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Forest Ecology and Management 103 (1998) 265–276

Forest Ecology and Management

Hurricane–fire interactions in coastal forests of the south: a review and hypothesis

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Received 17 January 1997; accepted 17 January 1997

Abstract

The extent to which periodic wildfires, burning in increased forest fuels following severe hurricanes, influenced coastal plain forest ecosystems prior to European settlement is unknown. A review of the literature suggests that, in many forests, conditions after exceptionally strong hurricanes promote the occurrence of fires of higher than normal intensity. While post-hurricane fires have not been prevalent or widespread in recent times in the southern US, a credible line of reasoning plus observations from outside the US supports the hypothesis of a hurricane–fire interaction, particularly in the era before organized fire suppression. The drastic effects caused by strong hurricanes and subsequent fire is likely to have been a significant part of the long-term disturbance regime of many ecosystems. Due to their infrequent occurrence and the difficulties involved in their study, these effects have been overlooked, minimized, or ignored. The hypothesis is presented that a hurricane–fire interaction influenced vegetation in specific ways in the presettlement South. Further, the present-day absence of this process may in part account for the continuing decline of certain plant communities. Opportunities for large-scale restoration of declining communities and ecosystems exist in areas where extensive vegetation change has already come in the form of drastic natural disturbance, such as that caused by severe hurricanes. Land managers may be able to facilitate the long-term process of restoring diverse, fire-maintained ecosystems by using a regime of frequent prescribed fires in areas impacted by strong hurricanes. © 1998 Elsevier Science B.V.

Keywords: Hurricane; Fire; Hurricane–fire interactions; Fire ecology; Restoration ecology

1. Introduction

Hurricanes have long been an important and recurring type of natural disturbance along the Atlantic and Gulf coastlines of the United States, as well as in Central America and the Caribbean, shaping forest ecosystems for millions of years (Lugo et al., 1983; Weaver, 1989; Boucher, 1990). It is now recognized that hurricanes have a broad range of influences on species composition, structure, and natural succession in many forests (Foster, 1988; Conner et al., 1989; Gresham et al., 1991; Platt and Rathbun, 1993; Snook, 1996; Myers, 1996). However, relatively little is known about specific roles of hurricanes in disturbance ecology for the majority of forest types. Consequently, practical questions exist such as whether present-day forests could be better managed by utilizing strategies that prepare for the possibility of hurricanes, or if there are methods that optimize

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PII S0378-1127(97)00223-5

resource objectives and recovery potentials following hurricanes.

The extent to which periodic wildfires, burning in increased forest fuels following severe (probably Saffir/Simpson scale category 3 or greater) hurricanes, influenced coastal plain forest ecosystems prior to European settlement is unknown. This question, as with others about landscape-level processes altered by human activities, may never be answered satisfactorily. In this paper, we briefly review a range of known influences of hurricane disturbance in southern coastal forests, provide evidence for the existence of a hurricane–fire interaction, and propose a general hypothesis about how such an interactive disturbance mechanism may have once influenced the development of certain forest plant communities. Such a hypothesis could provide the framework for designing experiments that test land management approaches for restoring species, plant communities, and ecosystems on the verge of disappearing after 300 yrs of intensive land use in the South.

2. Hurricane frequency and severity

Hurricanes are not unusual events in many regions of the world. Although hurricanes that cause catastrophic effects may be infrequent within human lifespans, they occur rather often in the context of evolutionary time. Geologic evidence suggests that powerful tropical storms have been affecting US coastlines for many millions of years (Ball et al., 1967). If hurricanes occurred throughout the Pleistocene Epoch and previous time periods as often as their present-day frequency would indicate, then increased scientific scrutiny is warranted to assess their role as agents for change in forest ecosystems.

Climatic records indicate that from 1871 to 1994, 1008 hurricanes or tropical storms have occurred in the Atlantic tropical cyclone basin (Neumann et al., 1993). Over the past 50 yrs, one to three hurricanes have crossed or passed close to US coastlines in most years. Some unusual years (e.g., 1985) have had as many as six hurricanes (Fig. 1). By extrapo-

