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Hurricane impacts on US forest carbon sequestration

Steven G. McNulty*

USDA Forest Service, 920 Main Campus Drive, Venture Center II, Suite 300, Raleigh, NC 27606 USA

"Capsule": *A single hurricane can convert 10% of the total annual carbon storage for the US into dead and downed forest biomass.*

Abstract

Recent focus has been given to US forests as ι sink for increases in atmospheric carbon dioxide. Current estimates of US forest carbon sequestration average approximately 20 Tg (i.e. 10^{12} g) year. However, predictions of forest carbon sequestration often do not include the influence of hurricanes on forest carbon storage. Intense hurricanes occur two out of three years across the eastern US. A single storm can convert the equivalent of 10% of the total annual carbon sequestrated by US forests into dead and downed biomass. Given that forests require at least 15 years to recover from a severe storm, a large amount of forest carbon is lost either directly (through biomass destruction) or indirectly (through lost carbon sequestration capacity) due to hurricanes. Only 15% of the total carbon in destroyed timber is salvaged following a major hurricane. The remainder of the carbon is left to decompose and eventually return to the atmosphere. Short-term increases in forest productivity due to increased nutrient inputs from detritus arc not fully compensated by reduced stem stocking, and the recovery time needed to recover leaf area. Therefore, hurricanes are a significant factor in reducing short-term carbon storage in US forests. © 2001 Published by Elsevier Scicncc Ltd. All rights reserved.

Keywords: Hurricane; Carbon sequestration; Forest; Detritus

1. Introduction

On average, a major hurricane (Saffir Simpson scale 3 5) makes landfall along the eastern US coastline 2 out of 3 years (Smith, 1999). In addition to the extensive economic damage caused by hurricane impacts with sustained winds greater than 178 km h^{-1} (Saffir–Simpson scale 3 or greater), hurricanes are also a major disturbance factor in forest ecosystems. Of the 64 major hurricanes making landfall between 1900 and 1996, 60 hurricanes came on shore along the southern US coast (NOAA. 1997), which is over 55% forested (USDA Forest Service, 1988). Hurricanes can destroy wildlife habitat (Davis et al., 1996), orchards (Crane et al., 1994), increase insect infestations (Yates and Miller, 1996), and increase tire risk (Wade et al., 1992), but the most apparent forest impact of a hurricane is on timber damage (Gresham et al., 199 1; Merrens and Peart, 1992; Haight et al., 1995). which can exceed $1 billion (Miranda, 1996). In addition to the economic value of wood. US forests arc also a sink for some of the increasing atmospheric carbon dioxide, associated with global warming. Hurricanes may negatively impact the ability of US forests to sequester atmospheric carbon.

Current global circulation models predict that average annual global surface air temperatures may increase by approximately 2.5°C by the end of this century (NAST, 2000). **Much** of the increase in air temperate has been attributed to the increase in atmospheric carbon dioxide (CO_2) over the past 100 years (NAST, 2000). Although estimates of the amount of carbon that is (and could be) absorbed by forests vary (Aber et al., 2001), major forest disturbances such as hurricanes may significantly alter total forest carbon storage capabilities. Therefore, this paper examines the impact of historic hurricanes on immediate and long-term forest carbon sequestration.

Three questions must be addressed to determine if hurricane impacts arc positive or negative forces on US forest carbon sequestration. First, how much carbon is transferred from living to dead carbon as a direct (i.e. stem breakage and uprooting) and indirect (e.g. increased fire and insect damage) affect of hurricanes. Second, the fate of the downed biomass should be determined. If the biomass is salvaged, then the potential exists that the biomass could be put into long-term sequestration pools (e.g., lumber). However, if the biomass is burned, consumed by insects. or decomposes,

* Tel.: + 1-919-515-9489; fax: + 1-919-513-2978.
E-mail address: steve_mcnulty@ncsu.edu (S.G. McNulty).

