

A Review of Spatial Aspects of Forest Damage and Recovery on the South Carolina Coast Following Hurricane Hugo

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Abstract

Southern US coastal forests are subject to damage by major Atlantic Hurricanes at a frequency that influences forest succession. Forest species may be: a) resistant: unchanged in mortality and growth; b) susceptible: increase in mortality and decrease in growth, and c) resilient: increase in mortality but increase in abundance and growth, or d) usurper: absent prior to disturbance and increase abundance and growth afterwards. Although there is a wide literature on resistance of temperate species found in the southern US to hurricane wind and salt damage, long-term ecological implications are poorly understood outside of the tropics. Hurricane Hugo struck the South Carolina Coast with an estimated wind speed of 60 m/s. Due to the relatively fast forward movement of the storm, high wind speed and severe forest damage extended nearly 100 km inland from the coast. In depth studies of immediate damage were reported for four sites and seven forest types. Species resistance to hurricane damage was found to be similar to that reported after other major hurricanes (Camille, Katrina, and Rita) although mortality percentages were influenced by position in the wind field. Susceptible species were highly dependent on position (wind speed) and proximity to the ocean (salt water in storm surge). Loblolly pine (*Pinus taeda*) and sweetgum (*Liquidambar styraciflua*) varied between resilient and usurper roles in response to mortality percentage of susceptible species.

Keywords: Hurricane; Cape Verde Islands; Mortality

Introduction

Forests of the southeastern US are frequently struck by Atlantic hurricanes [1]. Hurricanes impact forests primarily by the effects of wind, although salt spray and tidal surge can affect trees close to the coast. Trees can be defoliated, lose branches, be broken in the main bole, either above or below the first branch, or be completely uprooted. The immediate effects of wind and salt of recent southeastern US hurricanes have been summarized [1-4]. The relative resistance of tree species to wind and salt have been determined from the results of studies following hurricanes that struck large forested sections of the southeastern US (e.g., Camille [5], Hugo [6] and Katrina [3]).

The long-term ecosystem impacts of hurricanes are much less well understood. Lugo [7] calls ecosystem impacts of hurricanes “visible” and “invisible”. Visible are the immediate impact of wind and water while invisible are the long term shifts in species distributions brought about by hurricane damage and subsequent recovery. Outside of the tropics the most complete understanding of these invisible effects has been developed from studies in New England [8-10]. As indicated above the direct effects of hurricanes on southeastern forests are quite well understood. The longer term or invisible effects are less well understood for this region.

The roles of individual species in ecosystem recovery can be viewed as one of four pathways [11,12]. 1. A species can be resistant to damage with equal numbers and growth rate before and after the disturbance. 2. A species can be resilient with numbers being reduced by the disturbance but an increase in growth and number after the disturbance. 3. A species can become a usurper being absent before the disturbance and increasing in numbers and growth afterwards. 4. A species can be susceptible with numbers being reduced by the disturbance and numbers and growth declining after the disturbance. In this paper we will examine damage and recovery of southeastern US forest species following Hurricane Hugo in South Carolina. We will examine how several important spatial determinants of damage by the

storm have influenced the roles of key species during the first 15 years of recovery.

Factors Important to the Extent of Original Damage

Wind

Hurricane Hugo originated near the Cape Verde Islands on September 10, 1989 and struck St. Croix at midnight September 17-18th with sustained winds measured at 62 m/s [140 mph] [13]. It continued to Puerto Rico on the 18th with measured winds between 41-59 m/s [98-132 mph]. The storm declined in intensity after crossing Puerto Rico but regained strength over the Atlantic between the 18th and 21st. It struck north of Charleston SC near midnight September 21-22 with winds near 60 m/s [135 mph] and a forward speed of 48 k/h [30 mph] passing through the state by morning of September 22nd. The rapid forward progress resulted in high wind across all of northeastern South Carolina [13,14] (Figure 1).

