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Integrating a process-based ecosystem model with Landsat imagery to assess impacts of forest disturbance on terrestrial carbon dynamics: Case studies in Alabama and Mississippi

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[1] Forest ecosystems in the southern United States are dramatically altered by three major disturbances: timber harvesting, hurricane, and permanent land conversion. Understanding and quantifying effects of disturbance on forest carbon, nitrogen, and water cycles is critical for sustainable forest management in this region. In this study, we introduced a process-based ecosystem model for simulating forest disturbance impacts on ecosystem carbon, nitrogen, and water cycles. Based on forest mortality data classified from Landsat TM/ETM + images, this model was then applied to estimate changes in carbon storage using Mississippi and Alabama as a case study. Mean annual forest mortality rate for these states was 2.37%. Due to frequent disturbance, over 50% of the forest land in the study region was less than 30 years old. Forest disturbance events caused a large carbon source (138.92 Tg C, 6.04 Tg C yr^{-1}; 1 Tg = 10^{12} g) for both states during 1984–2007, accounting for 2.89% (4.81% if disregard carbon storage changes in wood products) of the total forest carbon storage in this region. Large decreases and slow recovery of forest biomass were the main causes for carbon release. Forest disturbance could result in a carbon sink in few areas if wood product carbon was considered as a local carbon pool, indicating the importance of accounting for wood product carbon when assessing forest disturbance effects. The legacy effects of forest disturbance on ecosystem carbon storage could last over 50 years. This study implies that understanding forest disturbance impacts on carbon dynamics is of critical importance for assessing regional carbon budgets.

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1. Introduction

[2] Forests are the largest terrestrial carbon (C) pool compared to other land ecosystems, which remove CO_2 from the atmosphere and maintain it in soil organic matter and standing biomass [*Dixon et al.*, 1994; *Pan et al.*, 2011a]. The current C stock in tree biomass comprises half of atmospheric storage and is continuing to increase due to environmental change and management [*Watson et al.*, 2000; *Schimel et al.*, 2001; *Pan et al.*, 2011b; *Xiao et al.*, 2011]. Tree mortality rates are one of the key factors controlling long-term dynamics of forest ecosystems. Forest disturbance (including harvest) has been reported to significantly change forest structure, productivity, C sequestration, hydrological cycle, and soil biogeochemistry [*Birdsey and Heath*, 1995; *Johnson and Curtis*, 2001; *Birdsey et al.*, 2006; *Woodbury et al.*, 2007; *Hansen et al.*, 2010; *Liu*, 2011; *Williams et al.*, 2012], while impact magnitudes are determined by disturbance intensity and frequency. Many previous studies were focused on landscape- or stand-level forest disturbance events and their impacts, with much less emphasis on regional or continental scale events. This may be due to several challenges including limited understanding of governing processes and lack of large-scale high-resolution data and accurate modeling algorithms as noted by *Liu* [2011].

[3] Since forest biomass increases with stand age, delaying harvesting to the age of biological maturity may result in the formation of a larger C sink [*Alexandrov and Yamagata*, 2002; *DOE*, 2007]. Therefore, most incident forest disturbance events could greatly decrease forest biomass. In addition to the impacts on biomass and productivity, disturbance could greatly influence organic C storage in forest soils and wood products. *Covington* [1981] suggested that forest floor organic matter declines by 50% within 20 years after harvest, and this decline was attributed to accelerated decomposition and changes in litter inputs. The shape of Convington's curve was revisited by other scientists [e.g., *Yanai et al.*, 2003], indicating that this curve may be affected by other factors

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(e.g., soil and litter mixing, management practices, fire) except for decomposition and litter inputs. Except for its direct impacts on C cycle, forest disturbance also greatly affects the ecosystem hydrological cycle and other biogeochemical cycles (e.g., nitrogen (N) and phosphorus), which will in turn indirectly influence the C cycle [*Thiffault et al*., 2011]. Forest soil N dynamics after disturbance generally follow a paradigm as described by *Allen et al*. [1990] and *Heath et al*. [2003]. Soil N is generally increasing in the undisturbed forest soil due to microbial or fungus fixation and atmospheric N deposition. After forest disturbance, the relatively closed N cycle may be greatly disrupted. Soil N may increase within the short-term (such as 1–5 years) since more litter may be added into the soil; however, the accumulated soil N could soon be lost through NO_3^--N leaching, biomass removal, or denitrification (emissions of N_2O, NO or N_2 gases) [*Allen et al*., 1990]. This loss of N may cause future nutrient deficiency, thereby decreasing productivity over the long-term period [*Thiffault et al*., 2011]. Considering the complexity of forest disturbance impacts and the interactions among C, N, and water, it is necessary to apply a process-based model with a full coupling of C, N, and water cycles to dynamically track C cycling processes after disturbance [*Yanai et al*., 2003].