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the forest has less long-term carbon sequestration potential. Third, what are the impacts of hurricanes on long-term soil productivity and forest stocking? If short-term losses in forest carbon stocks and productivity are offset by long-term increases in forest productivity due to increased storm induced nutrient inputs, then hurricanes may have a positive impact on forest carbon sequestration. Depending on the answers to these questions, hurricanes could either increase or decrease carbon sequestration in eastern US forests. The paper will also, discuss how forest management can be used to minimize negative hurricane impacts on forest carbon sequestration.

2. Materials and methods

2.1. Recorded hurricane landfalls

Hurricanes have always been a natural force in shaping the forest landscape of southeastern North America. The earliest recorded hurricane impact dates to 1667 Jamestown, VA, where on 27 August it was recorded that a "dreadful hurry cane," produced "such violence that it overturned many houses, burying in the ruins much goods and many people" (Anon., 1667).

Other significant documented hurricanes include the 29–31 July 1715 hurricane that destroyed a Spanish armada off the coast of Florida; the 1 October 1893 hurricane that flooded most of New Orleans, LA and killed over 1800 people; and the 8000 people killed and 20,000 left homeless following the 8 September 1900 Galveston, TX hurricane. Significant forest damage likely resulted from each of these storms. However, no quantitative forest damage was recorded because of the low value of timber relative to high loss of human life and property.

Beginning in 1900, more systematic notation of hurricane landfall has been kept. Between 1900 and 1996, 158 hurricanes have hit the US mainland, and of these 64 were considered major with a Saffir–Simpson category 3, 4 or 5. Of the 64 major hurricanes that have impacted the US mainland since 1900, 14 hurricanes occurred between 1900 and 1920, 13 hurricanes occurred between 1921 and 1940, 23 hurricanes occurred between 1941 and 1960, 10 hurricanes occurred between 1961 and 1980, and 17 hurricanes occurred between 1981 and 2000 (NOAA. 1997).

Hurricane tracking is a coordinated effort of ocean buoys, ship. aircraft and weather station monitoring. The intensity of a hurricane varies over time. However, open sea hurricane strength has little or no negative impacts on terrestrial forests carbon sequestration. Therefore. this paper will focus on hurricane strength at the point of landfall and will rely on meteorological station that record hurricane strength.

2.2. Current hurricane monitoring

Currently, the US has over 2100 metrological stations that measure wind direction, speed, and gusts. At each station, wind direction is determined by averaging the direction in 10° increments over a 2-min period in relation to true north. The wind speed is determined by averaging the speed over a 2-min period using an anemometer. The wind speed data for the most recent 10 min is examined to evaluate the occurrence of gusts. Gusts are indicated by rapid fluctuations in wind speed with a variation of 10 knots or more between peaks and lulls. The speed of a gust is the maximum instantaneous wind speed.

2.3. Historic forest damage monitoring

Prior to the creation of the USDA Forest Service in 1905, no single agency was charged with managing US natural resources at a national scale. The road network over much of the country was very poor. The problems in transportation were further complicated following a hurricane. For these reasons, there is little information on hurricane impact to forests prior to the 1920s.

2.4. Current forest damage monitoring

US forests are a mosaic of federal, state and private ownership. Approximately 180 million ha of forest are divided between by 11 million landowners. Another 105 million ha of forest are controlled by federal agencies (United Nations, 1997). Given the number and diversity of US owned forests, comprehensive estimates of forest damage are only practical for large-scale disturbances. Often these assessments of damage are conducted by FEMA, the US Department of the Interior, the USDA Forest Inventory Assessment team, or by other USDA groups using aerial surveys, and will be the source of forest hurricane damage in formation for this paper.

2.5. Estimating detritus pool increases following a hurricane

Standing and destroyed forest biomass is most commonly measured in board feet and cordage because of the associated economic value of these to measures. A board foot is an English forest products term equal to a board 12x 12x 1 in. (2.36×10^3 cm^3). A standard cord of wood has an area of $4\times4\times8$ ft (3.62 m^3), including bark and air space. Estimates of forest biomass moved from the living to the dead carbon pool using measured board footage of damaged and destroyed timber after a hurricane impact are presented in Ey. (1). and measured damaged and destroyed forest cordwood estimates are presented in Eq. (2).