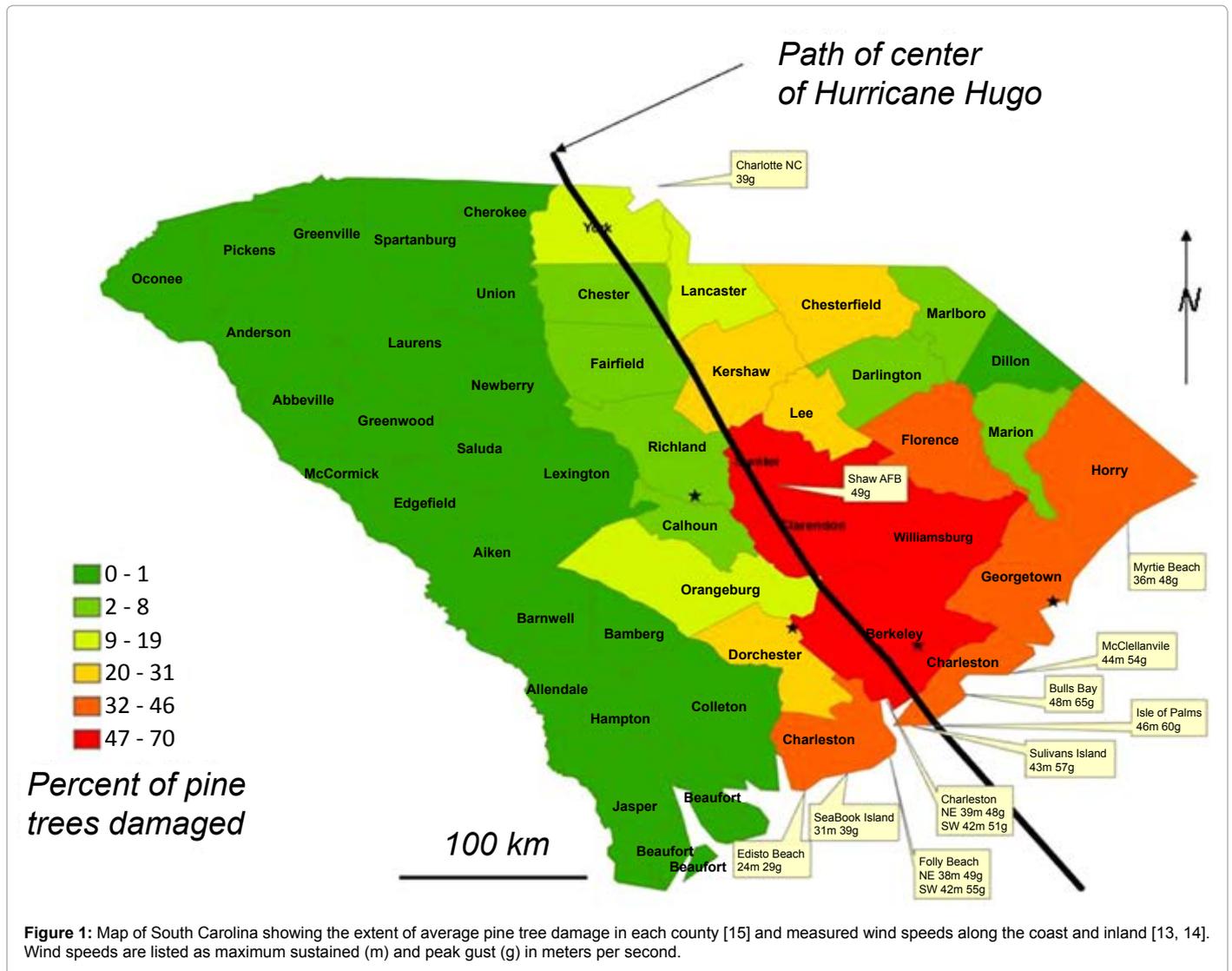
The most extensive survey of hurricane damage came from examination of the Forest Inventory and Analysis (FIA) plots [15]. Figures 1 and 2 display data on percent damage in the FIA plots averaged by county. The FIA plot data were also used by Pittman et al. [16] to estimate inland wind speeds using the Fugita method (Figure 3). These figures display the most important spatial factor, the relation of a forest stand to the general wind pattern of the hurricane. As found

