The impacts of tropical cyclones on the net carbon balance of eastern US forests (1851–2000)

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Abstract
In temperate forests of the eastern US, tropical cyclones are a principal agent of catastrophic wind damage, with dramatic impacts on the structure and functioning of forests. Substantial progress has been made to quantify forest damage and resulting gross carbon emissions from tropical cyclones. However, the net effect of storms on the carbon balance of forests depends not only on the biomass lost in single events, but also on the uptake during recovery from a mosaic of past events. This study estimates the net impacts of tropical cyclones on the carbon balance of US forests over the period 1851–2000. To track both disturbance and recovery and to isolate the effects of storms, a modeling framework is used combining gridded historical estimates of mortality and damage with a mechanistic model using an ensemble approach. The net effect of tropical cyclones on the carbon balance is shown to depend strongly on the spatial and temporal scales of analysis. On average, tropical cyclones contribute a net carbon source over latter half of the 19th century. However, throughout much of the 20th century a regional carbon sink is estimated resulting from periods of forest recovery exceeding damage. The large-scale net annual flux resulting from tropical cyclones varies by up to 50 Tg C yr\textsuperscript{−1}, an amount equivalent to 17%–36% of the US forest carbon sink.

Keywords: tropical cyclones, carbon cycle, land–atmosphere interactions, ecological disturbances

1. Introduction

Natural disturbances, including fires, insect outbreaks, and storms, have been shown to have important implications for regional carbon balances (Kurz et al 2008a, 2008b, Lindroth et al 2009, Turetsky et al 2011, Uriarte and Papaik 2007). In eastern US forests, tropical cyclones are the principal agent of catastrophic wind damage with dramatic impacts on forest structure and functioning (Boose et al 1994, Boose and Chamberlin 2001, Dolan et al 2011, Frohlich et al 2009, Negrón-Juárez et al 2008, McNulty 2002, Uriarte and Papaik 2007, Vargas and Allen 2008). Hurricane Katrina, for...
instance, was estimated to have killed or severely damaged 320 million trees (Chambers et al. 2007). The 105 Tg C of live biomass loss from this single storm was equivalent to 50–140% of the annual US carbon sink in forest trees (Chambers et al. 2007, Pacala et al. 2001). On average the US coastline experiences a major hurricane (wind speed greater than 178 km h⁻¹) in 2 out of 3 years (Smith 1999). Between 1851 and 2000, 1.75 million km² of the coterminous US were impacted by tropical cyclones with winds in excess of 63 km h⁻¹ (Zeng et al. 2009).

Substantial recent progress has been made to quantify the forest damage and gross carbon emissions caused by tropical cyclones (McNulty 2002, Chambers et al. 2007, Zeng et al. 2009, Dolan et al. 2011); however, understanding the net effects of tropical cyclones on the regional carbon balance requires quantification of not only the release of carbon following a disturbance, but also the carbon uptake during recovery from a mosaic of past events. In an idealized case with constant growth and disturbance rates, one would expect the system to reach a dynamic equilibrium, with local sources from recent disturbance balanced by sinks in recovering areas. However, tropical cyclone patterns vary both spatially and temporally (Zhang and Delworth 2006, Delworth and Mann 2000, Kerr 2000, 2005) with repeat intervals ranging from years to hundreds of years (McNulty 2002, Zeng et al. 2009). Variations in storm activity could thus potentially result in a regional source or sink depending whether disturbance or recovery dominates in any given time period.

While data on tropical storm activity is available over the US, attribution of the impacts of variations in storm activity per se on the regional net carbon balance is a major challenge. In particular, it is difficult to track disturbance and recovery, and isolate the effects of storm damage from the potentially confounding effects of a large number of other processes simultaneously affecting the landscape carbon balance. Progress towards quantification and attribution could potentially be advanced by models able to simultaneously track and isolate relevant phenomena, and run repeatedly over large scales. This study combines an advanced terrestrial ecosystem model, mapped reconstruction of tree mortality from tropical storms impacting the US from 1851 to 2000, and a mapped land-use history reconstruction. A factorial modeling experiment was run to isolate the effects of storms on the carbon balance and to investigate the effects of previous disturbances on the impacts of storms. Changes in carbon stocks and fluxes (gross and net) were analyzed through time across the area of the US affected by tropical storms over the period.

2. Methods

The ecosystem demography (ED) model (Hurtt et al. 1998, Moorcroft et al. 2001, Hurtt et al. 2002) was modified to track the net impacts of tropical cyclones on the carbon balance of US forests. The ED model provides a framework that simulates the dynamics of growth and recovery from disturbance and land-use, while formally scaling up physiological processes from vegetation dynamics to ecosystem scales using established submodels of leaf level physiology, organic matter decomposition, hydrology, and functional biodiversity. The version used here was based on the original version developed for use evaluating the effects of land-use on the carbon balance of the US (Hurtt et al. 2002) and modified to use prescribed natural disturbance rates for past tropical cyclone activity for each grid cell annually.

