Impacts of tropical cyclones on U.S. forest tree mortality and carbon flux from 1851 to 2000

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Tropical cyclones cause extensive tree mortality and damage to forested ecosystems. A number of patterns in tropical cyclone frequency and intensity have been identified. There exist, however, few studies on the dynamic impacts of historical tropical cyclones at a continental scale. Here, we synthesized field measurements, satellite image analyses, and empirical models to evaluate forest and carbon cycle impacts for historical tropical cyclones from 1851 to 2000 over the continental U.S. Results demonstrated an average of 97 million trees affected each year over the entire United States, with a 53-Tg annual biomass loss, and an average carbon release of 25 Tg y^{-1}. Over the period 1980–1990, released CO_2 potentially offset the carbon sink in forest trees by 9–18% over the entire United States. U.S. forests also experienced twice the impact before 1900 than after 1900 because of more active tropical cyclones and a larger extent of forested areas. Forest impacts were primarily located in Gulf Coast areas, particularly southern Texas and Louisiana and south Florida, while significant impacts also occurred in eastern North Carolina. Results serve as an important baseline for evaluating how potential future changes in hurricane frequency and intensity will impact forest tree mortality and carbon balance.

carbon balance | forest biomass | hurricanes | spatial–temporal dynamics | wind field

Tropical cyclones cause extensive impacts on both society and natural ecosystems (1, 2). Chambers et al. (3), for example, estimated that hurricane Katrina caused death and severe structural damage to ≈320 million trees with a total biomass loss equivalent to 50–140% of the net annual U.S. carbon sink in forest trees. Other studies demonstrated interannual and interdecadal variation in tropical cyclone frequency and intensity (4–6), with concomitant effects on tree mortality and forest carbon sequestration. Changes in disturbance intensity could also act as a positive feedback to global climate warming (3), yet little research has focused on the dynamic impacts of historical tropical cyclones on forested ecosystems.

There has been heightened concern on the potential effects of global warming on the occurrence of Atlantic hurricanes, particularly after 1995 when hurricanes became more active in the North Atlantic (4). Because tropical cyclone activity is closely related to environmental factors such as sea surface temperature (SST) >26 °C, global warming has the potential to increase the intensity of tropical cyclones. Emanuel (7) studied the intensity of Atlantic hurricanes and found the increased trend was positively correlated with SSTs over the past 30 years. Other studies, however, indicate difficulties attributing the Atlantic hurricane increase with global warming (8). Wang and Lee (9), for example, predicted that vertical wind shear may increase under global warming conditions, which would reduce potential development of Atlantic hurricanes. However, once a tropical cyclone forms and moves through an atmospheric and oceanic environment favorable for the maintenance of cyclone structure (e.g., low wind shear, high sea surface temperatures), higher SSTs often result in more intense storms (10).

Tropical cyclones can severely impact the structure and function of forests, which play important roles as terrestrial carbon sinks. Pacala et al. (11) estimated that forest trees in United States sequestered 110–150 Tg of carbon per y^{-1} over the period 1980–1990. Hurricane Katrina in 2005 produced an estimated biomass loss with committed carbon emissions of 105 Tg, of comparable magnitude to the annual U.S. forest tree carbon sink. In southern New England, annual average damage by hurricanes between 1620 and 1997 were estimated at 0.93–1.68 tons of carbon per ha^{-1} y^{-1} (12). In contrast, maximum hectare-scale biomass loss from Hurricane Katrina was up to 77.6 Mg ha^{-1} in the most severely damaged forests (13). Yet despite the significant contribution of dead and damaged trees to atmospheric CO_2, few studies have focused on forest tree biomass losses from historical tropical cyclones at regional scales (3, 12).

Here, we synthesized field measurements, forest inventory data, satellite image analysis, and empirical models to simulate impacts from all tropical storms and hurricanes over the entire continental United States in terms of tree mortality and damage (referred to as "forest impact"), biomass loss, and carbon release. Forest inventory plots were first established in forests impacted by hurricane Katrina in 2005, and tree mortality and damage was quantified. Field-measured forest impact demonstrated a strong correlation with the change in the nonphotosynthetic vegetation (NPV) signal between the satellite images before and after the hurricane (3). NPV includes woody vegetation structures, coarse woody debris (CWD) [see supporting information (SI) Table S1 and Fig. S1], and surface litter. In addition, the change in the NPV fraction (ΔNPV) showed a significant correlation with maximum wind speed during the storm. Forest impact could therefore be simulated by using empirical models connecting field-measured tree mortality and damage, ΔNPV from satellite images, and wind speeds from hurricane intensity models. We applied a meteorological model HURRECON (14) to simulate wind fields for all Atlantic hurricanes causing tropical storm force winds or higher to impact the surface from 1851 to 2000. HURRECON is a meteorological model that can simulate the wind field based on tropical cyclone track data (i.e., maximum wind speed and its radius, the locations of cyclone center). Hurricane track data were from the HURDAT data archive (15).