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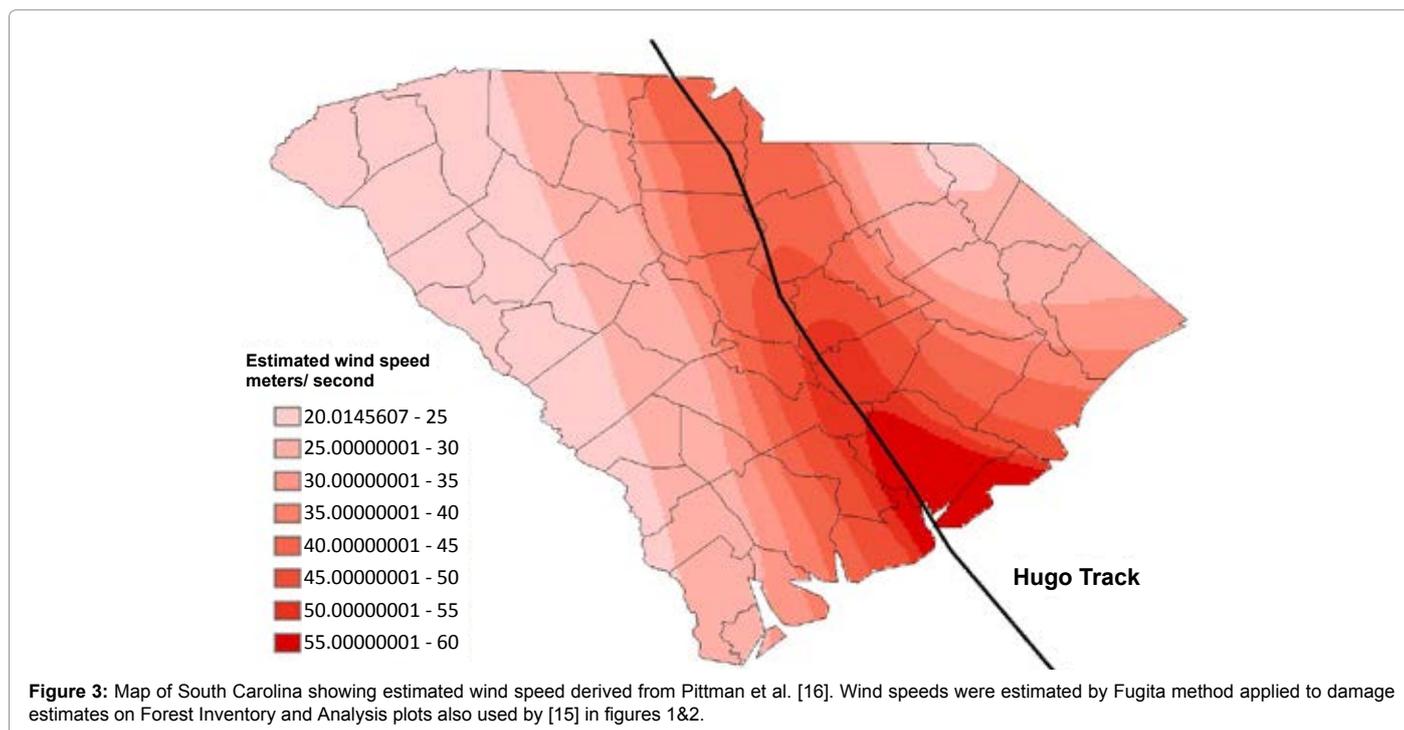
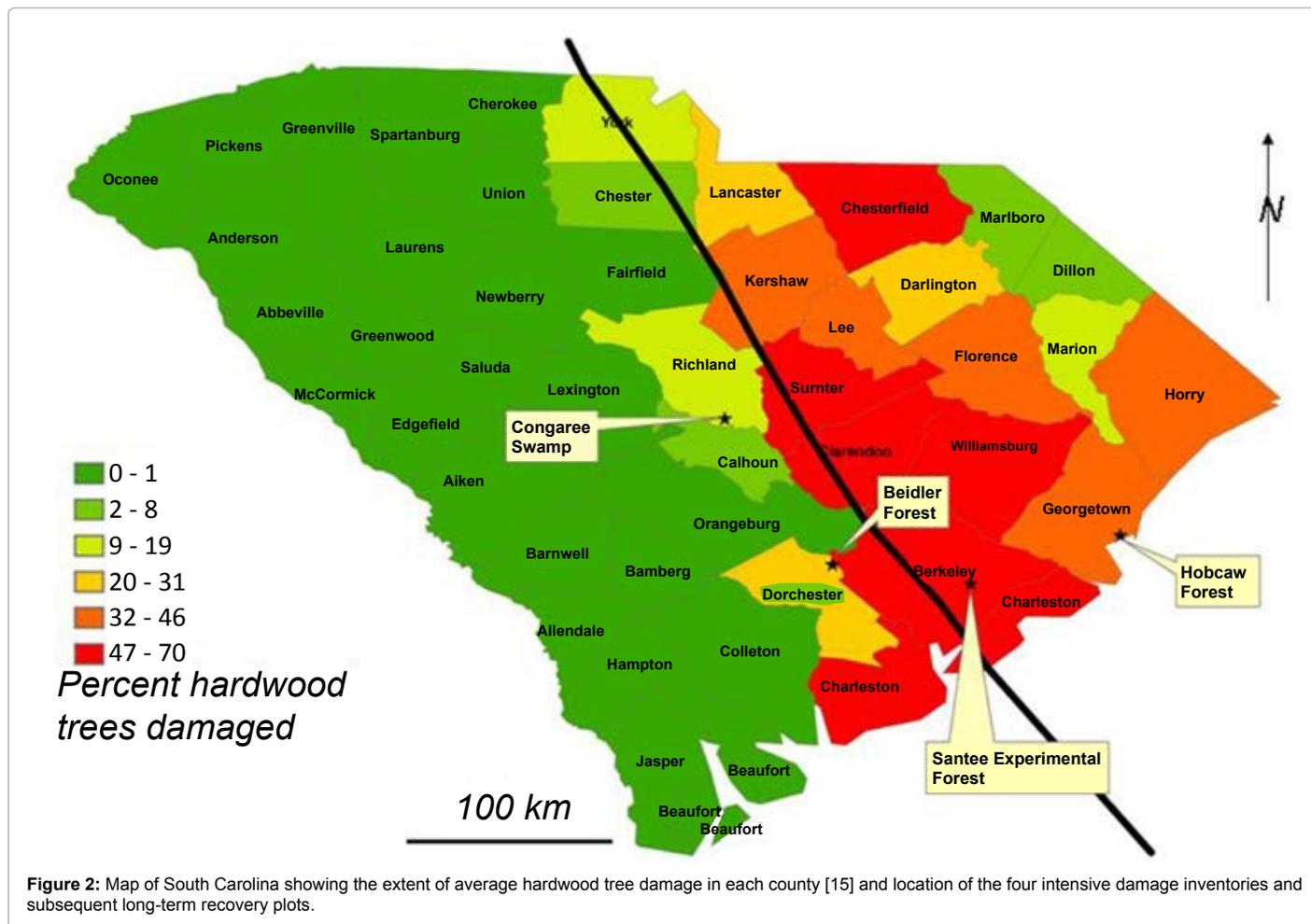
by Busby [17] wind speeds in the north and east of the storm track are generally higher. Only very near the coast and very near the eye wall are equally strong SW winds likely. In South Carolina, severe damage was spread nearly 100 km inland north and east of the storm track. Figure 2 reveals that there is also an interaction of wind speed and tree species. In Charleston, Chesterfield, Darlington, Kershaw, Lee, and Lancaster counties a greater proportion of hardwood species were damaged than pines.

