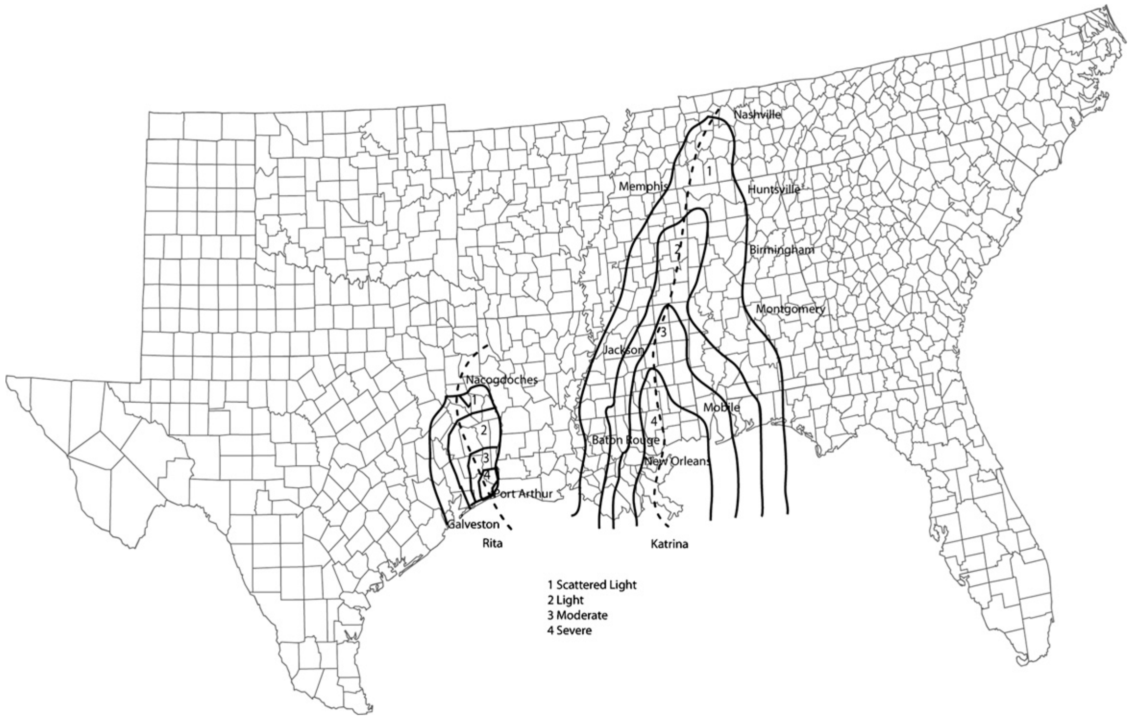

Fig. 3. Tracks of Hurricanes Katrina and Rita with estimated forest damage zones (Timber Damage Assessment Maps). Zone 4 is heavy damage (approximately 67% or more of overstory trees uprooted, snapped off, leaning more than 45°, or otherwise likely to die within 12 months), zone 3 is moderate damage (34–66% damaged), and zone 2 is light damage (3–33% damage). Zone 1 is scattered light damage. *Sources*: FIA (2005) and Texas Forest Service (2005).

nearshore environment in a fashion similar to wind damage, which is by bending or breaking. Substrate movement caused by the storm surge may cause localized effects such as blowouts, or displacement where intact stems and roots are moved with soil and deposited landward. In the Everglades of southern Florida, high winds and waves displace portions of mangrove into long ridges forming debris dams that prevent saltwater intrusion (Conner, 1998). Scouring and erosion may expose root systems leading to desiccation, or deposition may lead to root suffocation. Salinity and inundation increased by the storm surge can cause mortality; particularly as saltwater is channeled up tidal creeks into areas not normally reached by brackish water (Williams, 1993; Conner, 1998).

4.2.3. Rain

Torrential rains accompanying hurricanes cause localized flooding in areas not normally subject to inundation, leading to tree mortality from anoxia. Flooding and rainfall saturates soil, which may increase susceptibility to windthrow in shallow soils. Even at some distance from the hurricane center, after wind velocities have abated below hurricane strength, saturating rains with moderate winds may cause windthrow. Accelerated soil erosion and mass movements have been noted in interior mountains (Emanuel, 2005).

5. Hurricanes Katrina and Rita 2005

From a class 5 hurricane with maximum sustained winds of 202 km h^{-1} in the Gulf, Katrina had abated to a class 3 when it slammed into lower Louisiana and then Mississippi on 29 August 2005 (Fig. 3). Earlier estimates were a class 4 hurricane at landfall. Hurricane Rita followed one month later, making landfall on 24 September 2005 on the southwest coast of Louisiana. In comparison to Hurricane Ivan, the last major hurricane in the area, the width of hurricane force winds of Katrina at landfall was 18% wider and Katrina's hurricane force winds persisted 36% further inland than did Ivan's. Tropical storm force winds were 27% wider and persisted approximately 96% further inland than for Ivan. Putting Katrina into perspective, she caused devastation over an area of almost 233,000 km^2—an area larger than Great Britain.

5.1. Manage the event

If disturbances such as major hurricanes are in the threat matrix, policies and procedures should be in place prior to an event to manage effects. Experience from Hurricane Hugo in South Carolina provides some guidelines (Haymond et al., 1996). Preparation and pre-positioning equipment to restore access and communication will pay dividends once the hurricane makes landfall. Rapid assessment of damage is needed to guide recovery efforts and to mobilize the political and financial support necessary to meet short-term needs as well as for long-term recovery.