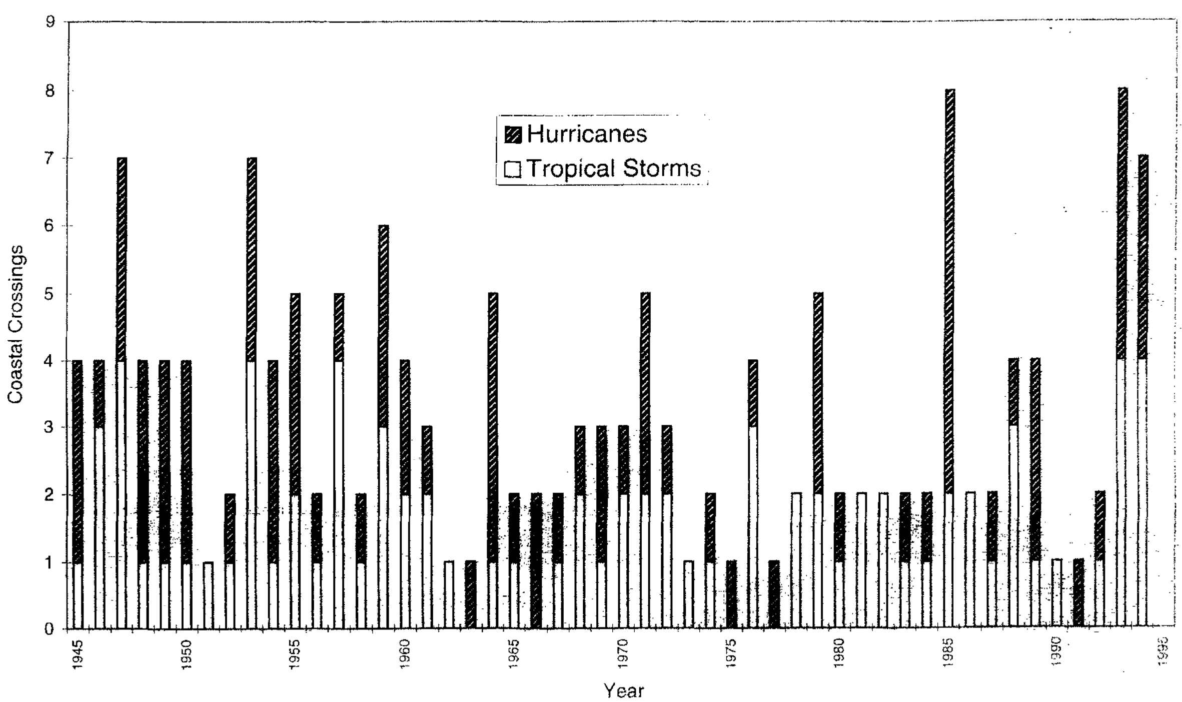

Fig. 1. Annual distribution of the 82 Atlantic hurricanes and 81 tropical storms that have crossed or passed adjacent to the United States coastline (Texas to Maine), 1945 through 1994. One crossing per storm is shown even though multiple crossings may have occurred. (From Neumann et al., 1993).

lating 20th century hurricane frequency, Ball et al. (1967) surmised that from 160,000 to 320,000 hurricanes may have impacted the Florida Keys in the last 2 million yrs. Purvis (1973) noted that of the 25 'memorable' hurricanes affecting South Carolina from 1870 to 1964, four were considered as either 'great' or 'extreme'. Hurricane Hugo's occurrence in 1989 yields a total of five very powerful storms that have affected this smallest of southeastern states in the last 125 yrs.

Since little can be garnered from the historical record alone about periodicity of storms of different magnitudes at specified locations, a method was developed for estimating these frequencies called HURISK (Neumann, 1987). This model fits site-specific tropical cyclone histories to probability functions and estimates return periods of storms of specified force for specific sites. With this technique, the Francis Marion National Forest (FMNF) in South Carolina has been shown to be especially vulnerable to hurricanes, due largely to its proximity to the coast. HURISK indicates that there is a 60% chance that Saffir/Simpson category 1, 2, 3, and 4 hurricane-induced winds (Table 1) will be experienced every 14, 43, 90, and 260 yrs, respectively, on the FMNF. Category 3 hurricanes—those with maximum winds similar to those attained during Hurricane Hugo—have a near 100% chance of recurring every 400 yrs (see Hooper and McAdie, 1995).

3. Interpreting reports of hurricane effects

The term 'hurricane' describes an exceedingly broad array of physical conditions, a fact that causes confusion in the literature on hurricane effects in forests. For example, a wide range of wind speeds (74 mph up to 200 mph or higher) may occur during the weather event known as a hurricane. This range results in drastically differing effects to forests and highly variable degrees of damage to human-made structures (Table 1). The spectrum of forces on objects generated by minimal up to maximal hurricane winds is wider still, since wind force is proportional to the square of wind velocity (Webb, 1958). The strongest winds of a minimal hurricane therefore have very different effects on forests from those of, for example, the maximum winds of a category 4 storm. Similarly, the extreme wind speeds near the center of a category 4 storm exert much greater effects than the lesser winds of the same hurricane experienced at locations distant from the eye.