In addition to the general assessment made across the state, four separate intensive studies of forest damage were located on Hobcaw Forest [18], Santee Experimental Forest [19], Beidler Forest [20], and Congaree National Park [(21)] (Figure 2). In general each of these authors found results consistent with estimates of relative wind susceptibility found in the rest of the southeast [3-6]. Live oak (*Quercus virginiana*), cypress (*Taxodium distichum*), swamp (*Nyssa sylvatica* var. *biflora*), and water tupelo (*Nyssa aquatica*), were usually the most resistant, while laurel (*Quercus laurifolia*), willow (*Quercus phellos*), and water (*Quercus nigra*) oaks and spruce (*Pinus glabra*) and pond (*Pinus serotina*) pines were quite susceptible.

Pines were found to vary in susceptibility at the four sites. Spruce

pines, found only at the Beidler Forest, experienced over 90% mortality [20]. Pond pine was more prevalent at Hobcaw and experienced 27% mortality in the lower speed winds there [18]. At Hobcaw, loblolly pine was more susceptible to wind than longleaf pine (*Pinus palustris*) with 10% vs. 7.3% in damage classes that were considered fatal [18]. However, at Santee both species experienced roughly equal mortality with nearly 90% mortality [19]. More loblolly pines were broken than uprooted with the opposite being true for longleaf pine [19].