Lessons learned from previous major hurricanes make it clear that coordination and communication are critical to successfully mitigating immediate effects. The immediate response following Hurricane Hugo in 1989 focused on three areas: salvage to recover value, mitigation of wildfire hazard, and reforestation (Haymond et al., 1996). Some aspects of

Table 2
Damage area and potential damaged volume from Hurricanes Katrina and Rita, by damage zone

Damage zone	Area timberland damaged (10^3 ha)	Potential damaged volume (10^6 m^3)		
		Total timber	Softwood	Hardwood
Katrina				
4	807	22	12.9	8.6
3	897	22	13.0	8.7
2	330	6	3.2	2.8
All zones	2035	49	29.2	20.1
Rita				
4	40	2	1.3	1.0
3	85	8	2.9	4.7
2	39	4	2.2	1.8
All zones	164	14	6.4	7.5

Data from FIA (2005), Prestemon and Wear (2005) and Texas Forest Service (2005).

the recovery plan were patterned after the response to Hurricane Camille, which struck the Mississippi coast in 1969 (Colvin, 1996) but generally, the response to Hurricane Hugo was initiated by state officials (the Governor's office and South Carolina Forestry Commission) who quickly established committees and planning groups in each of the three focal areas. Updated guidance is being prepared after Hurricanes Katrina and Rita by the Southern Group of State Foresters and by the Regional Forester of the federal Forest Service (Janet Anderson, personal communication, 2006).

5.1.1. Rapid assessment of damage extent, severity, and significance

Damage estimates for timberland were begun within days of landfall by Katrina and Rita, using a projected damage map based on observed windfield and rainfall data combined with forest inventory data and modeled timber damage potential (Jacobs and Eggen-McIntosh, 1993; Prestemon and Wear, 2005; Texas Forest Service, 2005). Subsequent aerial surveys and limited field measurements were used to refine the damage boundaries and produce Timber Damage Assessment Maps (Fig. 3).

Hurricane Katrina left a swath of damage through the coastal and inland forests of Mississippi, Louisiana, and Alabama. Approximately 2 million ha of timberland were damaged (Table 2); approximately 90% of the damage was within 100 km of the coast and 67% of the damage was in Mississippi (FIA, 2005). Nearly 20% of the standing volume of timber was destroyed, with up to 40% loss near the coast (FIA, 2005). For comparison, Hurricane Camille made an almost identical landfall in 1969 and resulted in an average loss of 11% of standing volume (Colvin, 1996). The damage from Hurricane Rita occurred mostly in the coastal plain forests of Texas. The area of damaged forestland was estimated at 164,000 ha (Table 2), with a further 136,000 ha suffering scattered light damage or affected such that future growth is likely to be impaired (Texas Forest Service, 2005).

The wind damage from Hurricane Katrina was estimated at a total of 22 million m^3 of timber (Table 2) in the zones of heavy damage (approximately 67% or more of overstory trees uprooted, snapped off, leaning more than 45°, or otherwise likely to die within 12 months), moderate damage (34–66% damaged), and light damage (3–33% damage). Hurricane Rita damaged a smaller area with correspondingly lower estimates of volume loss, 164,000 ha of timberland and 14 million m^3 of timber (Table 2). Hurricane Katrina caused greater losses of pine timber (over 29.2 million m^3) than hardwood (20.1 million m^3), reflecting their relative distribution in the damage zones (Table 2). Estimates of damage from Hurricane Rita suggest that there was more damage in hardwood stands (7.5 million m^3) than in pine stands (6.4 million m^3) (Table 2).

The human toll from Katrina is inestimable and the nature of the emergency response will be debated for some time. Although we do not have precise estimates of direct and indirect damage and economic effects of this major event, the estimated economic loss from wind damage to timber is from \$1.4 billion to \$2.4 billion, based on low and high stumpage price scenarios (Prestemon and Wear, 2005). Most of the value lost was in the sawtimber class (92%) and most of this was pine sawtimber (59%). Salvage operations may recover some of this lost value; however experience from past hurricanes suggests this may be small. After Hurricane Hugo, an Atlantic Coast hurricane that struck South Carolina in 1989, salvage recovered 37% of volume but only 10% of value, partly because the highest value was in inaccessible hardwood swamps. Studies of other disasters indicate that prices may be elevated in the region for 5–15 years after the initial salvage, which could mitigate some of the damages suffered in the short run (Prestemon and Holmes, 2000, 2004).

Damage from Hurricane Rita was estimated to be 14 million m^3, worth approximately \$462 million. Additionally, 136,000 ha of timber were estimated to be affected by hurricane winds, with an estimated loss of \$371 million. The total of damaged and affected volume in East Texas from Hurricane Rita was about 6% of growing stock volume (Texas Forest Service, 2005). In total, Hurricanes Katrina and Rita damaged approximately 2.23 million ha of timberland, with estimated financial losses from wind damage alone of the timber base of \$2 billion to \$3 billion in four coastal states.

5.2. Protect resources and recover value

Decisions made in the immediate aftermath of a hurricane to recover value from downed timber by salvage logging risk long-term ecological damage to sensitive ecosystems or habitat for species of concern (Lindenmayer et al., 2004) unless precautions are taken. An adaptive approach would have managers plan for major disturbance and set policy beforehand to exempt areas from salvage logging where ecological values outweigh potential financial value (Beatty and Owen, 2005). Strict guidelines for operating in sensitive areas should also be set in advance, such as riparian zones and endangered species habitat. Additionally, potential salvage will be constrained by manpower needs for other recovery efforts, safety of woods workers in the damaged stands, the poor quality of severely damaged trees, and the rapid development of fungal stains in the wood that further degrade quality. The economic incentive for salvage will be depressed by the downward pressure on stumpage prices from the large amounts of wood on the market. In other hurricanes, such as Hugo, private sector forestry leaders have asked public land agencies to reduce their salvage efforts to allow private landowners an opportunity to market their salvaged timber.