In addition to impact rate, to predict the number of affected trees and biomass loss from historical tropical cyclones, land-use

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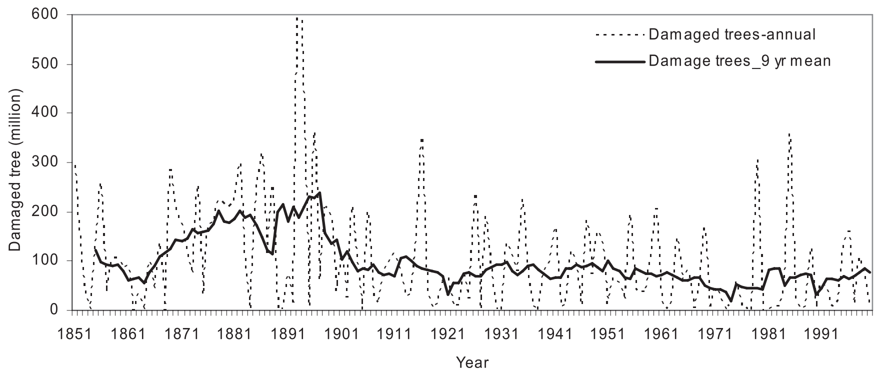

Fig. 1. The number of trees killed and damaged by tropical storms and hurricanes across the entire United States from 1851 to 2000.

cover and forest structural data were required over the same period. The historical land-use data (forest fraction value) from the Global Land-Use Modeling database (16) was used to calculate the fraction of forested areas in each pixel. The forested area was further defined by forest type by using potential natural vegetation (17). The large quantity of inventory data from the U.S. Forest Service (Forest Inventory and Analysis National Program, FIA) enabled us to simulate the distributions of stem density and biomass for different forest types across the entire United States (18). Thus, forest impact for each pixel was calculated as the product of forest fraction, pixel area, stem density, and damage rate. The pixel's biomass loss was the sum of dead and damaged tree biomass, weighted by the loss rates, which may vary for different trees. Finally a Monte Carlo model integrated all of the regression models (from field mortality to wind speed) and distributions (stem density, tree biomass, and snap rate), and simulated the total number of affected trees and biomass loss within the tropical storm area in each year. Further, the release of CO_2 from coarse woody debris was simulated by a CWD decomposition model revised from the model by Chambers et al. (19) (see also Fig. S1).

Temporal Dynamics of the Impacted Forests

Atlantic tropical cyclones had significant impacts on forests in the continental U.S. Tropical cyclone tracks made U.S. landfall every year over the 150-year study period except in 1862 and 1864. The hurricanes in 1862, however, occurred very close to the eastern seaboard, with a small land area experiencing tropical storm wind speeds. On average, U.S. forests lost 97 million trees (dead or damaged) each year, with an average biomass loss of 53 Tg y^{-1}. There were more forest impacts and greater biomass loss between 1851 and 1900 than during the 20th century. On average, 147 million trees were affected each year between 1851 and 1900. Those damages contributed a 79-Tg annual biomass loss. Average annual forest impact and biomass loss between 1900 and 2000 were 72 million trees and 39 Tg, which were only half of the impacts before 1900. This is accordance with historical records showing that Atlantic tropical cyclones were more active during the period from 1870 to 1900 (20), especially during the hurricane landfall peak in late 19th century (9). In addition, more forested areas existed before 1900 (especially old forests) providing more tree exposure (16). Thus, biomass loss before 1900 might be underestimated because losses are sensitive to forest size and age structure (Fig. S2).