[4] Forest area and structure changes subjected to disturbances such as land use change, hurricane, storm, wildfire, insects, and diseases and forest harvest for wood product demands have greatly affected forest ecosystems in the southern United States [*McNulty*, 2002; *Birdsey et al*., 2006; *Woodbury et al*., 2007; *Chambers et al*., 2007; *Hansen et al*., 2010]. Forest biomass was reported to have greatly increased during past decades, and southern forests were a major contributor to C sinks in the United States [e.g., *Han et al*., 2007; *Xiao et al*., 2011; *Tian et al*., 2012], mainly due to increased atmospheric CO_2 concentration, N deposition, and forest management [*Allen et al*., 2005; *McKeand et al*., 2006; *Fox et al*., 2007a, 2007b; *Albaugh et al*., 2007; *Tian et al*., 2012]. However, reports also indicated that forest disturbance in this region may significantly reduce this C sink [e.g., *McNulty*, 2002; *Han et al*., 2007]. *Chambers et al*. [2007] estimated that Hurricane Katrina caused a C emission of 50% ~ 140% of the net U.S. forest C sink in 2005. As another major forest disturbance, forest harvests are also frequent in this region [*Birdsey et al*., 2006; *Woodbury et al*., 2007]. Although young forests have higher productivity, the entire ecosystems could still be a C source due to the short rotation age, slow recovery of biomass, loss of aboveground litter, and disturbed soil and vegetation structure.

[5] A few studies have addressed regional C dynamics after forest disturbance in the United States; however, these studies are limited either by a high spatial resolution and long-term forest disturbance data or a fully coupled process-based ecosystem model [e.g., *Houghton and Hackler*, 2000; *McNulty*, 2002; *Chambers et al*., 2007; *Liu*, 2011]. With its advantages of high spatial resolution, short-time gapping, and long-term observations, Landsat TM/ETM + images were used widely to quantify forest mortality rate due to disturbance events at a landscape scale and even expanded to a larger scale such as regional or continental scales due to the recent technology advances in computation and modeling algorithms [*Huang et al*., 2009a, 2009b; *Goward et al*., 2004; *Masek et al*., 2008; *Williams et al*., 2012; *Zheng et al*., 2011]. Based on the vegetation change tracker model, *Huang et al*. [2009a, 2009b, 2010] and *Li et al*. [2009a, 2009b] generated large-scale forest disturbance maps from Landsat TM/ETM + images for many states in the southeastern United States. The dynamic land ecosystem model (DLEM) is a highly integrated process-based model, which fully couples C, N, and water cycles. DLEM has been widely used to estimate the impacts of multiple environmental factors on C, N, and water cycles [e.g., *Ren et al*., 2011; *Zhang et al*., 2010, 2012; *Liu et al*., 2008, 2012; *Lu et al*., 2012; *Chen et al*., 2012; *Tian et al*., 2010a, 2010b, 2011a, 2011b, 2012]. Based on the main DLEM framework, we further developed a forest management and disturbance module to specifically address the impacts of forest management and disturbance on ecosystem dynamics. In this study, we integrated these high-resolution forest mortality data and the DLEM model to estimate changes and recovery of forest C storage after disturbance using Mississippi and Alabama as a case study. As a central location in the southern United States, Mississippi and Alabama are typical states with high forest coverage and frequent disturbance events. Therefore, this study may have important implications to the future estimation of C budgets as influenced by different forest disturbance events in the United States and North America.