5.2.1. *Second order effects*

Potential second order effects from Hurricanes Katrina and Rita are from increased wildfire hazard and changes of inundation regime, including water chemistry. Potential wildfire hazards are a greater concern in pine forests than in the wetter bottomland and swamp forests but as Saveland and Wade (1991) noted, none of the major hurricanes causing damage in southern forests over the last 50 years were followed by catastrophic wildfires. Although the potential existed, for numerous reasons it was not realized. The immediate concern for increased fire risk is the loss of access due to downed timber and the increased safety risks to fire fighters working in storm damaged stands. Most fires in the southern U.S. are suppressed quickly and confined to relatively small areas because initial attack is so effective, which is aided by ready access. In hurricane damaged stands, however, the potential for wildfires to burn large areas is increased and the ability to maintain fire lines to control escaped fire is lessened (Saveland and Wade, 1991). Salvage logging to remove large downed and standing dead material (1000 h fuels) also reduces the amount of smoke produced in subsequent prescribed burns, which is critical to managed pine forests (Achtemeier et al., 1998, 2002).

Wildfire can adversely affect wetter minor bottoms and small depressional wetlands with vegetation that is not adapted to fire. In coastal areas of the affected states, there are extensive areas of bottomland hardwood and cypress swamp forests that have been damaged by wind, heavy rains and flooding, as well as salinity from the storm surge or alterations in coastal hydrology (Pezeshki et al., 1990, 1995; Williams, 1993). Besides obvious signs of current damage, these stresses will lead to later declines, loss of vigor, and insect and disease problems.

5.2.2. *Protect other resources*

Values and benefits from resources other than timber should be considered in decisions of which stands to salvage or not. Similarly, salvage operations need to be conducted in ways that protect other resource values. Large downed logs are ecologically valuable as habitat for a number of insects and herpetofaunal. In longleaf pine stands, large downed logs provide temporary refugia from fire for regeneration of longleaf pine and other plant species (Hermann, 1993). Once these logs dry sufficiently to ignite and burn, another microhabitat is created of open soil for colonization of other plant species.

The desire to act following natural disasters can lead to ill-considered clean-up and restoration activities that cause more damage to aquatic systems than the disturbance. Hurricane Katrina may have actually rejuvenated many of the sand-bottom streams in the coastal plain (Adams, 2006). Heavy-handed salvage and restoration in riparian areas, including road

Fig. 4. Aerial (helicopter) view of damage from Hurricane Katrina; Thompson Creek on the Chickasawhay Ranger District, DeSoto National Forest, Mississippi. Note the blowdown cluster in the lower left quadrant (photo courtesy of Kevin Leftwich, USDA Forest Service).

building and debris removal, would damage these wood-starved streams (Melvin Warren, personal communication, 2006). On several districts of the National Forests of Mississippi, pre-hurricane research and stream surveys, including watershed analyses of land-use on 256 stream reaches, provided an opportunity to assess damage to aquatic systems. The coastal zone districts of the forest were severely damaged by Katrina, with initial estimates of from 50 to 80% of the overstory down or damaged (Melvin Warren, personal communication, 2005).

A field assessment was conducted by a hydrologist and an aquatic ecologist (Marion and Leftwich, 2005). District personnel were concerned about fire control; before Hurricane Katrina the perennial streams had been used as fire lines and forest staff felt that downed stems across channels could provide a fuel path for a fire to escape. They were also concerned about effects of altered flooding regime on an endangered plant. Field inspection (by helicopter and along roads) showed that blowdown was more frequent along openings such as roads and power lines and edges between stands of different age classes or stem densities (Fig. 4). In general, blowdown in riparian areas was found to be lower than initial estimates. The review team recommended that stream-side and riparian blowdown be left as is, because over time it will collapse and decay in place, thereby improving channel stability and sediment storage. Positive impacts should result: water quality and aquatic diversity should improve. Burn blocks can be re-designed to utilize other fire breaks, or new fire lines can be built (Marion and Leftwich, 2005).

The red cockaded woodpecker (*Picoides borealis*) was listed as an endangered species in 1970 and for two decades, few severe hurricanes made landfall within its range, which extends from Texas to Virginia (Hooper and McAdie, 1996). Hurricane Hugo in 1989 caused extensive damage to South Carolina forests, including the red cockaded woodpecker (RCW) colonies on the Francis Marion National Forest. The storm killed 67% of the birds and the number of groups was reduced by half (Hooper and McAdie, 1996). Because the RCW is a cavity nester, it is particularly vulnerable to wind damage to nest trees, which are more prone to breakage. The toll of Hugo would have been greater if artificial cavities had not been installed in residual trees (Hooper and McAdie, 1996).

Maintaining RCW habitat and aiding in recovery efforts should be included in the overall hurricane response plan. Some features of the recovery strategy for RCW will help maintain viable populations, despite increased hurricane frequency. Inland populations have survived major hurricanes. Wide spatial distribution of colonies should reduce the overall risk of catastrophic loss of populations. Leaving even small diameter but older stems in damaged areas of longleaf pine that already contained heart rot could provide cavity trees and younger trees can be fitted with artificial cavities (Hooper and McAdie, 1996).

Clearing downed material from roads and around structures and recreation sites in the forest will generate large quantities of debris requiring disposal, most likely by outdoor burning. Although this is the only practical method for disposing of the massive amounts of forest and urban debris, it will produce smoke that can obstruct vision on highways, leading to automobile accidents and fatalities, and adds to the health burden of sensitive groups in local populations (Achtemeier et al., 2002). Smoke models that can predict smoke development and transport are available to provide guidance on safe conditions for burning (Achtemeier, 2001), especially in coastal areas where sea breezes make prediction of smoke movement very difficult. Emissions from prescribed fires on timberland that may be contaminated by toxic chemicals from industrial emissions and other waste are also of concern; local and regional models of smoke movement exist that can predict where these emission products will be transported over a period of several days (Yongqiang Liu, personal communication, 2005). These models can help managers select burn days when the smoke will be transported out to sea or over sparsely populated land areas, thus avoiding population centers.