The initial state of the ecosystem was estimated by using the temporally averaged disturbance rate for each grid cell during a model spin-up period to reach dynamic equilibrium. Starting in simulation year 1851, prescribed gridded annual disturbance rates were applied. Live biomass loss from tropical cyclones and net ecosystem flux for each year in each grid cell were tracked. Net ecosystem flux was calculated as the net change in carbon stored in soils and biomass in each grid cell each year.

ED was dynamically forced with gridded annual stem mortality and damage rates from Zeng et al. (2009) for all tropical cyclones impacting the US between 1851 and 2000. These mortality and damage estimates were based on an empirical model relating wind speed to stem mortality and damage based on field measurements, forest inventory data and the change in the non-photosynthetic vegetation (ΔNPV) signal in remote sensing images before and after hurricane Katrina (Chambers et al. 2007, Zeng et al. 2009). Wind fields for historic hurricane tracks from the HURDAT (National Hurricane Center 2007) data archive were simulated using the meteorological model HURRECON (Boose et al. 2004). For our simulations, the mortality and damage rates, reported separately as fraction of stems killed or damaged, were aggregated to 1° annual resolution for use in forcing ED. As there can be a wide range in non-mortality damage we bracketed our estimates with a low-damage case to represent leaf stripping and a high-damage case to represent near complete live biomass loss of the damaged trees.

Storm impacts depend not only on the storm strength, but also on the size and extent of affected forests, which could depend both on land-use change and the legacy of prior disturbances. Land-use dynamics were simulated using land conversions and harvesting from the global land-use model (GLM) (Hurtt et al. 2006). GLM classified four land-use categories: primary land, secondary land, crop, and pasture and provided the fractional values of each category and rate of transition between each type for each grid cell. Land-use transitions and harvesting were applied in ED, beginning in simulation year 1700, to convert land between land-use types, harvest forests, and track the resulting structure of recovering secondary lands. We quantified how forest area change resulting from land-use and structural change resulting from the legacy of prior disturbances affect storm impacts by comparing simulations using both processes to simulations excluding either forest area changes or the forest structural changes from past disturbances, or both.

Land-use has previously been shown to have a large effect on the carbon balance of forests (Hurtt et al. 2002, Froliking et al. 2009, Shevliakova et al. 2009). To isolate the net impacts of tropical cyclones on the carbon balance from the effects of land-use, we ran paired simulations, one set forced with the
Figure 1. Time series of live biomass loss resulting from tropical cyclones. Estimates from ED using dynamic vegetation and land-use (dark black line—primary simulation) are compared to that predicted using static vegetation without land-use (green line), using dynamic vegetation with land-use (thin black line), using static vegetation with land-use using static vegetation (blue line), and estimates from Zeng et al (2009) (red line).

Figure 2. Cumulative live biomass loss resulting from tropical cyclones over the period 1851–2000 comparing estimates using static or dynamic vegetation, with or without the effects of land-use, to the estimates from Zeng et al (2009). Error bars on model estimates show a range from potential non-mortality damage rates from leaf stripping to near complete live biomass loss. Error bars on the results from Zeng et al (2009) show the 95% confidence interval on those estimates.

3. Results and discussion

Rigorous validation of these simulations is difficult, however, simulations of live biomass loss resulting from tropical cyclones compare favorably to those produced by Zeng et al (2009) (figures 1 and 2). On average, ED predicts 21 Tg C live biomass loss annually resulting from tropical cyclones, which is ~20% lower, but within the 95% confidence range of their estimates. Similar to that study, we find a large variation in live biomass losses over the time period with annual losses between 0 and 196 Tg C. Live biomass losses over the last half of the 19th century were simulated at 31 Tg C yr$^{-1}$ which was more than double the average rate of the 20th century of 14 Tg C yr$^{-1}$. In addition to a peak in land-falling hurricanes during the period 1870–1900, both forested area and age and size structure of forests play a role in the greater impacts in the 19th century.

The legacy of prior disturbances can have a large effect on a storm’s regional and local impact. Figures 1 and 2 compare the time series and cumulative tropical cyclone-induced losses of live biomass from simulations including disturbance-induced structural change (dynamic vegetation) and forest area change (with land-use) to simulations excluding either the effects of past disturbances on forest structure (static vegetation) or forest area change (without land-use), or both. In the simulation excluding the area and structural effects, where all storms impacted fully mature vegetation (static vegetation without land-use), cumulative loss of live biomass was estimated to be 8.2 Pg C over the 150 year period (range 5.0–8.9 Pg C depending on non-mortality damage assumptions). However, accounting for the reduction
in standing biomass resulting from the legacy effects of previous storms on forest structure (dynamic vegetation without land-use) reduces the cumulative live biomass losses by 13% to 7.2 Pg C (range 4.8–7.8 Pg C). Similarly, the effects of reduced forest area from land-use change without the effects on forest structure (static vegetation with land-use) results in a live biomass loss estimate of 4.1 Pg C (range 2.5–4.5 Pg C), 50% lower than the maximum potential. Our primary simulation, using the combined effects of both forest area and structural changes (dynamic vegetation with land-use), yields a cumulative loss of live biomass of 3.1 Pg C (range 2.0–3.3 Pg C) which is approximately 62% lower than the maximum potential scenario.