2. Methods

2.1. Study Region

[6] In this study, we selected two states, Mississippi and Alabama, in the southern United States as an example to estimate the impacts of forest disturbance on the terrestrial C cycle. These two states have high forest coverage and a large area of forested wetland (Figure 1). Any disturbances to the wetland could significantly change the C and N cycles in this region. Most forests in the two states are young forest (i.e., <60 years old) because forests are frequently disturbed by hurricane/storm, insect/disease, and harvest events [*Pan et al*., 2011b].

2.2. Data Description

[7] Based on a large collection of many scenes of Landsat TM/ETM$^+$ images and a vegetation change tracker (VCT) model, which is an automated forest change mapping algorithm designed for analyzing dense time series stacks of Landsat images, *Li et al*. [2009a, 2009b] and *Huang et al*. [2009a, 2009b] derived the forest change information for Mississippi and Alabama. *Huang et al*. [2009a, 2009b] further identified the forest disturbance area in each investigation year (a map for every 2 years during 1984–2007). Seven categories were classified (Figure 2). The category "disturbed in this year" (Figure 2) was treated as the disturbed grid cells. The forest mortality defined here was the forest area that disappeared during the 2 years' observations. Landsat images can identify patched forest mortality with a minimum disturbed area of 30 × 30 m but difficult to monitor the mortality of a few trees (e.g., natural turnover or background mortality). If disturbance occurs in a 30 m grid cell, then all the trees in that grid cell is cleared (i.e., forest age = 0). Thus, the generated VCT mortality rate for each grid cell has only an attribute with either 0 (no disturbance) or 1 (forest is cleared). Due to too many grid cells to compute in

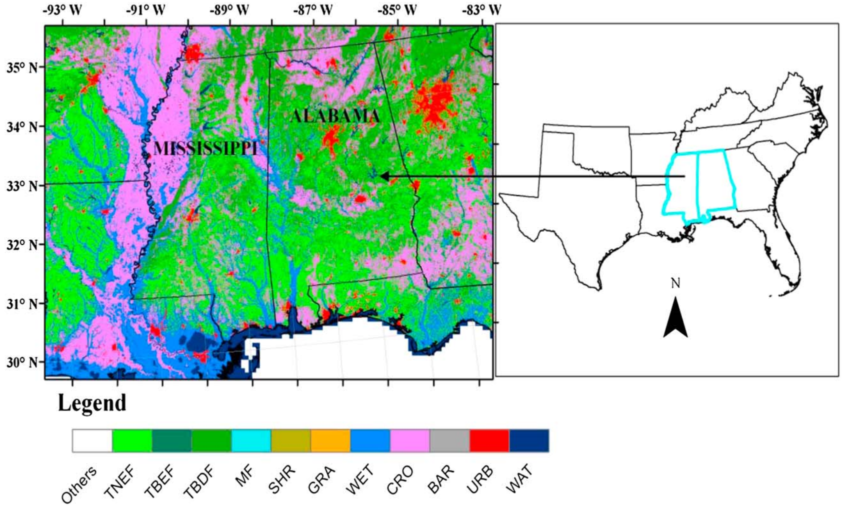

Figure 1. Boundary and land cover and land use map for Alabama and Mississippi states. TNF: temperate needleleaf forest; TBD: temperate broadleaf deciduous forest; MF: mixed forest; SHR: temperate deciduous shrubland; GRA: grassland; WET: wetland; CRO: cropland; BAR: barren land; URB: urban and built-up land; WAT: water (Source: MODIS 2005 land cover map, http://www.cec.org).

our current model version, the 30 m resolution data were scaled up to 1 km forest mortality rate. The 30 m VCT products were first translated into percentage mortality data at 1 km (represented as the ratio of disturbed 30 m grid cell numbers to total 30 m grid cell numbers within a 1 km grid cell). For example, if there is only a 30 m disturbed grid cell in a 1 km grid cell range, the aggregated mortality rate for the 1 km grid cell is 1/33. Since percentage mortality rate in each grid cell indicates a partial disturbance, it can no longer reflect the patched forest disturbance information such as stand age and canopy coverage. To preserve more accurate forest age information, the percentage forest mortality rate at 1 km resolution was then transformed to attribute data of 0 and 1, with a mortality rate higher than the determined threshold value being disturbed (assigned attribute 1) and lower than the threshold value being not disturbed (0). The threshold value was determined by meeting the total disturbed area. This transformation might lose some spatial accuracy for representation of disturbance effects but more accurate for ecosystem models to simulate forest recovery for the biogeochemical (e.g., C, N, and water cycles) and biophysical (e.g., canopy and age structure) processes. These Landsat images were able to estimate mortality rate but not able to identify the exact reasons for tree mortality, which could be caused by forest harvest, wildfire, hurricane, or other factors. In our modeling studies, we defined two general groups for causes of mortality: forest harvest and natural disturbance events. Based on Forest Inventory and Analysis (FIA) data, *Zheng et al*. [2011] found that forest harvest was the major disturbance type in Mississippi and Alabama. Forest harvest (including salvage harvest) resulted in human interventions to the ecosystems, and most of the harvested wood biomass can be removed as products.