5.2.3. *Recover value*

Many technical obstacles stand in the way of rapidly salvaging timber value following a hurricane. The amount of timber affected will represent several times more than the annual harvest, thereby taxing the available logging and transportation resources. Wood processing facilities will be overwhelmed by the pulse of salvaged wood following a major hurricane. Following Hurricane Katrina, higher wages were offered to clean up trees in urban areas than for salvage logging, creating a labor shortage of qualified woods workers (Janet Anderson, personal communication, 2006). Two responses, finding new markets outside the affected area and storing wood for later use, were attempted after Hurricane Hugo. The committee formed to coordinate post-Hugo salvage set a goal of recovering 25% of the affected volume and 10% of the value. Despite discounted rail transportation, increased road weight-limits on trucks, and regulatory concessions for out-of-state logging trucks, nevertheless 90% of the salvaged timber was used in-state (Marsinko et al., 1993).

Available silvicultural information can be used to help triage damage conditions by categorizing stands that should be salvaged immediately and restored, stands probably not seriously damaged, or stands that may not appear to be damaged but that are likely to develop problems later and should be monitored and treated if problems develop. Value can be defined in financial terms or habitat suitability terms. The evaluation is in two parts: assessing the damage to individual stems (Table 3) and determining the extent of damage in the stand relative to the values at risk. Stands need to be evaluated to see if they have sufficient residual value to justify continued management, or should simply be regenerated.

5.2.3.1. Salvage or not. Existing research about the rates of stand rehabilitation and recovery in naturally regenerated pine stands affected by wind damage indicates how to proceed in hurricane damaged stands, by basing that decision on the given level of stocking (Baker and Shelton, 1998a) and condition of the surviving trees in the stand (Baker and Shelton, 1998b,c). This allows for prioritization of what is likely to be a limited budget for stand re-establishment efforts, directing reforestation treatments to those sites where recovery seems less likely

Table 3
Managing hurricane-damaged forests in the Gulf Coastal Plain may require immediate salvage to recover value and control secondary insect and disease problems

Damage type	Pines			Hardwoods		
	Salvage immediately	Monitor 1 year	Monitor 1–5 years	Salvage immediately	Monitor 1 year	Monitor 1–5 years
Breakage	Salvage if tops are gone or three or fewer large limbs remain	Monitor for bark beetles; sanitation removal if retained trees infected	Monitor for pest activity: yellow needles; pitch tubes on bark; boring dust around base; bark beetle infestation	Broken tops and lost limbs more likely to result in value loss than mortality; salvage highest value trees now	Harvest lesser valued hardwoods with broken tops or large limb (>10 cm) damage	Harvest lesser valued hardwoods with broken tops or large limb (>10 cm) damage
Twisting	Salvage if damage obvious or pitch flow evident	Salvage if pitch flow evident or if bark beetle infested		Significant value loss; retain for future harvest	Harvest damaged trees for pulpwood, fuelwood	Harvest damaged trees for pulpwood, fuelwood
Bending	Salvage older trees or if pitch flow evident	Salvage if pitch flow evident or if bark beetle infested		Harvest bent trees over 4 m tall	Trees with sap flow from cracks indicating internal damage (ring shake, splintering) should be harvested for pulpwood or fuelwood	Trees with sap flow from cracks indicating internal damage (ring shake, splintering) should be harvested for pulpwood or fuelwood
Root damage	Uprooting less likely for most pines; salvage if root-sprung	Salvage if pitch flow evident or if bark beetle infested		Windthrow more likely than breakage; salvage windthrown and root-sprung trees as soon as possible	Root-sprung trees will decline over several years; harvest as soon as possible	Root-sprung trees will decline over several years; harvest as soon as possible
Wounds	Salvage if major wounds are on lower bole or large roots	Salvage if pitch flow evident or if bark beetle infested		Entry sites for stain and decay fungi; salvage high value trees as soon as possible	Harvest wounded trees in next scheduled harvest	Harvest wounded trees in next scheduled harvest; monitor for pest activity: Yellow needles; Boring dust around base
Salt damage	May lose needles; if no evidence of other damage or bark beetles, can be retained	Salvage if retained trees do not refoliate or if bark beetle infested		Defoliated crowns or burned leaves do not indicate mortality; crowns should refoliate	If new leaves do not form, may indicate saltwater intrusion; stressed trees may die	Monitor for pest activity: Yellow leaves; Boring dust around base

Monitoring may be needed for 1–5 years, depending upon species and damage type. *Sources*: Conner and Wilkinson (1982), Conner et al. (1989, 1997) and Barry et al. (1993).

to occur. On public lands and non-industrial private forest lands, and to a lesser extent on industry lands, naturally-regenerated stands can quickly recover from more under-stocked conditions than most people think. Loblolly pine responds rapidly to release at advanced age, and can often be restored to full-stocking from stocking levels as low as 30% of full-stocking more rapidly by managing the existing stand than by starting over (Baker and Shelton, 1998a). Surviving trees with at least 20% live crown ratio, not flat-topped, and at least 5 cm in diameter at the base of the live crown can survive and rebuild new crowns.

In pine plantations, bending and breaking of stems raises the question of whether to replant or let the stand continue to develop. Based on work done after Hurricane Hugo, pine trees of any age with $>45^{\circ}$ of lean, and trees age 8 and older with $>25^{\circ}$ of lean, should probably be harvested and replanted immediately after storm damage (Dunham and Bourgeois, 1996). These trees will grow significantly slower, and be undesirable for solid wood products because of a higher proportion of compression wood. Any trees with less than 25° of lean, and trees age 4 or less with less than 45° of lean, will recover from storm induced lean and produce wood with properties acceptable for producing solid wood products (Alexander Clark, personal communication, 2004).