Carbon biomass moved to the detritus pool from measurements of damaged and destroyed timber board footage after a hurricane impacts are presented below Eq. (1).

$$(Bdftloss) \times (Carb\ Frac) \times (Spfgrav) \times (bgfrac) \times (stmratio) \times (conv) \quad (1)$$

Carbon biomass moved to the detritus pool from measurements of damaged and destroyed cord wood after a hurricane impact are presented below [Eq. (2)].

$$(cord) \times (bdftcordconv) \times (Carb\ Frac) \times (Spfgrav) \times (bgfrac) \times (stmratio) \times (conv) \quad (2)$$

where Board feet timber loss (*Bdftloss*) was estimated as timber loss in thousands of board feet for each recorded hurricane using aerial and ground surveys of impacted areas. This analysis examined the impact of four separate hurricanes (Table 1).

Carb Frac is the carbon fraction as a total proportion of total tree biomass. The carbon fraction varies from 0.50 for northern and southern hardwoods (Birdsey, 1992; Martin et al., 1998), to 0.53 for southern pine species (Birdsey, 1992) (Table 2).

Spfgrav is equal to the specific gravity of hardwoods and softwoods, expressed as a weight per unit area. The specific gravity ranges from 0.38 for northern US softwoods (Birdsey, 1992), to 0.58 for southern hardwoods (Birdscy, 1992; Martin et al. 1998) (Table 2).

Typically, forest damage associated with hurricanes is expressed in economic terms (i.e. board feet and cords of wood). Therefore, to estimate total carbon loss (as opposed to economic loss), the leaf, root, and stem wood carbon fraction must be estimated as a proportion of timber loss. The amount of tree biomass below ground is very difficult to measure. Fine root biomass is a function of tree size, growing location, species, and time of year. However, for a wide range of species, ages and growing conditions an average below ground carbon fraction (*bgfrac*) of 0.20 was used, based on forest measurements by Birdsey (1992), Wells et al. (I 975), and Schultz (1997) (Table 2).

Growing location, tree age, time of year, and species also determine how much carbon is allocated to branch, and leaf tissue. The variation in carbon allocation is greater for softwoods than for hardwoods (Table 3). As tree size increases, the proportion of stem wood to total wood increases (Birdsey, 1992; Martin et al., 1998).

In addition to expressing economic losses in terms of board feet destroyed, timber loss is also expressed as cord wood loss. Cordwood is used as fuel and for producing paper products. Downed trees are considered as cordwood if they has insufficient size, form or value for use as timber. A standard cord of wood has an area of 4×4× 8 ft (3.62 m^3), including bark and air space. Given the average amount of air space between stacked wood, and tree bark thickness which has a much lower specific density, one cord of southern hardwood is equal to 901 Bd ft (2.12 m^3), a cord of southern softwood is equal to 884 Bd ft (2.08 m^3), one cord of northern hardwood is equal to 957 Bd ft (2.33 m^3), a cord of northern softwood is equal to 1020 Bd ft (2.40 m^3) (Forbes and Meyer, 1955; Conner, 1998). Northern forest species generally have more board feet of wood per cord because of thinner bark compared to southern US tree species.

3. Results and discussion

This section is divided into three parts that relate to the three yuestions presented in the introduction. First the paper will examine how much carbon is transferred from the living to dead carbon pools during a hurricane, and management strategies to minimize hurricane damage. Second, the fate of post-hurricane carbon pools will discuss salvage logging, fire, and insect outbreaks as mechanisms for altering the forest carbon storage. Finally, this section will discuss how hurricanes impacts long-term soil productivity and forest regeneration. Based on the relative contribution of these three factor areas, and then I will discuss whether hurricanes positively or negatively impact the carbon sink potential of US forests.