For pines and oaks, damage increased as diameter increased. For example, Gresham et al.[18] found loblolly pine with light damage had an average diameter of 20 cm while heavily damaged trees had an average diameter near 40 cm. An exception to this general rule was found at the Congaree National Park site [21] where very large loblolly pines, >100 cm in DBH, showed only 29% heavy damage, compared to nearly 45% for 80-100 cm and 75% for 60-80 cm. This result may be due to a characteristic of these very large pines or a result of the reduced wind speeds at that site. Since such large trees were only present on the National Park site there is no way to resolve this question. Stand structure was also important with greater damage in stands of medium density. Damage was especially severe in recently thinned pine plantations.



All four intensively studied sites also showed a marked difference in damage by landscape position. The differences are probably much more likely due to species distribution by landscape position than any differences in wind speed associated with the subtle topography of the coastal plain. At all four study sites the lowest landscape positions were occupied by cypress-tupelo forest type, with bottomland hardwoods at higher elevations, and mixed pine hardwood or pines on the higher portions of the landscape sampled only by [18,19]. Wind damage to cypress-tupelo types exceeded 20% only at the Francis Marion National Forest [22] and was less than 10% at the Beidler Forest [19]. The bottomland hardwood type had over 50% damage at Santee [19], Beidler[20], and Congaree[21]. Probably the main reason for greater damage in the bottomland hardwood type was the presence of more susceptible oak and sweetgum species in this forest type. Likewise, the upland pine-hardwood stands on Hobcaw Forest and pine stands at both Hobcaw and Santee have oaks and loblolly pines that are much more susceptible than cypress or tupelo

Tidal surge

In addition to wind, forests were also influenced by salt water carried inland by the tidal surge. The distribution of measured surge

heights (Figure 4) was similar to the distribution of wind speeds with the highest surge also occurring at Bulls Bay [14]. Further north at Hobcaw Forest marsh detritus was found in the forest at elevations suggesting a tidal surge of 3-4 m [23]. Salt induced tree mortality was limited to elevations less than 3m. Initial measurements of salt concentrations in the soil and shallow groundwater found highest concentrations in the highest landscape positions under pine stands and relatively low concentrations in the lowest landscape positions under cypress-tupelo stands. Water table records from before and during the early parts of the storm suggested that soils in lower positions were saturated by rain prior to the surge [23].

Initial salt concentrations did not correspond to later tree mortality. While maximum concentrations were initially on the highest landscape positions mortality was more pronounced at lower positions (Figure 5). Relatively large rains (40-70 mm) occurred during the fall of 1989 and were thought to have diluted salt beneath the pines [23]. Eighteen months after the storm a series of multi-level piezometers and ground water samplers were installed across a ridge-swale section of the eastern forest. Pressure and concentration data showed that the rain had flushed salt deep (5m) into the water table aquifer beneath the pine stands along the ridges [24]. During the 18 months this