The question of manage or regenerate in bottomland hardwood forests has been addressed, primarily in response to a legacy of high-grading (Manuel et al., 1993). An expert system decision model can be used to establish an index for

Table 4
Damaging organisms that develop within 2 years in storm damaged timber

Overstory species	Year 1	Year 2
Pinus spp.	Bark and ambrosia beetles, blue stain and soft rot fungi	Decay fungi
Quercus spp. and *Carya* spp.	Borers, ambrosia beetles, stains, soft rot fungi	Sapwood decay fungi
Other broadleaves	Borers, ambrosia beetles, stains, soft rot fungi	Sapwood, heartwood decay fungi

Sources: Blakeslee et al. (1980), Conner and Wilkinson (1982), Thatcher and Barry (1982), Barry et al. (1993) and Solomon (1995).

stand conditions according to stocking levels of desirable species, tree preference class, and individual tree characteristics. A stand meeting or exceeding a cutoff index value qualifies for continued management. Below the index value, the stand should be regenerated by clearfelling (Meadows and Stanturf, 1997). The cutoff index value can be adjusted to meet different ownership objectives.

The manage or regenerate decision will determine the degree of harvesting to undertake in a stand, in addition to salvaging broken and severely damaged stems (Table 3). Also to be considered are the values at risk over the short-term (up to 2 years post-hurricane) from other factors such as fungal stains, decay organisms, and boring insects (Table 4). General factors include the value of the timber that potentially could be recovered, access to the stand, factors affecting harvesting cost such as ease of operation and distance to mills, as well as safety of workers in storm-damaged stands.

5.2.3.2. Salvage operation. Experience with past hurricanes suggests some general principles for salvage operations (Barry et al., 1993). Salvage promptly, in one operation, to reduce vulnerability of residual trees to bark beetles, borers, and fungi. For the same reasons, minimize logging damage to residual trees, particularly high-value broadleaves (e.g., Meadows, 1993). Remove twisted trees or those with root damage, as well as all trees with major wounds. They will retain little value in the future, if they do survive, and can serve as brood trees for damaging insects. Because pines develop fungal stains rapidly that degrades value and are more susceptible to pest outbreaks than broadleaves, pine stands should be salvaged first. On the other hand, there may be more timber value in broadleaved stands, so trade-offs will have to be made by individual owners. After Hurricane Hugo, wet weather reduced accessibility of many broadleaved stands during the salvage period.

Several factors limit the ability to capture pre-hurricane levels of value from salvaged pine timber, including a depressed market caused by the sheer quantity of salvaged material and the rapidity of fungal stain development. Besides finding markets outside the damage zone, a strategy that did not work well after Hurricane Hugo (Marsinko et al., 1993), logs can be stored under water until markets improve and mill capacity recovers (Luppold, 1996).

5.3. Manage the system after the disturbance (1–5 years)

Stands within the damage zones that are not salvaged will require monitoring for up to 5 years to detect delayed mortality, infestation of insects, or development of diseases (Tables 3 and 4). Appropriate responses will depend on severity and options available, particularly whether timber markets are conducive to salvage harvest. Fire danger in the damaged areas will be high for at least one season, but risk of wildfire will depend mostly on weather conditions (Saveland and Wade, 1991). A particular concern following large disturbances is the spread of exotic invasive species, particularly plants.

The 2005 hurricane season in the northern Gulf of Mexico provides an opportunity to restore coastal forest ecosystems to less vulnerable conditions (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 1998). Long-term restoration of coastal areas may require expensive efforts to build defensive structures and restore natural sediment replenishment processes, especially along the Louisiana coast. Coastal forests could be restored to more effectively provide protection inland from storm surges and hurricane winds. Financial and ecological losses could be reduced by lowering the vulnerability of coastal forests. Available knowledge can provide a rationale for prioritizing site treatments, as well as guidance on restoration techniques adapted to sites and stand conditions. In the recovery of pine plantations post-Katrina, we must decide whether to replant loblolly pine in areas prone to destruction by hurricanes or convert stands to the more resilient longleaf pine.

5.4. Manage recovery process (1 year to the next disturbance)

Beyond the initial flurry of cleanup and salvage logging, the recovery process will take many years and require the investment of much time and resources. After previous hurricanes, many small forest owners lacked the financial resources or the desire to reforest their damaged stands (Colvin, 1996; Purvis, 1996) and natural regeneration may be a preferred option anyway (Haight et al., 1996). The recovery period should be utilized to examine long-term risks and seek to reduce vulnerability.

5.4.1. Reduce vulnerability

Vulnerability can be lessened by converting to species that are less susceptible to hurricane damage (Table 5), by controlling stand structure, and by dispersing harvesting and thinning operations to lower the risk of losses. Longleaf pine has been observed to be more resistant to breakage and mortality following hurricanes than the more widely planted loblolly pine. We simulated these observations by examining the potential damage due to stem breakage for a set of nine theoretical stands of pine trees. Potential stem breakage was estimated for each of the four damage categories mapped for Hurricane Katrina (Fig. 3), as a function of sustained wind speed, tree height and tree spacing. The simulation followed the methodology of the GALES model, with most parameters set for *Pinus sylvestris* L., Scots pine (Gardiner et al., 2004). Species-dependent streamlining of the canopy is neglected here as wind tunnel data for the pine species used was unavailable; the canopy of each species of pine was treated as Scots pine. The only species-specific-parameter altered was the modulus of rupture (MOR) that defines stem failure. For loblolly pine this parameter was assigned a value of 50.33 MPa while for longleaf pine the value was 58.61 MPa (Alden, 1997).