Forest impacts also exhibited large interannual variation (Figs. 1 and 2), which covaried with the intensity and frequency of tropical cyclones. Here, we calculated correlations between forest impacts (damaged trees and biomass loss) and the number of tropical storms or hurricanes, and found forest impacts had correlation coefficient value of 0.26 ($P = 0.0014$) with the number of tropical storms and 0.40 with the number of hurricanes ($P < 0.0001$). The correlation varied in different time periods, but hurricanes always had a higher correlation than the tropical storms (Table S2). There were also some exceptional years that had fewer tropical cyclones but greater forest impact, or more tropical cyclones but less impact (Table 1). Some exceptional cases were caused by the landfalling locations of tropical cyclones in heavily forested regions.

Unlike forest impacts, carbon release after wind disturbance had much less interannual variation (Fig. 3) because of its cumulative function. Because forest impact was much higher before 1900 than after 1900, the released carbon reached a maximum value in 1896, after which it continuously decreased until 1978 (Fig. 3). This also means that an exceptionally strong hurricane, which induces severe damage, such as Katrina in 2005 (3), may significantly affect carbon release over the next several decades. Moreover, the decay rate had

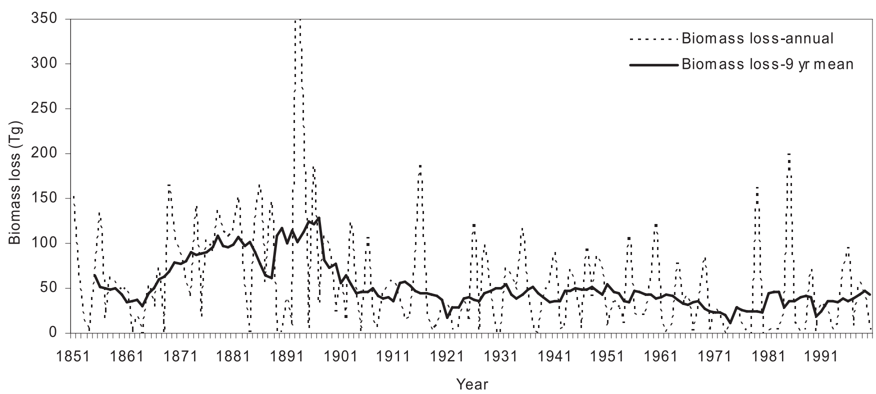

Fig. 2. The biomass loss due to the disturbance of tropical storms and hurricanes all over the United States from 1851 to 2000.

Table 1. Detailed damages and biomass loss in forests of the United States continent for some specific years

Year	Tropical cyclones/hurricanes	Landfall tropical cyclones	Damaged trees (million)	Biomass loss, Tg
1979	7/5	4	305	162
1985	11/7	6	359	200
1995	18/11	3	131	68
1996	13/9	2	161	95
1998	14/10	5	108	56

only a limited influence on the temporal patterns of carbon loss due to the cumulative function of decomposition (Fig. S3). The amount of released carbon was, however, sensitive to forest size structure (Fig. S4). Thus, forests before 1900 with larger older trees might produce even more CO_2 than demonstrated here. Based in part on an analysis of the Forests Service's Forest Inventory Analysis (FIA) data, United States forests sequestered from 110 to 150 Tg of carbon between 1980 and 1990 (11). Over the same period, U.S. forests emitted 12–21 Tg of carbon to the atmosphere due to disturbance from tropical cyclones. If the FIA data does not comprise a representative sample of forests impacted by tropical storms and hurricanes, the net carbon sink in forest trees could be underestimated by 8–19%.

Furthermore, there are also other indirect effects (e.g., delayed mortality) on forests that cause extra carbon release. One study found that only 15% of the total destroyed timber is salvaged after a major hurricane (21). The CWD left in the forest can also lead to increased breeding sites for detrimental insects (22) and potential fuel for forest fire (23), with increased risk to live trees that survive the immediate impacts from the storm. Delayed mortality in hurricane-impacted forests would further increase biomass loss and CWD stocks.

Spatial Pattern of the Forest Impacts

To evaluate spatial patterns in forest impact over the past 150 years, we used Weibull distributions to simulate the return frequency for each U.S. location that had experienced tropical storm-force winds or greater since 1850. The return frequency can be used to calculate the return interval with, for example, a return frequency of 0.1 corresponding to a 10 year return interval. The biggest impacts occurred in the forest areas with the highest return frequency. Altogether 1.75 million km^2 of the continental United States experienced tropical storm-force winds or greater during the 1851–2000 period (Fig. 4). As expected, higher frequencies were found closer to the coast. For example, the area corresponding to a <10-year return interval for tropical storms was found within 50-km distance of the coast, and all areas with a <100-year return interval for hurricanes were located within 20 km of the coast, except in south Florida, which reached 85 km inland. Moreover, highest return frequencies for both tropical storms and hurricanes were mainly located along the Gulf Coast and Florida (Fig. 4). Forest impacts were also mostly located in those high-frequency areas, except for regions that lack forests such as Southern Florida. Altogether a 17,500-km^2 area had a hurricane return frequency of 2% or greater, including 9600 km^2 (i.e., 55%) in southern Texas and Louisiana, 6,725 km^2 (38%) in southern Florida, and 1,175 km^2 (7%) in eastern North Carolina.