[8] Other model input data include daily air temperature (maximum, minimum, and average temperature) and precipitation, annual land use, N deposition, atmospheric CO_2 concentration, and non-time-step soil properties (e.g., soil texture, pH value, etc.), as well as topography data (e.g., digital elevation map, etc.). The generation methods for these data were described in *Tian et al*. [2010a, 2012], *Zhang et al*. [2010], and *Chen et al*. [2012].

2.3. Model Description

[9] The DLEM model is a highly integrated process-based terrestrial ecosystem model that simulates daily C, N, and water cycles driven by changes in tropospheric ozone concentration, atmospheric N deposition, CO_2 concentration, climate, land use and land cover, and disturbances (i.e., fire, hurricane/storm, and harvest) (Figure 3). The DLEM has been extensively used in studying terrestrial C, water, and N cycles over Monsoon Asia, the continental United States, and North America [e.g., *Tian et al*., 2010a, 2010b, 2011a, 2011b, 2012; *Xu et al*., 2010; *Chen et al*., 2012; *Ren et al*., 2007a, 2007b, 2011; *Liu et al*., 2008, 2012; *Zhang et al*., 2010, 2012; *Schwalm et al*., 2010; *Sulman et al*., 2012; *Huntzinger et al*., 2012].

[10] The DLEM includes five core components (Figure 3): (1) biophysics, (2) plant physiology, (3) soil biogeochemistry, (4) dynamic vegetation, and (5) disturbance, land use, and management. The biophysical component includes the instantaneous exchanges of energy, water, and momentum with the atmosphere, which involves micrometeorology, canopy physiology, soil physics, radiative transfer, water and energy flow, and momentum movement. The plant physiology component in DLEM simulates major physiological processes such as photosynthesis, respiration, carbohydrate allocation among various organs (root, stem, and leaf), N uptake, transpiration, and phenology. The component of soil biogeochemistry simulates mineralization, nitrification/denitrification, decomposition, and fermentation so that DLEM is able to estimate simultaneous emission of multiple trace gases (CO_2, CH_4, and N_2O). The dynamic vegetation component simulates two kinds of processes: the biogeographic redistribution of plant functional types under environmental change, and plant competition and succession during vegetation recovery after disturbances. Like most dynamic global vegetation models (DGVMs), DLEM builds on the concept of plant functional types (PFT) to define vegetation