Nine hypothetical stands were created from combinations of three tree heights (20, 25 and 30 m) and three spacings (2.5, 5.0, and 7.5 m). For each of the nine stands the maximum bending moment at a height of 1.3 m above the ground was determined for both the interior of the stand and its edge with the result compared to the bending moment that signifies stem failure for

Table 5
Susceptibility of tree species to damage from hurricanes by breakage, uprooting, salt damage, or deterioration by insects and diseases

Breakage		Uprooting	Salt damage	Deterioration by insects and diseases
Species	Common name			
Most susceptible				
Carya illinoensis	Sweet Pecan	*Carya illinoensis*	*Acer rubrum*	*Pinus taeda*
Acer rubrum	Red Maple	*Carya aquatica*	*Magnolia grandiflora*	*Pinus elliottii*
Carya aquatica	Water Hickory	*Acer rubrum*	*Carya illinoensis*	*Pinus palustris*
Pinus taeda	Loblolly Pine	*Quercus nigra*	*Carya aquatica*	*Acer rubrum*
Pinus elliottii	Slash Pine	*Magnolia virginiana*	*Quercus pagoda*	*Carya illinoensis*
Pinus palustris	Longleaf Pine	*Pinus taeda*	*Magnolia virginiana*	*Carya aquatica*
Platanus occidentalis	Sycamore	*Pinus elliottiii*	*Platanus occidentalis*	*Magnolia virginiana*
Quercus nigra	Water Oak	*Magnolia grandiflora*	*Quercus nigra*	*Nyssa silvatica*
Quercus pagoda	Cherrybark Oak	*Quercus pagoda*	*Liquidambar styraciflua*	*Magnolia grandiflora*
Magnolia virginiana	Sweetbay	*Pinus palustris*	*Taxodium distichum*	*Quercus pagoda*
Magnolia grandiflora	Magnolia	*Platanus occidentalis*	*Nyssa silvatica*	*Taxodium distichum*
Nyssa silvatica	Water Tupelo	*Liquidambar styraciflua*	*Pinus taeda*	*Platanus occidentalis*
Liquidambar styraciflua	Sweetgum	*Nyssa silvatica*	*Pinus palustris*	*Quercus nigra*
Taxodium distichum	Baldcypress	*Taxodium distichum*	*Pinus elliottii*	*Liquidambar styraciflua*
Astrocaryum jauari	Palm	*Astrocaryum jauari*	*Astrocaryum jauari*	*Astrocaryum jauari*
Least susceptible				
Quercus virginiana	Live Oak	*Quercus virginiana*	*Quercus virginiana*	*Quercus virginiana*

Adapted from Barry et al. (1993).

each pine species. The MOR was constant at all spacings, which is realistic for pine plantation management in the southern U.S. The wider spacings would result from thinning, not initial planting spacing (Alexander Clark, personal communication, 2006). Note that we looked only at stem breakage and not damage due to uprooting of trees and therefore these modeling results are intended only as an illustrative tool rather than a detailed species-specific study of tree failure.

Comparison of the damage zones from Hurricane Katrina (Fig. 3) with estimated sustained wind data allows the four zones to be related to an approximate wind range for comparison to the critical wind speed for stem failure estimated through GALES (Table 6). For the interior portion of the stand, tree height was a primary factor in determining stem failure (Fig. 5). In damage zone 4, most stands would likely have experienced extensive damage with the exception of young (i.e. short) trees in dense stands. Since the wind is assigned at tree-top the wind speed at the top of all stands is the same; however, taller trees increase the length of the lever through which the force of the wind is transferred to the breaking point of the stem. With a longer lever less force is required to break the stem. For damage zone 3, the 20-m-tall stands were undamaged regardless of planting density and the 25-m-tall closed stand of longleaf pine were also undamaged, but the 25-m-tall closed stand of loblolly pine was on the threshold of damage. Zone 2 damage areas showed potential damage to all of the 30-m-tall loblolly stands plus the 25-m-tall open loblolly stand while for longleaf only the open and semi-closed stands receive damage. In the class 1 damage zones, only the 30-m-tall open loblolly stands were likely to receive damage.

Table 6
Approximate sustained wind speed associated with each damage zone from Hurricane Katrina, expressed in miles per hour (mi h^{-1}) and meters per second (m s^{-1})

Damage zone	Sustained wind speed	
	mi h^{-1}	m s^{-1}
1	20–40	9–18
2	41–60	19–27
3	61–80	28–36
4	80–120	36–54

The threshold for damage due to stem breakage is much lower along stand edges rather than in the interior of the stand (Fig. 6). Damage would be highly likely along all windward edges in the areas identified as damage zones 3 and 4 (Fig. 3), with only short, closed stands escaping damage in zone 3 conditions. In damage zones 1 and 2, tree spacing is more important in avoiding damage than tree height, suggesting that management may be able to reduce losses due to wind damage by altering planting densities along stand edges. The steep slopes of the bending moment curves along the stand edge minimize the differences in critical wind speeds for stem failure between loblolly and longleaf pines.

Edge in this simulation realistically portrays conditions of large openings (at least five times tree height in the GALES model; Gardiner et al., 2004) such as recent clearcuts, open water, or agricultural fields. These large openings fully expose the stand to the oncoming winds while more narrow openings, such as along roads, only partially expose the stand. Areas of partial exposure introduce another complicating factor not accounted for in these simulations, locally generated shear vorticity. With hurricane strength winds the vortices produced would supply an additional twisting stress to trees along the edge. Damage in longleaf stands has been observed to be worse along power lines, roads, and open fields where winds have access to stands. The southern forests are highly fragmented