The net effect of cyclones on the carbon balance of eastern US forests was found to depend strongly on the time period and spatial domain of interest. Between 1851 and 2000 large interannual variations in the net ecosystem flux (figure 3) and carbon storage (figure 4) results from tropical cyclones. Individual years range from a net regional source of 31.7 Tg C in 1892 to a net regional sink of 20.7 Tg C in 1976. Similarly, there is sizable decadal variation in flux ranging from a mean annual carbon source of 7.6 Tg C yr\(^{-1}\) in the 1890s to a mean annual carbon sink of 8.2 Tg C yr\(^{-1}\) in the 1970s. Carbon storage in live biomass is estimated to have varied by over 340 Tg C during the period. Total ecosystem carbon storage (biomass and soils) is estimated to have varied by over 240 Tg C. The change in total ecosystem carbon storage lags behind the change in biomass as downed trees enter the soil pool and are slowly released into the atmosphere through decomposition. Temporal variability in total ecosystem carbon storage also exhibits lower amplitude (is more muted) because of the residence time of dead biomass, which acts to smooth out the more punctuated changes to the live biomass pool by cyclone-induced mortality. Additionally, we find that tropical cyclones caused a net carbon sink over the 20th century resulting from recovery following the peak in land-falling storms during the late 19th century.

The results presented here illustrate the importance viewing disturbance events both in terms of the damage caused, and in the broader context of recovery from a complex mosaic of past events. While individual storms result in carbon loss, the large-scale net carbon balance can vary between source or a sink depending on the magnitude of storms, accumulated debris, and the state of recovering lands. Longer-term patterns in storm activity can result in multi-decadal trends in the carbon balance. A study of the carbon balance of the US demonstrated a carbon sink in forests between 140 and 300 Tg C yr\(^{-1}\) during the 1980s (Pacala et al. 2001). We find that recovery from previous tropical cyclone activity contributed to the sink during that period, while increased storm activity in the 1990s contributed a net source. Furthermore, we estimate that the contribution of tropical cyclones to annual ecosystem flux varied by up to 50 Tg C yr\(^{-1}\) resulting in potential annual variations in the regional carbon sink between 17 and 36%. Decadal ecosystem flux varies by nearly 16 Tg C yr\(^{-1}\), which could cause decadal-level variations in the estimated sink of 5–11%.

While the effects of tropical cyclones on the interannual and decadal carbon balance can be estimated using the methods presented here, long-term trends in the net effects of tropical cyclones are difficult to ascertain due to lack of quantitative knowledge of historical cyclone activity prior to 1851. Conservatively, our analyses assumed the rate of
tropical cyclone damage before 1851 equal to the long-term average rate post 1851. To assess the potential importance of rates prior 1851 and the sensitivity of this assumption, in subsequent analyses we bracketed the base assumption with two additional cases: no prior tropical cyclone activity prior to 1851, and double the base rate. With no prior tropical cyclone activity, the region appears as a net source of carbon of 19 Tg C yr⁻¹ over the period as the system responds to the apparent increase in tropical cyclones. With double the rate of prior tropical cyclone activity, the region appears as a net carbon sink of 9.8 Tg C yr⁻¹ as the system recovers from previous high disturbance. However, in all cases tropical cyclones result in a average carbon sink of between 1.5 and 6.5 Tg C yr⁻¹ between 1970 and 1995, and an average carbon source of between 1.3 and 2.6 Tg C yr⁻¹ over the period 1995–2000, suggesting the robustness of the recent trends.

Future trends in the tropical cyclone patterns have the potential to alter this balance. There is growing concern over the links between climate change and increased tropical cyclone activity. Recent studies provide evidence linking higher sea surface temperature (SST) to increased tropical cyclone intensity, although there is large uncertainty in how other factors, such as wind shear, will affect storm formation (Emanuel 2005, Goldenberg et al 2001, Hoyos et al 2006, Knutson and Tuleya 2004, Saunders and Lea 2008, Trenberth 2005, Webster et al 2005). Projections from coupled hurricane-resolving climate models suggest that although the overall frequency of tropical storms may decrease, the number of intense, category 4 or 5, hurricanes could nearly double by the end of the century (Bender et al 2010). Changes to these patterns could have substantial affects on both the gross and net carbon balance of terrestrial ecosystems.

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