Another difficulty that arises when discussing hurricane strength and resulting effects to forests is that the Saffir/Simpson scale categorizes storm strength by maximum measured sustained 1-min winds, while most forest change is probably effected by maximum gusts lasting only a few seconds (Savill, 1983). Since individual storms have their own unique pattern (number, frequency, duration) of peak gusts and embedded tornadoes, resultant impacts in forests may vary greatly even among storms assigned the same Saffir/Simpson strength class (Hook et al., 1991).

Lastly, there is no standardized quantitative method for comparing hurricane effects in different forests. Lugo et al. (1983) suggested that in developing such a method, hurricane intensity should be described in terms of duration of hurricane winds and wind speed. More recently, Everham (1995) proposed that comparative criteria should include both mortality and structural impacts, described in terms of decrease in forest basal area. It is critical that researchers describe forest responses to specific storm events in concert with estimates of peak gust and sustained wind speeds. Otherwise, generalizations and misconceptions about 'hurricane effects' will inevitably be added to those that already exist

4. Hurricane effects on forests

Hurricane effects in ecosystems and across landscapes depend on frequency of storm occurrence, as well as on factors associated with the individual storm, including wind velocities, rainfall amounts, number of embedded tornadoes, soil conditions, forest structure, and saltwater flooding (Weaver, 1989; Gardner et al., 1991; Hooper and McAdie, 1995). Many effects that hurricanes exert on forests have been reviewed by Conner et al. (1989), Brokaw and Walker (1991), and Conner (1995).

The majority of hurricanes crossing US coastlines are category 1 and 2 storms (Neumann et al., 1993).

Table 1
The Saffir/Simpson Hurricane scale (from Neumann et al., 1993)

Category	Wind (mph)	Description
1	74–95	Damage primarily to shrubbery, trees, foliage, and unanchored mobile homes. No real damage to other structures. Some damage to poorly constructed signs. And/or: storm surge 4–5 ft above normal. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorages torn from moorings.
2	96–110	Considerable damage to shrubbery and tree foliage; some trees blown down. Major damage to exposed mobile homes. Extensive damage to poorly constructed signs. Some damage to roofing materials of buildings; some window and door damage. And/or: storm surge 6–8 ft above normal. Coastal roads and low-lying escape routes inland cut by rising water 2–4 h before arrival of hurricane center. Considerable damage to piers. Marinas flooded. Small craft in unprotected anchorages torn from moorings. Evacuation of some shoreline residences and low-lying island areas required.
3	111–130	Foliage torn from trees; large trees blown down. Practically all poorly-constructed signs blown down. Some damage to roofing materials of buildings; some window and door damage. Some structural damage to small buildings. Mobile homes destroyed. And/or: storm surge 9–12 ft above normal. Serious flooding at coast and many smaller structures near coast destroyed; larger structures near coast damaged by battering waves and floating debris. Low-lying escape routes inland cut by rising water 3–5 h before hurricane center arrives. Flat terrain 5 ft or less above sea level flooded inland 8 miles or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.
4	131–155	Shrubs and trees blown down; all signs down. Extensive damage to roofing materials, windows and doors. Complete failure of roofs on many small residences. Complete destruction of mobile homes. And/or: storm surge 13–18 ft above normal. Flat terrain 10 ft or less above sea level flooded inland as far as 6 miles. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes inland cut by rising water 3–5 h before hurricane center arrives. Major erosion of beaches. Massive evacuation of all residences within 500 yards of shore possibly required, and of single-story residences on low ground within 2 miles of shore.
5	156 +	Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors. Complete failure of roofs on many residences and industrial buildings. Extensive shattering of glass in windows and doors. Some complete building failures. Small buildings overturned or blown away. Complete destruction of mobile homes. And/or: storm surge greater than 18 ft above normal. Major damage to lower floors of all structures less than 15 ft above sea level within 500 yards of shore. Low-lying escape routes inland cut by rising water 3–5 h before hurricane center arrives. Massive evacuation of residential areas on low ground within 5–10 miles of shore possibly required.