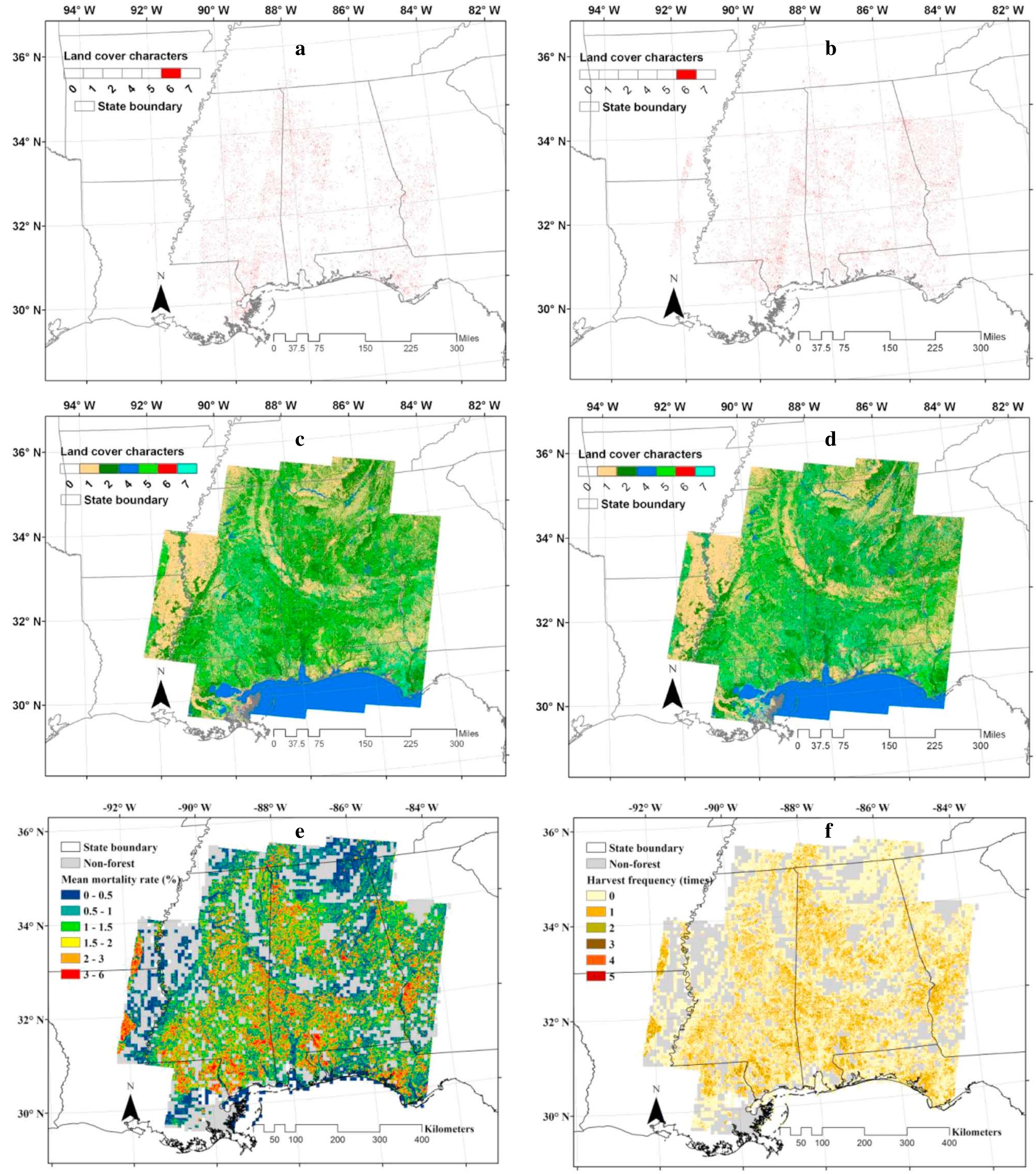

Figure 2. Forest disturbed areas (Red-colored areas) at 30 m resolution in (a) 1986 and (b) 2007 (including five scenes of images from 2005 and 2006) and other land cover characters in (c and d) the 2 years (1986 and 2007) based on classification of Landsat TM images [*Li et al*., 2009a, 2009b; *Huang et al*., 2009a, 2009b, 2010], as well as aggregated (e) mean annual mortality rate (%) and (f) disturbance frequency (times) at 1 km resolution. Note: Major categories of land cover characters include the following: 0—background area, 1—persisting nonforest, 2—persisting forest, 4—persisting water, 5—previously disturbed but looked like forest by this year, 6—disturbed in this year, and 7—post-disturbance nonforest.