Table 1
Notable hurricanes and forest destruction estimates

Hurricane	Saffir–Simpson scale	Forest impacted (Ac)	Timber destroyed (billion bdft)	Pulp and fuel wood destroyed (millions of cords)	Increase in detritus carbon pool Tg (g 10^{12})
1938	3	NA	3.0	NA	3.8
Fran	3	8.2	8.7	15.0	20.0
Hugo	4	4.5	10.3	13.2	20.0
Camille	5	1.0	1.8	1.4	2.9

Table 2
Eastern US forest characteristics

Forest type	Specific gravity	Carbon fraction	Reference
Southern hardwood	0.58	0.50	Birdsey, (1992). Martin et al. (1998)
Southern softwood	0.51	0.53	Birdsey (1992)
Northern hardwood	0.54	0.50	Birdsey (1992)
Northern softwood	0.38	0.52	Birdsey (1992)

Table 3
Carbon allocation in hardwood and softwood forests of two six classes

Tree type/size	Foliar fraction	Branch fraction	Stem fraction	Root fraction	Reference
Hardwood/sawtimber	1	15	64	20	Birdsey (1992). Martin et al. (1998)
Hardwood/sapling	1	15	64	20	Birdsey (1992), Martin et al. (1998)
Softwood/sawtimber	5	10	65	20	Wells et al. (1975)
Softwood/sapling	30	13	37	20	Schultz (1 997)

3.1. Changes in the carbon detritus pool

During and after a hurricane, forest biomass is converted from living to dead carbon. However, unlike other natural disturbances such as wild fire, there is very little change in the state of carbon (i.e. from solid to gaseous phase). Therefore, the question of whether or not hurricanes increase or decrease carbon sequestration is dependant on the prc and post hurricane forest conditions that land managers can at least partially control. This section will examine the factors that determine hurricane damage to forests, post hurricane impacts on negative and positive forest carbon sequestration, and potential management strategies to minimize the negative carbon sequestration factors of hurricane impacts.

The most immediate impact of hurricanes of forests is a massive increase in the amount of tree biomass that is converted from living to dead wood. The total amount of detritus created from the four storms in this study ranged from a low of 2.9 Tg to a high of 20.0 Tg (i.e. Cx 10^9 kg) (Table 1). By comparison, US forests annually sequester an 80×350 Tg C year$^-$ (Schimcl et al., 2000). Estimates of carbon sequestration based on forest inventory data were 280 Tg C year^{-1} (Birdsey and Heath, 1995). Therefore, ii single hurricane can convert the equivalent of 10% of the total annual US forest carbon sequestration from living to dead wood (assuming on average value of 200 Tg of carbon is scqucstcred across all US forests). Initial conversion of forest carbon from living to dead material is only the first phase in determining if hurricanes are mechanisms for decreased forest carbon sequestration.

3.2. Fate of carbon in downed biomass

Hurricanes do not immediately change the state of carbon in downed wood. Howcvcr, shortly after the biomass has been uprooted or broken off: it begins to decompose. The fine, high nitrogen content leaves are first decomposed, followed by branch, stem and roots. It is the relative proportion of the downed salvaged wood to down non-salvaged wood that will determine how much of the post-hurricane debris is lost from the carbon sequestration pool.

3.2.1. Hurricane timber salvage

The fraction of salvaged timber varies with the total amount destroyed, the timber value and access to salvageable lumber. Following, a highly damaging storm such as Fran or Hugo, the timber market was glutted with up to 7 times the pre-hurricane average amount of salvaged timber available (Marsinko et al., 1996). Increased supply drives the price for timber down to approximate half of its pre-harvest value (Marsinko et al., 1996). if the salvaged timber is of marginal quality or difficult to remove, it is unlikely that the timber would be salvaged. For these reasons, only 13% (3.9× 106 m^3) of timber was salvaged in the months following the Hurricane Hugo (Miranda, 1996). The 13% timber salvage rate represents only stem wood. **Assuming** that stem wood only represents 64% of the total tree biomass (Table 3) carbon salvage recover following Hurricane Hugo was less than 9%. Even the 9% recovery rate was only possible through a well-coordinated post-hurricane timber salvage effort (Miranda, 1996). Therefore, the majority (> 90%) of the wood is left to decompose within the forest.