Methods

Wind Field Simulation. The meteorological model HURRECON (14) was used to simulate the wind field (with a pixel size of 5 Km) for all tropical storms and hurricanes in each year. HURRECON is a meteorological model that can simulate the wind field based on the tropical cyclone track data (i.e., maximum wind speed and its radius, the location of cyclone center). The Atlantic tropical cyclone track data (including maximum wind speeds and geographical locations of the hurricane centers) were from the HURDAT data archive (15); whereas the radius of the maximum wind speeds were calculated by using a function of the maximum wind speeds and the latitude of the cyclone center (24). The model was validated in previous studies by Boose et al. (14). Here, we further validated the model with another airflow model H*WIND (25). Wind field estimates from the 2 models where highly correlated (averaged $r = 0.92$ and $P < 0.0001$).

Forest Impact Model Series. A series of mortality models were developed by synthesizing field measurements, satellite images, and wind fields so that the wind fields alone could be applied in simulating the tropical cyclone impacts each year. The relationship between field measurements and satellite images was carried out in a study of hurricane Katrina (3). Chambers et al. (3) found the field-measured forest impact rate had significant correlation with Landsat ΔNPV (the difference of the nonphotosynthetic vegetation before and after hurricane). Here, we expanded the regression models from Chambers et al. (3) and united these models with the wind-field data (i.e., the maximum wind speeds) to predict forest impact by using the following relationship:

$$\Delta NPV = -0.8906 + 0.257 \cdot \log(s), \quad [1]$$

where s is the wind speed in m s^{-1}. This empirical regression model had a r^2 of 0.41 and P value <0.0001.

Calculation of Damaged Trees, Biomass Loss, and Carbon Release. The number of impacted trees of each pixel was calculated by using forest-impact estimates, the fraction of each pixel occupied by forest, and the stem density distribution.

$$Tr = M \cdot Lf \cdot Ds, \quad [2]$$

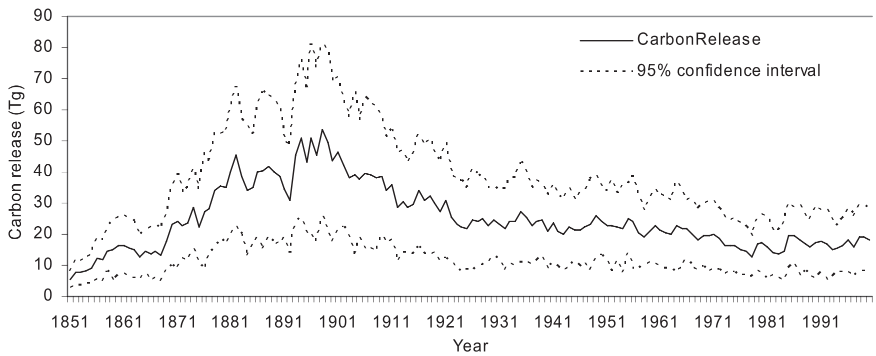

Fig. 3. The released C from the coarse woody debris created by tropical cyclones all over the United States continent.