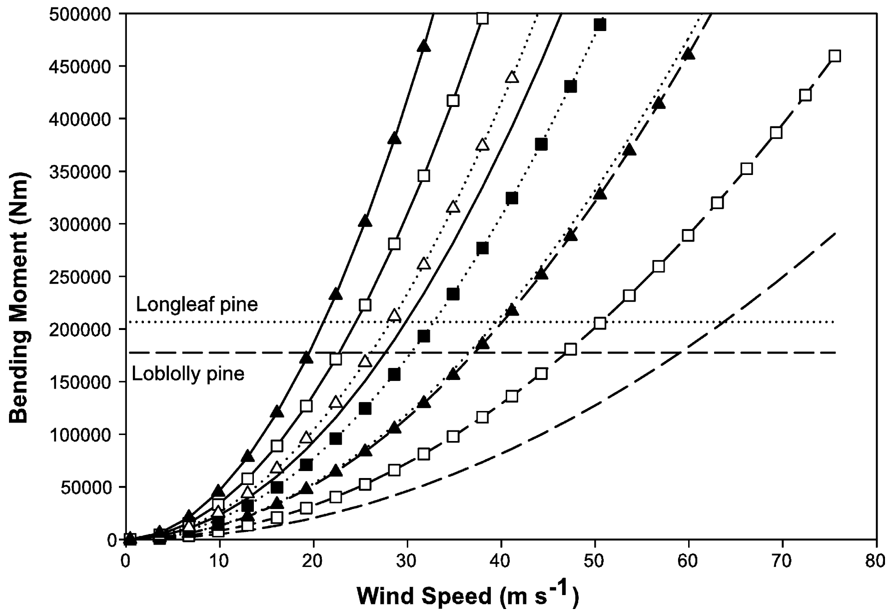

Fig. 5. Bending moments expressed in Newton meters (Nm) of trees at the stand-interior as a function of wind speed. Dashed black, gray, and solid black curves represent 20-, 25- and 30-m-tall trees, respectively; curves with no symbol are closed stands (tree spacing of 2.5 m), squares symbols represent semi-closed stands (spacing of 5 m), and triangles are open stands (spacing of 7.5 m).

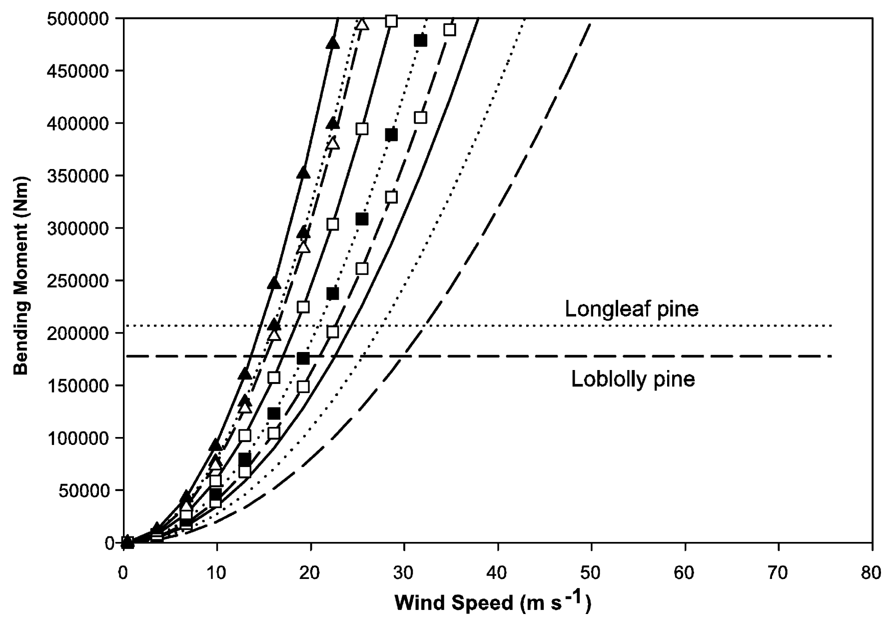

Fig. 6. Bending moments expressed in Newton meters (Nm) of trees at the stand-edge as a function of wind speed. Dashed black, gray, and solid black curves represent 20-, 25- and 30-m-tall trees, respectively; curves with no symbol are closed stands (tree spacing of 2.5 m), squares are semi-closed (spacing of 5 m) and triangles are open stands (spacing of 7.5 m).

and parcelized (Riitters and Wickham, 2003), creating these vulnerable conditions. Although little can be done about such fragmentation, management decisions can be informed by this knowledge. For example, small landowners with isolated stands near large open areas should probably clearcut entire stands when economically mature, rather than conducting several partial cuts to spread out their income over time. Large landowners and public managers may apply this knowledge to prefer singletree and small group selection rather than clearcuts to lessen overall vulnerability.

In damaged pine stands, conversion from the widely planted loblolly pine to the more resistant longleaf pine is an option, especially for public land managers. For stands that are already slated for conversion from loblolly pine to longleaf pine, quick intervention will be critical to remove any salvageable timber and then burn the site to retard natural loblolly regeneration before planting longleaf pine. On the other hand, areas previously dominated by longleaf may contain sufficient advance longleaf regeneration but very little loblolly, allowing site treatments to be delayed. Restoration of the longleaf pine

Table 7
Common riverine species' tolerances of flooding in relation to season and duration; all species shown are tolerant of flooding to some degree

Continuous flooding		Periodic flooding		
January–June	January–May	January–May	January–April	January–March
Taxodium distichum L. (Baldcypress)	*Diospyros virginiana* L. (Persimmon)	*Liquidambar styraciflua* L. (Sweetgum)	*Platanus occidentalis* L. (Sycamore)	*Quercus shumardii* Buckl. (Shumard oak)
Quercus lyrata Walt. (Overcup oak)	*Fraxinus pennsylvanica* Marsh. (Green ash)	*Quercus nigra* L. (Water oak)	*Populus deltoides* Bartr. ex. var. Marsh. var. *deltoides* (Eastern cottonwood)	*Quercus pagoda* Raf. (Cherrybark oak)
Carya aquatica (Michx. f.) Nutt. (Water hickory)	*Quercus laurifolia* Michx. (Swamp laurel oak)	*Quercus phellos* L. (Willow oak)	*Carya illinoensis* Wangenh. (Sweet pecan)	*Quercus michauxii* Nutt. (Swamp chestnut oak)
Nyssa aquatica L. (Water tupelo)	*Quercus nuttallii* Palmer (Nuttall oak); *Salix nigra* L. (Black willow)		*Celtis laevigata* willd. (Sugarberry)	

Source: Meadows and Stanturf (1997).

forest that once dominated the coastal plain is a popular idea in the region, and methods are well developed (e.g., Brockway et al., 2005).