These minimal to moderate hurricanes bring heavy rains and relatively mild wind-induced structural change to coastal and near-inland forests (Purvis, 1973). Slow-moving storms, regardless of wind speeds, often cause extremely high rainfall and flooding, both in riparian forests as well as on poorly drained upland sites. Storm surges may inundate belts of forestland adjacent to coastlines and estuaries with saline floodwaters (Gardner et al., 1991). Strong gusts and tornadoes may cause localized severe wind impacts. Catastrophic effects to forests, where the majority or all of the overstory canopy is removed, are most often associated with the extreme winds near the centers of category 3 and stronger storms (Hook et al., 1991; Hooper and McAdie, 1995).

In general, effects of hurricane-force winds include defoliation, stem breakage, and uprooting of some trees (Lugo et al., 1983). Other impacts include stem wounding, limb breakage, and physical effects to understory plants when windthrown trees or broken tree crowns topple (Frangi and Lugo, 1991).

Large trees are more likely than small trees to be broken or windthrown by hurricanes, and storm effects are most pronounced on flats or on slopes facing the wind (Brokaw and Walker, 1991).

Some studies indicate that different tree species respond in distinct ways to hurricane winds (Grano, 1953; Derr and Enghardt, 1957; Touliatos and Roth, 1971; Foster, 1988). Gresham et al. (1991) speculated that species associated with coastal regions, e.g., longleaf pine (*Pinus palustris*), baldcypress (*Taxodium distichum*), and live oak (*Quercus virginiana*), have become selectively resistant to hurricanes. However, it is likely that site and soil conditions are integrated in many species responses to high winds. For example, while pond pine (*P. serotina*) is damaged easily by strong wind, it is often associated with unstable soils (Bramlett, 1990; Gresham et al., 1991). Likewise, Platt and Rathbun (1993) observed that longleaf pine windthrow after a hurricane was greatly increased on wetter soil units where effective rooting depth was decreased.

Few studies have investigated how individual tree species respond to various levels of wind intensity (see King, 1986; Hedden et al., 1994). There are indications, however, that when threshold wind speeds are exceeded, most larger trees—independent of species—will be killed by uprooting or bole snapping (Hook et al., 1991; Sheffield and Thompson, 1992; Hooper and McAdie, 1995). An exception may be baldcypress, which has been noted to be exceptionally windfirm (Gresham et al., 1991).

Along southern coastlines, hurricanes up to category 2 strength (sustained winds up to 110 mph) are relatively common events, occurring repeatedly in the life of individual long-lived trees. Since most hurricanes are either category 1 or 2, the *average* storm seldom results in widespread tree mortality. However, it is probably not the effects of average hurricanes or even the cumulative impacts of repeated minimal hurricanes that have the most significant long-term influence on forest structure and composition. As Visher (1925) observed decades ago, "The biota is less affected by normal or average conditions than by extremes." Severe (category 3 and greater) hurricanes, while relatively rare, have the capacity to profoundly change forests.

The strong winds and storm surges associated with the centers of severe hurricanes can cause unprecedented forest mortality, eliminating up to 100% of an existing forest canopy. Recent examples of such exceptional storms include Hurricanes Camille, David, Gilbert, Joan, Hugo, and Andrew, all of which caused widespread mortality to forest trees across large areas (Hedlund, 1969; Lugo et al., 1983; Whigham et al., 1991; Boucher et al., 1990; Hook et al., 1991; Myers et al., 1993; Loope et al., 1994).

The combination of extreme hurricane winds and mature pine forest can result in particularly high rates of tree mortality (Hedlund, 1969; Boucher et al., 1990; Hook et al., 1991; Hooper and McAdie, 1995). Camille and Hugo were notable for causing high rates of mortality in areas where winds exceeded some threshold level, with only minor impacts in nearby forests (see Hedlund, 1969; Touliatos and Roth, 1971; Hook et al., 1991; Gresham et al., 1991). While not as strong as Camille at landfall, Hurricane Hugo in South Carolina demonstrated in dramatic fashion that hurricanes can be extraordinary agents of change in forests. Thus, severe hurricanes represent a unique kind of disturbance, periodically affecting biotic communities, ecosystems, and landscapes across large geographic areas.

5. Roles of hurricanes in disturbance ecology

There is limited information that characterizes hurricanes as a process in the functioning or maintenance of ecosystems. This is due to the random nature of hurricane occurrence in space and time plus the extended periods required to observe responses (Lugo et al., 1983; Conner et al., 1989). Consequently, many ecological effects of hurricanes (especially their interaction with other disturbance types) are poorly understood, and are often based on short-term results. Long-term studies involving large study areas are needed since they alone can provide opportunities to observe rare events such as severe hurricanes that, while infrequent, have far-reaching effects (Sugden, 1992).