3.2.2. Increased fire risk

Given that most of the downed wood is never salvaged, the debris and litter becomes fuel for wild fires during the following years. For example, following Hurricane Hugo, forest debris was 1 .5 3 m deep in many areas (Miranda, 1996). In addition to the original damage caused by the hurricane, wildfires fueled by post hurricane slash posed a real threat to surviving vegetation.

To reduce fire risk following Hurricane Hugo, an intensive combination of public awareness against burning, and the creation of 6 m wide firebreaks were implemented during the first year after the hurricane. In the following 5 years, several forest management practices were used to reduce the accumulated fuel loads. Despite these efforts, the 1991–1992 fire season was the worst in 6 years with over 2600 fires and 8500 ha burned in the Hurricane Hugo impacted area (Miranda, 1996). Therefore, a short-term increase in the volitization of dead and living biomass is likely following a hurricane impact.

3.2.3. Increased insect and disease risk to carbon storage in living trees

Following a hurricane, photosynthetic capacity can be reduced by 50% which could lead to a reduced in oleoresin flow (in pines), and increased susceptibility to insect attack (Fredericksen et al., 1995). Hurricane Hugo damaged 23% of the conifer species and 30% of the deciduous species in the affected area (Sheffield and Thompson, 1996). This represents almost 3 times the amount of initial carbon converted from living to dead wood. Despite the possibility of increased insect attack on damaged living trees, no increases in insect infestation were recorded following hurricane impacts (Bess, 1944; Wilkinson et al., 197X; Frcdericksen et al., 1995; Yates and Miller, 1996).

3.3. Changes in long-term forest dynamics

Hurricanes can reduce the current amount of live standing carbon through tree up-rooting and stem breakage. However, mature forests grow more slowly than younger stands and have lower rates of net primary productivity (NPP). Hurricanes preferentially remove the most mature vegetation, and thus allow the potentially more productive forest understory to replace the overstory. The nutrients from leaf tissue, and increased surface soil aeration from uprooted trees could incrcasc overall soil productivity. The relative contribution of regeneration and changes in the soil nutrient pool will factor into whether or not hurricanes increase or decrease forest carbon storage. Each factor will be examined separately.

3.3.1. Changes in post-hurricane forest regeneration

The presence of a seed bank and pre-hurricane seedling development can be critical in determining how rapidly (and with which species) forest regeneration occurs following a hurricane (Turner et al., 1997). Shade intolerant species especially need a seed hank to colonize gap openings following a hurricane before resprouting of the residual canopy can occur (Tanner et al.. 199 1). Promotion of more productive, longer-lived forest species can be achieved by using a combination of cutting or herbiciding undesirable species and through species planting (Steele et al., 1992).

Generally, forests rapidly fill in gaps following a hurricane (Spurr, 1956; Brokaw et al., 1991). However, Men-ens and Pearl (1992) reported that plots established in Hubbard Brook following the 1938 hurricane had not reached stocking densities equal to not impacted areas after 49 years.

3.3.2. Changes in post-hurricane productivity

Defoliation of forests due to hurricane impacts can greatly influence nitrogen and other nutrient inputs to the forest. For example, Hurricane Hugo created 20 Tg of carbon (i.e. 40 Tg biomass) (Table 1), approximately half of which was deciduous and half which was coniferous. Given that 1% of the deciduous mass was foliage and 5% of the coniferous mass was foliage, then 2.4 Tg of foliage was removed from living trees and redeposited on the forest floor. If the average nitrogen concentration of conifer leaves was 1% and deciduous leaves was 2%, and then at least 3.6×10^5 tons of nitrogen was returned to the Hurricane Hugo impacted soil. This averages out to about 80 kg N ha-' returned to the forest floor across the entire 4.5 million ha of impacted land. This is approximately the same amount of N that is returned to the soil each autumn during leaf fall (Waring and Schlesinger, 19X5). In addition to nitrogen rich litter, nitrogen poor root, stem and branch tissue was also redeposited, so the CN ratio of the input material is high. As with logging operations, the greatest initial increased is soil nutrient availability will be due to increased soil warming due to increase direct solar warming, and through reductions in biological plant nitrogen demand.