In bottomland hardwood and swamp forests, site conditions such as flooding regime must be taken into account in attempts to favor more hurricane resistant species (Table 5). Species tolerances to flooding are generally known (Table 7). Changes in inundation regime caused by hurricane action must be considered, as well as possible changes in groundwater chemistry because of saltwater intrusion. Salt water overwash can cause changes in soil chemistry that may affect restoration plantings (Conner, 1995; Conner et al., 1997), although these moderate within a few seasons (Gresham, 1993). Methods for restoring bottomland hardwood forests are more developed than for deepwater swamp forests (Allen et al., 2001; Gardiner et al., 2002; Stanturf et al., 2004).

5.4.2. Multiple sequential interventions

Other strategies to reduce vulnerability include limiting exposure of individual stands by spatially distributing management treatments that could temporarily increase vulnerability to wind damage, for example thinning. By staggering thinning, a manager can limit the amount of recently thinned stands in an area. Balancing age classes also reduces the overall risk of catastrophic loss within an area or on an ownership. Wind damage to forests from hurricanes is quite variable spatially, but the greatest damage usually occurs close to landfall, close to the eyewall, and in the northeast quadrant of the hurricane track. Away from the most intense winds, however, complex stand structure may lower damage susceptibility. Controlling stand density to create windfirm stems will reduce the risk of damage, especially if resistant species are used (Table 5).

5.4.3. Lessons learned assessments

Every major disturbance event will be different in some respects from previous experience, thus an adaptive strategy is to plan to conduct after action studies that may suggest changes in policies and procedures that can be implemented before the next event. One lesson learned from Hurricanes Katrina and Rita was that hurricanes and other natural disasters create woody debris that could be used to generate bioenergy. Co-generation in power utility plants is possible but this is not a short-term solution unless facilities are already equipped to handle woody biomass. Suggestions have been made to develop methods for economically utilizing downed material, including strategically pre-positioning biomass gasification units (T. Rials and T. Elder, personal communication, 2006). Although transportation to a central plant would be a limitation of the strategy, small plants could be used to provide power for incident command centers during relief and cleanup efforts. Developing an in-woods bio-processing capability, technology that can convert woody biomass in the forest into higher-valued liquid fuels that are more easily transported, would provide greater flexibility.

6. Implications for the future

It is probable that coastal areas of the southern U.S. can expect higher event risk for hurricanes over the next 40 years, whether from natural cycles, effects of climate change, or both (Gornitz, 1995; Knutson et al., 1998; Easterling et al., 2000; Goldenberg et al., 2001; Nicholls, 2004; Meehl et al., 2005; Pielke et al., 2005; Webster et al., 2005). The rising costs of natural disasters is a result of increased vulnerability of coastal ecosystems, especially due to decisions made during a period of relatively low event risk that increased populations and infrastructure in coastal areas (Pielke and Landsea, 1998, 1999; Bartlett et al., 2000; Burbridge et al., 2005; Emanuel, 2005). Societal responses will be the key factor in the future (Michener et al., 1997; Pielke and Landsea, 1999) but the historical record is not encouraging (Moser, 2005); simultaneous disasters will tax government resources, especially as private insurance coverage declines, either by declining to insure or because higher premiums exceed the willingness of consumers to pay (Mills et al., 2005).

The coastal plain of the southern United States is frequently visited by hurricanes and some areas of the coastal states of Texas, Louisiana, and Mississippi are especially prone to severe hurricanes (Fig. 1). Two major hurricanes in 2005, Katrina and Rita, made landfall within one month, causing estimated wind damage to forest resources in the three states of between $2 billion and $3 billion. Experience from past hurricanes in the region, such as Hurricane Hugo in 1989, highlight the need for planning and communication before, during, and immediately after a major event. Nevertheless, these hurricanes provide an opportunity to examine forest management objectives, with an eye toward incorporating fine-scale disturbance effects such as more complex stand structures into ongoing forest management in order to reduce vulnerability to damage from future hurricanes. A better understanding of risk to natural resource systems may induce management changes to reduce vulnerability (Millennium Ecosystem Assessment, 2005; Olsen et al., 2005) and natural systems could be used to reduce vulnerability of urban areas and human populations (Millennium Ecosystem Assessment, 2005) if placed as a living buffer between the high-energy nearshore and structures. The impact of hurricane damage to small forest owners could be lessened by providing a form of risk insurance (Holecy and Hanewinkel, 2006).

Decreasing vulnerability of coastal forests to hurricanes requires that we understand event risk under changing climate conditions. While a simple event risk map such as Fig. 1 could be used to guide long-term monitoring and research efforts, in order to maximize the likelihood of obtaining pre-event measurements, spatially explicit risk information will be needed to guide management decisions aimed at reducing vulnerability. Research using a landscape-scale experimental design, focusing on spatial arrangement of stands of different species composition and stand structures, could provide needed information on how to manage coastal forests for maximum resiliency. Our simple simulation of stem breakage potential suggested that stand spacing and tree height were more important than species, but this could not take into account site differences that may be significant. Recent work in the United Kingdom comparing the effect of soil type and rooting depth on the anchorage of 12 coniferous species revealed significant species-site interactions (Nicoll et al., 2006). Additional research is needed on the effects on vulnerability of fragmentation, harvest systems, and stand structure. Because salvage following hurricanes has been so widespread, the ecological role of large amounts of downed woody debris is not sufficiently understood and recent hurricanes provide obvious opportunities to increase our understanding of the ecological effects of salvage logging.

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