Hurricanes influence patterns of nutrient cycling by sudden transformation of materials in living vegetation to components of woody debris and forest floor (Whigham et al., 1991). Necromass decomposition releases nutrients to soil where they become available for plant growth or microbial immobilization. Uprooting of trees brings chemical elements from near the bottom of the root zone to the surface where they are more available to vegetation (Botkin, 1993). Mound and pit topography from tree uprooting can be extensive in wind-prone forests and forms important habitats in post-hurricane landscapes, increasing site heterogeneity by creating variable soil microenvironments (Foster and Boose, 1995).

Some studies have described hurricane-induced structural changes in forests and made inferences regarding the role of wind disturbance in plant community development. Platt and Rathbun (1993) showed that a relatively mild hurricane (Kate, 1985, category 2) can result in significant mortality of the larger-sized trees in old-growth longleaf pine forests, and speculated that wind may exceed lightning as a source of large tree mortality. Conversely, Boucher et al. (1990) described the contrasting types of damage in tropical rainforest and pine forest resulting from a very strong hurricane (Joan, 1988, category 4) in Nicaragua. They noted that while most rainforest trees survived stem breakage by resprouting, survival of snapped-off pines was near zero, inferring that shoot production capability after crown loss may constitute a competitive advantage for trees in hurricane-prone areas.

Doyle (1980) predicted, using succession simulation models, that increased forest species diversity is related to hurricane disturbances, but did not indicate how hurricane frequency and magnitude influence this diversity. It is now generally accepted that the frequency of intense storms in hurricane-prone regions is sufficiently high to override other ecological factors. Thus, hurricanes are one factor preventing the development of stable steady-state ecosystems (Webb, 1958; Lugo et al., 1983; Boucher, 1990).

6. Fire after hurricanes

Fire is a well-known and frequent natural disturbance in southern forests, and has played an important role in shaping forest and grassland ecosystems (Chapman, 1932; Stoddard, 1935; Cooper, 1961; Komarek, 1974; Frost, 1993; Landers et al., 1995). Before the arrival of native Americans, wildland fires resulted from lightning strikes and were most prevalent in the region during late spring and early summer, as noted by Robbins and Myers (1989) for Florida and as indicated by data from the FMNF in South Carolina (Fig. 2). The coming of humans to the South about 12,000 yrs ago provided a new and more frequent form of ignition and extended the fire season. Fires, both lightning-caused and those caused

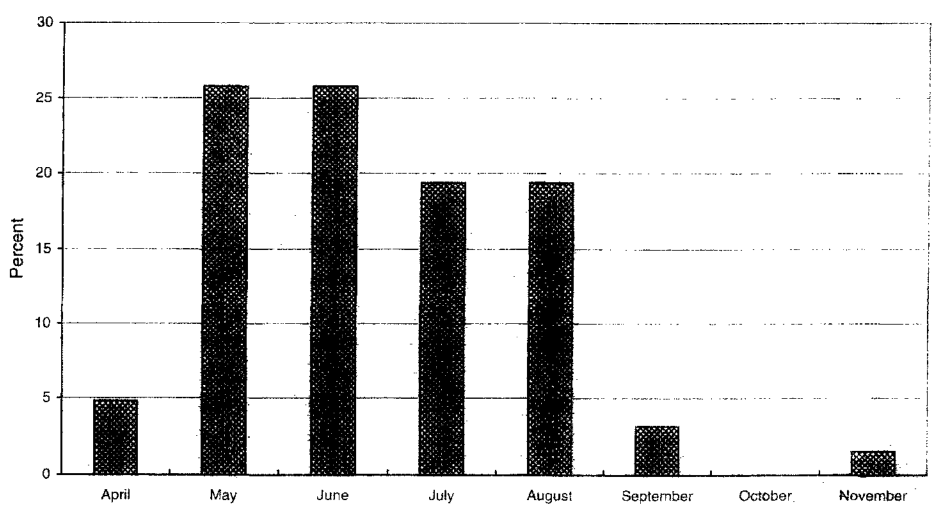

Fig. 2. Historical monthly frequency distribution of lightning-caused wildfires on the Francis Marion National Forest in South Carolina over the period 1935–1991. (From USDA Forest Service, Francis Marion National Forest wildfire history and occurrence maps).

by native Americans, were a prominent factor determining the composition and structure of vegetation in the South (Hudson, 1976; Pyne, 1982; Robbins and Myers, 1989; Williams, 1989).