Sanford et al. (1991) used the forest process model Century to predict the impact of repeated hurricane activity on Caribbean forest soil nitrogen status and forest productivity. They concluded that soil nitrogen concentration and long-term forest productivity would incrcasc. However, the results of their model have not been validated.

In South Carolina, an extensive study was conducted to assess the short and long term impacts of Hurricane Hugo on forest productivity. Following the hurricane impact in 19X9, the timber and growing stock in the area was heavily damaged (Table 1). Conifer and hardwood stands will not regain pre-hurricane productivity levels until 2003 and 2008, respectively (Conner, 199X). These values represent a 14 and 19 year recovery period following a major hurricane, These estimates of future forest productivity are based on historic recovery times but do not reflect potential increases in soil fertility.

3.4. Forest susceptibility to hurricane damage

Following the 1938 New England Hurricane, Brom-Icy (1939) cited six primary factors influencing tree susceptibility to hurricane destruction. These factors included; extreme wind speed; soil conditions; tree age; prior forest management; prior forest health; and tree species. Each of the predisposing factors will bc discussed and management options will be examined.

3.4.1. *Extreme wind speed*

This study found no extensive evidence for forest damage associated with hurricanes below 3 (17X km h^{-1}) on the Sappir-Sampson scale. However, there does not appear to be any relationship between wind speed and forest damage above sustained wind speeds of 17X kmh^{-1} ($\geqslant 3$ on the Sappir-Simpson Scale). In Puerto Rico, Francis and Gillespie (1993) recorded some branch breakage and uprooting at wind speed of 60 km h^{-1}, and the damage increased with wind speeds up to 130 km h^{-1}, above which level they found no additional correlation between wind speed and forest damage. Wind speed cannot bc controlled, so there are no management strategies for controlling forest damage due to this hurricane factor.

3.4.2. *Soil conditions*

Soil type, and long and short-term climate influence soil conditions. Bromley (1939) noted that trees growing on soil with restrictive rooting zones due to a hard clay layer were more susceptible to uprooting. A broad network of shallow surface roots have less ability to anchor a tree, compared to a tree that is better able to penetrate the soil with a deeper root structure. Long-term precipitation patterns also influence root structure. Rooting depth is inversely related to long-term soil moisture. Intense short-term precipitation saturates soil horizons, and reduces root-anchoring capacities of trees (Bromley, 1939). Soil saturation may be especially important in creating uprooting in shallow rooted trees, and in Sappir--Simpson scale class 3 hurricanes such as the 193X New England Hurricane (Foster, 1988). As with wind speed there are no available management options that would improve the soil conditions that reduce the possibility of tree uprooting.

3.4.3. *Tree age*

Tree age is a surrogate for tree size. As the amount of stem wood, branch area and leaf area increase and the amount of surf&e area impacted by wind also increases. For this reason. large (i.e., old) trees are more susceptible to uprooting compared to smaller (i.e., younger) trees (King, 1986; Foster and Boose. 1992; Shartiz et al., 1993).

Petty and Swain (19X5) found that maximum wind drag occurred when crown mass equaled approximately 10% of total surface mass, which occurs in mature forest trees. The greater the wind drag the greater the potential for stem breakage below the crown.