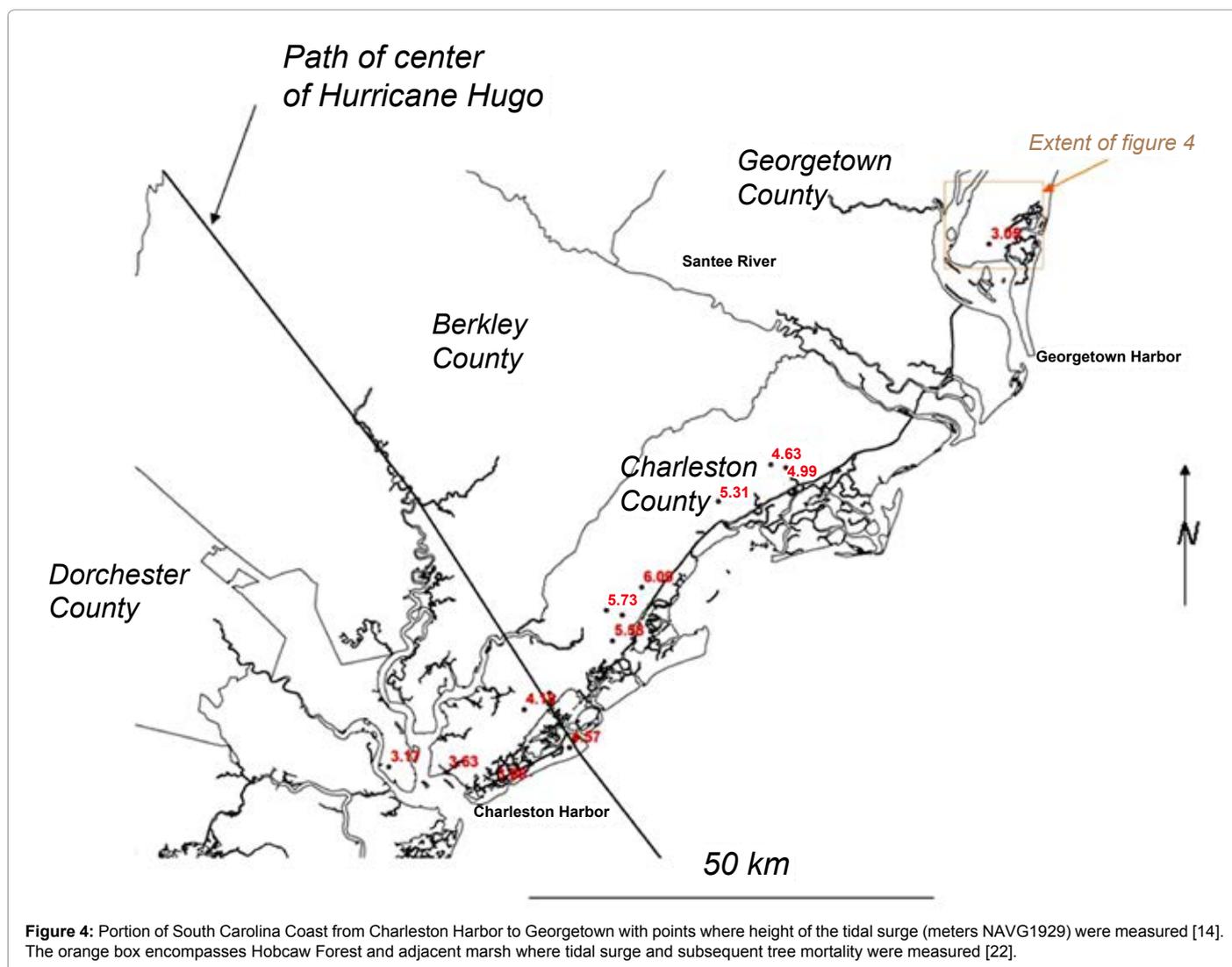


Figure 4: Portion of South Carolina Coast from Charleston Harbor to Georgetown with points where height of the tidal surge (meters NAVG1929) were measured [14]. The orange box encompasses Hobcaw Forest and adjacent marsh where tidal surge and subsequent tree mortality were measured [22].