Some authors have acknowledged the heightened risk of forest fires after hurricanes (Spurr, 1956; Webb, 1958; Craighead and Gilbert, 1962; Furley and Newey, 1979; Gardner et al., 1991; Hook et al., 1991; Whigham et al., 1991; Loope et al., 1994). Fire danger increases, especially following severe hurricanes, due to large fuel accumulations and optimum drying conditions in a microclimate of increased insolation and wind speeds (Gill et al., 1990; Loope et al., 1994). Even minimal hurricanes may increase fire hazard by causing additions of fine fuels to the forest floor in the form of wind-stripped foliage, twigs, and small branches. The potential for uncontrollable, catastrophic wildfire was quickly recognized after Hurricane Hugo in South Carolina (see Haymond et al., 1996).

When periods of dry, hot, windy weather occur in forests following hurricanes, the risk of fire is great, even on mesic sites normally considered immune to fire (Webb, 1958). For example, after Hurricane Hugo, Putz and Sharitz (1991) observed that the possibility of fire increases following severe hurricanes in southern bottomland forests. The absence of widespread uncontrolled fires after hurricanes in the US is most probably due to suppression efforts, alteration of natural vegetation and landscape patterns, and elimination of fires lighted by native Americans.

7. A hurricane–fire interaction

While the importance of a hurricane–fire interaction has been recognized in some Australian and Central American forest types, the idea has received little or no study in the US. Webb (1958) was among the first to examine hurricane effects on vegetation and to interpret consequent changes in terms of succession. He noted that species composition and structure of rainforests in north Queensland, Australia are affected by the interaction of hurricanes and fire, and that variation in frequency and intensity of these factors may produce different community types.

The perpetuation of mahogany (*Swietenia macrophylla*) forests in Central America may depend on periodic catastrophic disturbances involving the combination of hurricanes and fire (Snook, 1996). Adult mahogany trees resist strong wind, fire, and flooding more successfully than associated species. After catastrophic disturbance by wind and fire, surviving mahogany trees disperse seed across open areas, ensuring a large mahogany component in new even-aged forests.

We propose that a hurricane–fire interaction once played a major role in the development of ecosystems in the southern US, influencing their composition, structure, and pattern on the landscape. This review provides a sound basis for the intuitive premise that severe hurricanes—category 3 and stronger storms—have been followed by forest fires, especially in certain forest types. In southern coastal plain forests, where fire is generally accepted as the most significant natural disturbance factor, a hurricane–fire interaction makes sense. Fire hazard is increased after hurricanes as a result of additions to dead-fuel loadings, increased production of live ground layer fuels, and decreased drying times (Gill et al., 1990; Wade et al., 1993; Myers et al., 1993). An ignition source, coupled with lack of suppression efforts or firebreaks, would have allowed intense fires to consume fuels and alter ecosystems over thousands of hectares following hurricanes. Continued frequent burning would have prevented forest regrowth or, at the very least, reduced tree density. Surviving adult longleaf pines would have provided seed for gradual increases in tree stocking. Such scenarios could readily explain the origin and maintenance of prairies and savannas, and describe a long-term dynamic process whereby vegetation patterns shifted across landscapes.

An awareness of hurricane–fire interactions in forests may be crucial for a thorough understanding of the origin and maintenance of southern presettlement forest ecosystems and their constituent communities. As scientists increasingly recognize the importance of natural catastrophic disturbance in ecosystem dynamics (Lugo et al., 1983; Boucher, 1990), and with an increasing emphasis on restoration and management of rare ecosystems, the study of hurricane–fire influences on forests has become timely.

8. Implications for restoring the longleaf pine ecosystem

The longleaf pine ecosystem, composed of diverse associated communities, once occupied as much as 37 million ha in the Atlantic and Gulf coastal plains (Frost, 1993). Open pine flatwoods, pine savannas, treeless prairies and meadows, and canebrakes were described as common and widespread during the period of European settlement of the eastern US (Bartram, 1791; Hughes, 1966; Croker, 1979; Christensen, 1988).