Almost 20% of the southern US is forested in intensively managed pine plantations (Joyce et al., 2001). The rest of the southern forest is in naturally occurring deciduous, coniferous and mixed forest stands with lower economic value. In both natural and plantation forests, forest harvest is often oriented toward maximizing economic returns. As trees mature, increasingly more economic capital is tied up in the growing stock. Aside from catastrophic loss from fire, hurricane or insect outbreak, the dollar value associated with standing timber could be reinvested if the forest was harvested. Land managers could reduce rotation age to reduce forest susceptibility to uprooting and stem breakage due to hurricane impacts (Haight et al., 1995). The need to consider hurricane impact on forest economics and carbon sequestration may become even more important during the 21st century if hurricane intensity or frequency increases.

3.4.4. *Tree species*

Several species-specific factors influence a trees susceptibility to uprooting or stem breakage including, rooting system, and allometry. Deep, well or tap rooted tree species are able withstand uprooting better than shallow, poorly or diffusely rooted species (Bromley, 1939). Tree allometry is important in determining the proportional allocation of carbon between stabilizing root system and the wind absorbed by aboveground tree components. Tree species vary in the proportion of carbon allocated to stem, branch and leaf tissues. In addition to carbon allocation, little stem taper and a closed crown shape increase tree potential for uprooting (Anon., 1973). Tree species with a greater proportion of total carbon biomass above ground and in leaf tissue are more susceptible to uprooting (King, 19X6). The two ends of the species susceptibility to hurricane damage are loblolly pine (*Pinus taeda*) and Baldcypress (*Taxodium distichum*). Mature pines have closed, compact crown far from the ground, on stems with little taper. The pines often grow on sandy soils with poorly anchored root systems. Old growth baldcypress have a highly tapered trunk, is extremely well rooted, and has an open canopy. When both these southern Florida forest types were exposed to Hurricane Andrew in 1992, the pines experienced 25–40% damage while the bald cypress was less than 10% (Davis et al., 1996).

Even within pine species, there is a range of hurricane susceptibility to hurricane damage. Two hundred years ago, longleaf pine (*Pinus palustris*) dominated the southern US pine forests, but through selection and planting decisions, longleaf pine has been reduced to only small fraction of its original area (Collingwood and Brush, 197X). The longleaf pine stands have been has been replaced by loblolly and slash (*Pinus elliottii*) pine species. Although loblolly and slash pine generally out grow longleaf pine (Collingwood and Brush, 1978), longlcaf pine is more resistant to breakage, uprooting, fire, and insect and disease outbreaks (Anon., 1973). Given the continued risk of these disturbances, land managers may wish to consider shifting a greater proportion of forests toward more hurricane resistant pines (such as long leaf) and hardwoods (such as sweetgum (*Liquidambar styraciflua* and red oak *Quercus rubra*) in hardwood prone areas.

4. Conclusions

Intense hurricanes occur 2 out of 3 years across the eastern US. However, the extensive forest mortality and conversion of carbon from living to dead carbon pools is rarer due to the unique combination of climate, soil, and forest conditions that need to be present for heavy detritus conversion to occur. A single storm can convert the equivalent of 10% of the total annual US carbon sequestration to dead and downed biomass. Simpson and Lawrence (1971) cited that destructive storms return to the same locations across the eastern US at intervals range from 15 to 200 years. Given that forests require approximately 15–20 years to recover from a storm (Connor, 1998), a large amount of accumulated forest carbon is lost either directly or indirectly due to hurricanes. Although insect infestations do not appear to be a major factor in surviving tree in post-hurricane mortality, post-hurricane fire risk of additional biomass loss is a major concern. In addition to fire losses, only a small fraction of the total carbon in destroyed timber is salvaged. The remainder of the carbon is left to decompose and eventually return to the atmosphere. If increased carbon sequestration is going to one of the mechanisms used to reduce US net emissions of CO_2, then incentives to increase post-hurricane timber salvage need to be addressed. Short-term increases in forest productivity are probably not fully compensated by reduced stem stocking and the recovery time needed to recover leaf area. Therefore, hurricanes are a significant factor in reducing long-term carbon storage in US forests.

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