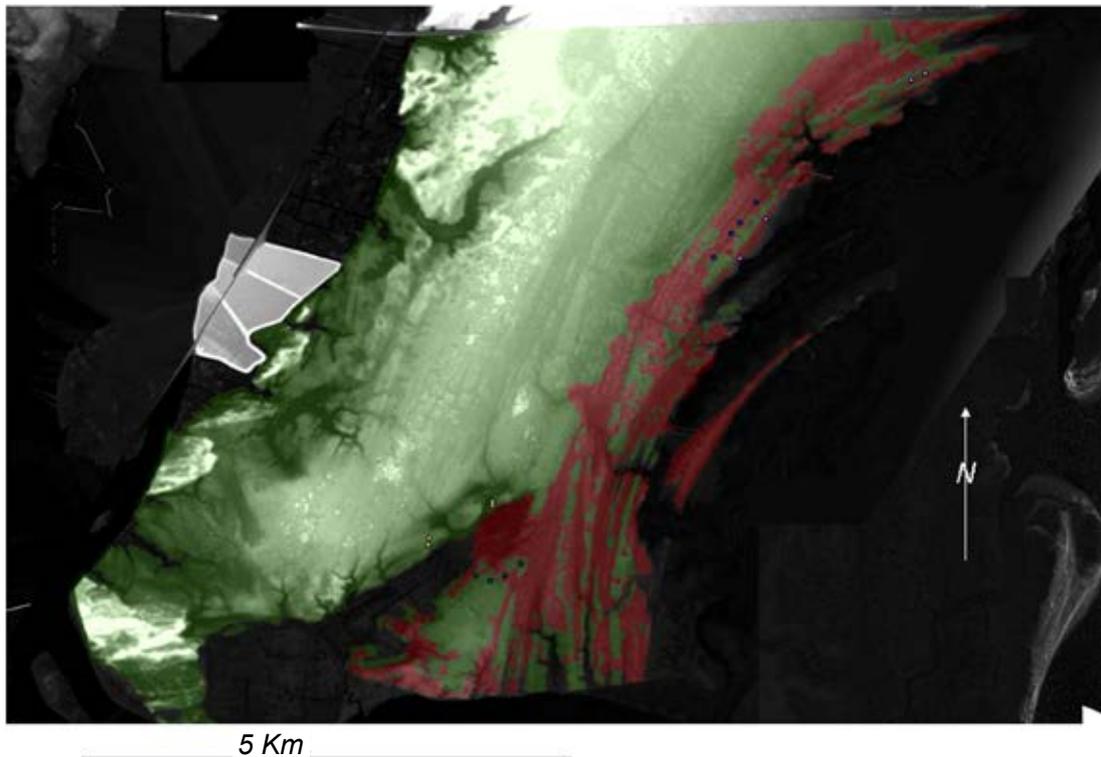


Figure 5: Shaded relief map of Hobcaw forest from LIDAR digital elevation model with portions of the forest that were alive (green) and killed by salt (red). Small dots are locations of Hobcaw Forest recovery plot centers. Blue – cypress tupelo; Pink –pine-hardwood; Green – longleaf pine; Yellow – upland hardwood.

deeper groundwater with entrained salt moved laterally to the adjacent cypress-tupelo stand in the swale. There it emerged as upward flow resulting in mortality in the cypress-tupelo stand [24]. By 1994, all of the tupelo trees had died and only a few *cypress* were left in the stand, consistent with the higher salt resistance of cypress [5,6].

Factors Influencing Stand Recovery

Despite the large number of studies of initial damage caused by Hurricane Hugo [3], there have been few publications outlining forest recovery after the storm. Cosentino[25] examined revegetation of the Santee Experimental Forest using Normalized Difference Vegetation Index (NDVI) with LANDSAT data. He found that a canopy with the same NDVI index as the pre-hurricane forest was present after ten years of recovery. This suggests that photosynthesis may have returned to pre-hurricane levels in this period.

After 12 years the original bottomland hardwood plots were re-measured to examine recovery of bottomland hardwoods at the Congaree National Park [21,26]. On these six plots they found species recruitment and ecological role of species depended on the original damage (21.2-67.9% of trees damaged). For example, red maple (*Acer rubrum*) was a usurper only on heavily damaged sites and loblolly pine was a susceptible species on plots where damage was high. Sweetgum was resilient on lower damage plots and usurper on highly damaged plots. They also found contradictory small increase in diversity of species in individual plots but an increase in homogeneity among the six plots.

In 1994 Gresham installed a study that included subsets of plots installed by [20] on the Beidler Forest and [21] at the Congaree National Forest. He then used a sampling protocol similar to those authors and

added plots on Hobcaw Forest and at the Santee Experimental Forest [27] (Figure 2). Despite efforts to replicate stand types across the study only cypress-tupelo types were present in all four sites, with bottomland hardwoods present at three, upland pine stands were only located at Hobcaw Forest and pine-hardwood types at Hobcaw and Santee.

The major findings of [27] are summarized in Table 1. Each forest type is represented for those locations where it was sampled. These results would suggest that the ecological role of a species in recovery is highly dependent on the severity of damage sustained by the stand during the storm. Cypress and tupelo are very resistant, unless there is very severe damage by wind or salt intrusion they will dominate the recovering stand. While loblolly pine is usually resilient it can become susceptible in conditions where other factors limit regeneration [21]. On Hobcaw, with salt-water surge and a plentiful seed supply loblolly pine became a usurper in longleaf and cypress-tupelo types. Similarly, longleaf pine is usually considered resistant to lower winds [5,18] but it became susceptible when salt surge was added to wind and plentiful loblolly seed sources were available.