Human land-use in the South during the past three centuries has altered natural processes and vegetation patterns, leading to a drastic decline in longleaf pine ecosystems (Landers et al., 1995). Human-induced changes include: (1) introductions of feral swine and open-range grazing of cattle, (2) intensive naval stores production, (3) harvest of longleaf pine for forest products without regard to its regeneration, (4) fragmenting of the landscape by rights-of-ways for highways, railroads, and utilities, (5) wide-scale and persistent suppression of fire, (6) land conversions for agriculture, towns, and dwellings, and (7)

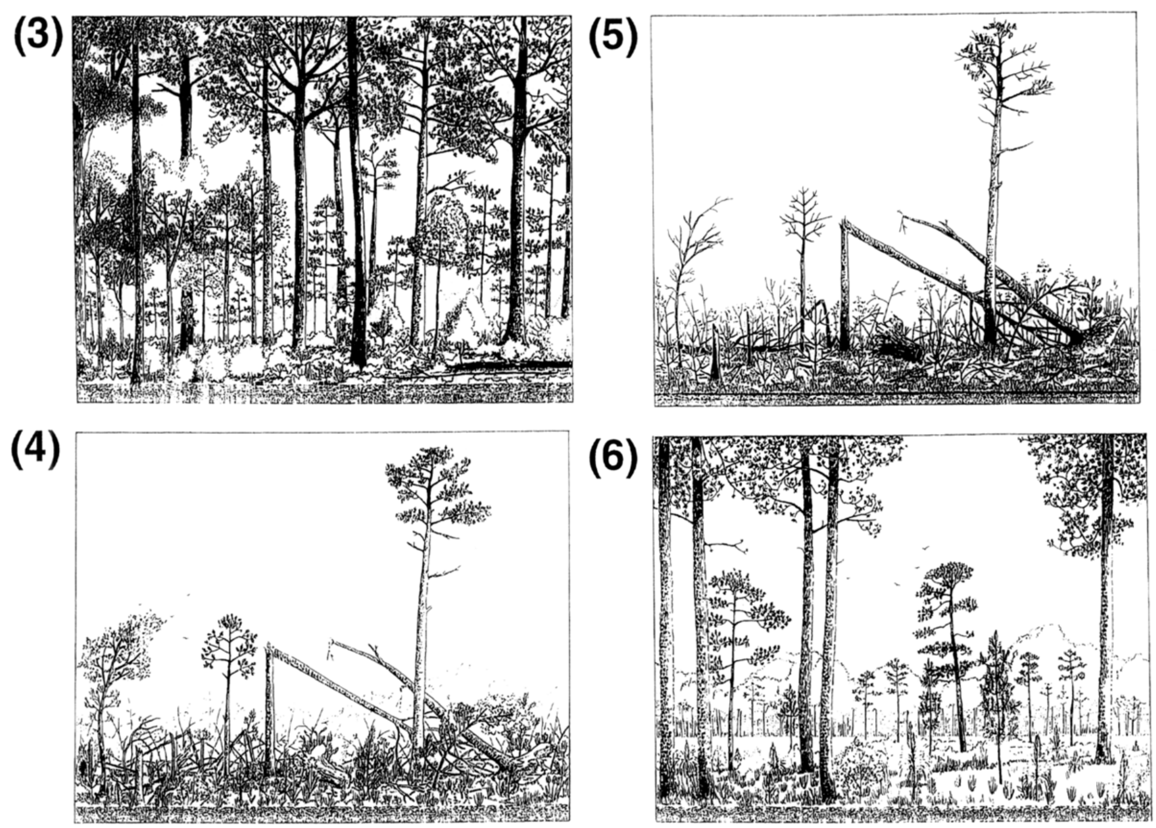

Fig. 3–6. Hypothetical transition of mature, infrequently-burned loblolly pine forest to longleaf pine savanna after a severe hurricane and several subsequent decades of frequent fire: (3) loblolly pine forest with scattered longleaf pine and prominent hardwood subcanopy; (4) 1-2 growing seasons after catastrophic hurricane impact; (5) 1-2 weeks after initial posthurricane fire; (6) development of open-structure longleaf pine forest/savanna, 75-80 years following hurricane and initiation of frequent fire regime. In the absence of an adequate longleaf pine seed source, longleaf seedlings (and other key species) could be planted as part of the restoration process.

widespread artificial and natural proliferation of loblolly (*P. taeda*) and slash (*P. elliottii*) pines for forest management purposes (Croker, 1979; Christensen, 1988; Frost, 1993).