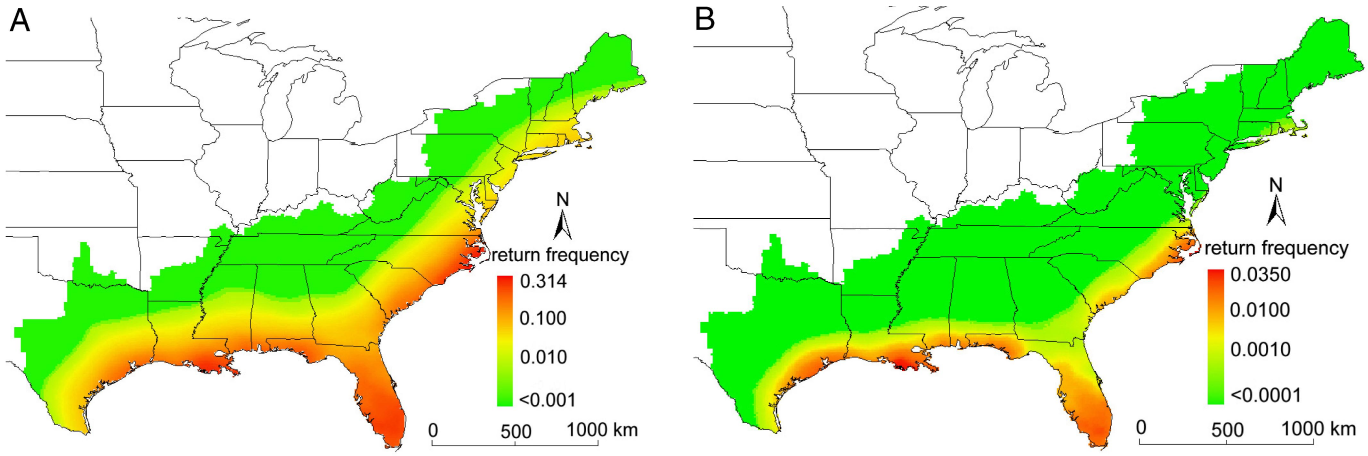

Fig. 4. The return frequency of tropical storms (*A*) and hurricanes (*B*).

where *Tr* is the total number of impacted trees in a pixel; *M* is the impact rate (i.e., the percentage of the dead and damaged trees); *Lf* is the fraction value of the forest coverage in the pixel; and *Ds* is the stem density.

The forest-impact rate (*M*) was calculated from the wind field through ΔNPV. Fractional forest coverage (*Lf*) was provided by the Global Land-Use Modeling (GLM) database (16). The GLM provided underlying land conversions (land-use transitions), wood harvesting, and resulting secondary lands annually, for the period 1700–2000. GLM classified 6 land-use categories: primary land, secondary land, crop, pasture, water, and ice and provided the fractional values of each category for each grid. Here, we assumed that primary and secondary land fraction values represented the percentage of forest areas. The distribution of stem density was simulated by using the inventory data from U.S. Forest Service (FIA National Program) (18). Stem densities were simulated separately for different forest types. Because the GLM model only provided the fraction values of forested area, rather than forest type, a potential natural vegetation map of United States was used to define the forest type for each pixel (17).

The biomass loss in each pixel was the sum of the loss of each tree within the pixel:

$$Bm = \sum_{i=1}^{Tr} Sp \cdot Bm_i, \qquad [3]$$

where *Sp* is the snap rate (a dead tree was given a value of 1, 0 for an intact tree, and a value between 0 and 1 for snapped but live trees); Bm_i is the biomass of tree *i*, sampled from a distribution constructed by using FIA data for different forest types. FIA provided tree table data, as well as forest plots, which included tree biomass. The simulation of tree biomass distribution is the same as the approach for simulating stem density.

Decomposition of coarse woody debris (CWD) from tree mortality and damage was calculated by a simple model using an exponential function with temperature (19). Chambers et al. (19) developed an exponential model to simulate the decay rate constant with the mean annual temperature by using the results from previous studies. This model was improved here by adding new results from recent studies. Historical temperature was gleaned from a meteorological model HadCRUT3 (26) and provided monthly global temperatures at a resolution of 5 × 5°. Here, we extracted the data for the East and Gulf Coast of the United States from 1851 to 2000 and calculated the annual mean temperature, which was used to estimate decomposition rates. Because CWD was cumulated from previous years, the released of carbon for the first few decades did not fully reflect the effects of tropical cyclones because of the lack of the storm and damage data before 1851.

Simulation of Return Frequency. The return frequency was simulated for each pixel (5 × 5 Km) by using wind speeds from 1851 to 2005 outputted by model HURRECON. We applied the extreme value distribution type III (Weibull distribution) to simulate the distribution of the extreme wind speeds (27). The cumulative frequency for wind speeds larger than *x* is calculated by:

$$F(x) = \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \qquad [4]$$

where *f*(*x*) is the probability density function of wind speed *x*, α is the scale parameter, and β is the shape parameter. To estimate the scale and shape parameter of the Weibull distribution for each pixel, a linear least squares technique was used to estimate the scale and shape parameter of the original Weibull distribution (27).

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