It is obvious that establishing a long-term recovery study that strives to encompass the variety of forest types damaged by a large hurricane is fraught with limitations. Recovery research is first restrained by locations of well inventoried plots of pre-disturbance and original damage conditions. It is also limited to locations where tree recovery will not be influenced by later activities. In South Carolina that has resulted in information from four sites, only good fortune resulted in sites with differing exposures to wind and salt water allowing some information to be developed for each type of damage. Several species showed consistent responses such as resistance for bald cypress and swamp tupelo and resilience for loblolly pine, sweetgum, and laurel

Forest Type	Location	1994 Basal Area	1994 Dominant species	Dominant Recovery Species	Response Type[11]
Cypress-Tupelo	Beidler	109.2	Bald Cypress Swamp Tupelo	Bald Cypress Swamp Tupelo	Resistant Resistant
Cypress-Tupelo	Congaree	69.7	Bald Cypress Swamp Tupelo	Bald Cypress Swamp Tupelo	Resistant Resistant
Cypress-Tupelo	Hobcaw	11.8	Swamp Tupelo Bald Cypress	Loblolly Pine Bald Cypress	Usurper Resistant
Cypress-Tupelo	Santee	23.4	Bald Cypress Sweetgum	Bald Cypress Laurel Oak	Resistant Usurper
Bottomland Hardwood	Beidler	42.8	Sweetgum Laurel Oak	Sweetgum Green Ash	Resilient Resilient
Bottomland Hardwood	Congaree	58.4	Sweetgum Green Ash	Sweetgum Amer. Holly	Resilient Resilient
Bottomland Hardwood	Santee	13.1	Red Maple Sweetgum	Red Maple Laurel Oak	Resilient Resilient
Pine-hardwood	Congaree	32.4	Loblolly Pine Sweetgum	Loblolly Pine Sweetgum	Susceptible Resilient
Pine-hardwood	Hobcaw	23.6	Loblolly Pine Pond Pine	Loblolly Pine Live Oak	Resilient Resistant
Upland pine hardwood	Santee	9.2	Loblolly pine Blackgum	Loblolly Pine Water Oak	Resilient Resilient
Upland hardwood	Hobcaw	22.1	Loblolly Pine Sweetgum	Loblolly Pine Sweetgum	Resilient Resilient
Longleaf Pine	Hobcaw	7.3	Longleaf Pine Loblolly Pine	Longleaf Pine Loblolly Pine	Susceptible Usurper

Table 1: Summary of plot information for various forest types damaged by Hurricane Hugo. Basal area is the average tree basal areas for all plots in the type at that location in m²/ha. Dominant species are based on tree basal area in all plots of that type at that location. Dominant recovery species are species that are expected to be important in the new stand based on either tree basal area or number of saplings.

oak. However, severity of damage resulted in differing response types for the same species; loblolly pine as susceptible at Congaree – pine hardwoods, resilient at most other sites, and a usurper at the Hobcaw-cypress-tupelo site.

Variability in both the degree of damage and the role of individual species in recovery has not been conducive to developing broader ecological principles of hurricane impacts. Results at Congaree were examined to test hypotheses that diversity imparted resilience, hurricane disturbance restructures species composition and enhances diversity, and hurricane disturbance accelerates succession [26]. None of these hypotheses were found to have been supported. The difference between the recovery rates of upland and lowland ecosystems was thought to be significant during initiation of studies by [27]. However, the results show that species differences and extent of damage are more important to both recovery rate and recovery species compositions than any topographic gradients in the sites.

Conclusions

The spatial pattern of hurricane damage and recovery has proven to be exceedingly complex. Although we understand the relative resistance of most southern species to wind, we cannot translate those ratings to estimates of potential damage due to our general lack of precise wind speeds associated with levels of damage for a single species. Storm size, intensity, and forward speed combine to create a unique distribution of wind speed after the storm comes ashore. Damage severity decreases with distance from the coast and distance from the center of the storm. Damage is also asymmetrical with more damage to the north and east of the center. Species differences can be seen at the general statewide scale but plot studies show a variety of damage at even a single location. Outside of relative small zones of high mortality, damage becomes a complex mosaic based on species composition, age, and density overlain by complex distribution of wind velocities as the hurricane interacts with land. On the immediate

coast wind disturbance is complemented by the movements of salt in the tidal surge and subsequent drainage across the landscape. Finally, individual species recovery and interactions are highly influenced by the degree of initial damage.

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