These changes have impeded or halted natural processes, particularly fire, from producing ecosystems similar to those of the presettlement period. As a result, the area of functional and self-perpetuating longleaf pine communities has dwindled to less than 2 million ha (Noss, 1989; Frost, 1993; Landers et al., 1995), and relatively little of this remnant retains the structure and integrity of natural, fire-maintained longleaf forests. Many species associated with longleaf pine have become increasingly scarce (Roberts and Oosting, 1958; Hardin and White, 1989). As Walker (1993) observed, an effective method for conserving this array of rare species will necessarily involve preserving or restoring the structure and functions of longleaf pine communities rangewide.

While there is increased interest in the restoration of longleaf pine ecosystems, questions are being raised about methods for management and expectations for results (Landers et al., 1995). We believe that opportunistic land managers can facilitate the long-term process of restoring diverse, fire-maintained coastal plain ecosystems by implementing or continuing a regime of frequent prescribed fires, without interruption, in forested areas impacted by strong hurricanes.

Early results from a new long-term study (Myers, 1996) indicate that conversion of a closed, second-growth loblolly pine-hardwood forest to an open-structured longleaf pine forest or savanna might proceed as follows. After extreme hurricane winds have eliminated much of the existing overstory canopy of mature stands, subsequent fires provide the means for controlling understory hardwoods and reducing woody plants that flourish in the period immediately following canopy removal. The initial fire after a hurricane has potential to be of high intensity (Myers, 1996). While of utility for killing larger established hardwoods and other fast-growing woody plants, such fires present containment and smoke-management problems. Where fine fuel loads are high because of wind effects and/or past fire exclusion, it is advised that, for the first burn, dormant-season backfires be used for safe fuel reduction. As soon as it becomes practicable, however, some burns should be applied during the early growing season (May–June), corresponding with the beginning of the lightning season in the South. Such a regime of frequent fire, carried out over an extended period and augmented as necessary with planting of key species such as longleaf pine that lack adequate natural seed sources, could result in the restoration of fire-maintained plant communities with composition, diversity, and structure similar to those of the presettlement period (Figs. 3–6). The FMNF in South Carolina is currently evaluating early responses to this approach in the period since Hurricane Hugo in 1989.

9. Conclusions

A wide range of effects may occur in forests as a result of disturbance by hurricanes. Few studies have clearly linked observed forest vegetation responses with hurricane magnitude. Impacts in forests are directly linked to hurricane strength (i.e., wind velocity), with severe hurricanes resulting in greatly differing effects than minimal storms. More objective and comparable descriptions of hurricane effects result when researchers report wind speeds and Saffir/Simpson storm category measured or estimated at the study site. Meaningful statements about hurricane effects on forests must necessarily be framed in reference to the specific conditions prevailing during the causal event. Failure to clearly describe storm strength leads to confusing generalizations and, in part, accounts for the general lack of scientific appreciation of the ecological role of hurricanes.

The biota that inhabit hurricane-prone regions have developed strategies for resilience that allow their perpetuation under a regime of recurring, though occasional, disturbance from hurricanes of various magnitudes. It is plausible and probable that prior to the colonial period, fire was a consequent disturbance following severe hurricanes. We hypothesize that many species and ecosystems of the southern US coastal plains have evolved with periodic catastrophic disturbance by hurricane and fire, and that this interaction has affected the pattern of ecosystems across the landscape. The perpetuation of some organisms and communities has almost certainly been altered, jeopardized, or prevented by the historically-recent, human-induced interruption of widespread and variable fire-regimes occasionally punctuated by hurricanes.

Managers of forests affected by severe hurricanes in the South can begin large-scale fire-adapted ecosystem restoration by introducing (or continuing) carefully planned and executed short-return interval fires in combination with natural or artificial regeneration of longleaf pine. Then, over the long-term and perhaps combined with introductions of other key rare or extirpated species, composition and vegetative structure of portions of the Atlantic and Gulf coastal plains could return to conditions similar to those of the presettlement period when the hurricane–fire interaction prevailed as a landscape-shaping process. While the efficacy of this suggested restoration mechanism has yet to be assessed, the chance for positive results is already apparent in some locations. A new long-term study on the Hurricane Hugo-affected Francis Marion National Forest in South Carolina is currently underway to evaluate the effects of post-hurricane fire as a tool for restoring fire-adapted plant communities.

Acknowledgements

We thank the USDA Forest Service Southern Research Station and Center for Forested Wetlands Research in Charleston, SC for providing the funding and research sites to begin the study of hurricane–fire interactions following Hurricane Hugo. We also acknowledge the fire management personnel on the Francis Marion National Forest and the staff at the Santee Experimental Forest for their assistance in implementing burning treatments and field work. Special thanks are due Dr. William R. Harms for his enthusiastic support of this study.

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