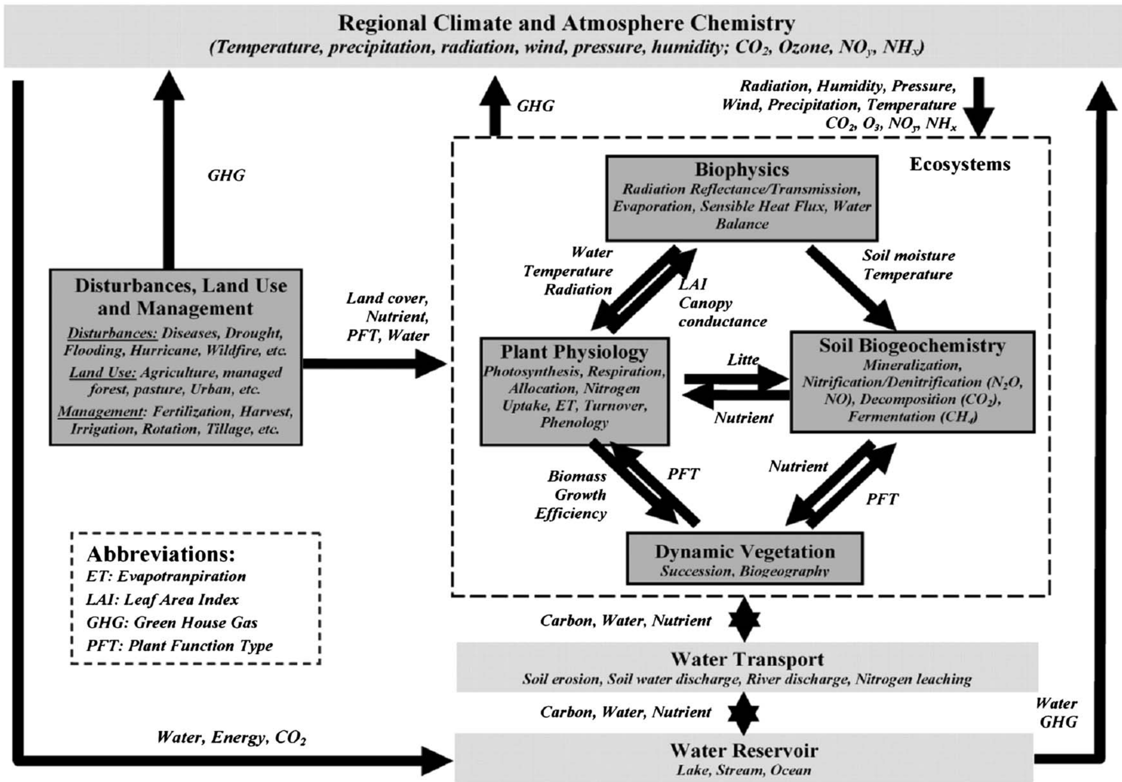

Figure 3. Framework of the dynamic land ecosystem model (DLEM). Note: ET: evapotranspiration; LAI: leaf area index; PFT: plant functional type [*Tian et al.*, 2010a, 2010b, 2011a, 2011b, 2012].

distributions. The disturbance, land use, and management component in DLEM simulates the impacts of anthropogenic and natural disturbance, land use change, and land management on C, N, and water cycles. We described the DLEM forest disturbance and management module in detail as follows.

2.3.1. Forest Management and Disturbance Module in DLEM

[11] In DLEM, we have developed a module for tracking impacts of forest management and disturbance. The C and N flows following forest disturbance are shown in Figure 4. After forest disturbance, parts of the biomass are removed from the ecosystem through slash burning and wood products, while others either enter into the litter pools [including slash, coarse woody debris (CWD), and residues after burning or wood processing] or become dead standing biomass. Some of the dead standing biomass will enter into the removed biomass through salvage harvest or litter pool through treefall. The removed biomass will be used as wood products or biofuel, which may partly replace fossil fuel as energy. There were four wood product pool groups: sawnwood, wood-based panels, paper/paper board, and others. These wood product pools are further classified as long-term (40 years half-life span), medium-term (10 years), and short-term (1 year) end-use products in terms of their decay rates. The end-use products will finally be recycled or enter into landfill or soil organic matter pools. The litter pool will be partly burned (i.e., site preparation) while the remaining enters into the soil organic matter pool through humification processes. The detailed C flows after forest disturbance are quantified as follows.

2.3.2. Biomass Losses Due to Forest Disturbance

[12] In this module, forest disturbance may be caused by both natural (i.e., wildfire, hurricane/storm, insect/disease, etc.) and anthropogenic (i.e., harvest, prescribed burning, etc.) events. Living forest biomass will be lost due to disturbance, with the impact level being dependent on the mortality rate and living biomass size:

$$DB_i = LB_i \times Mort_i. \quad (1)$$

where DB_i, LB_i, and $Mort_i$ are dead vegetation biomass

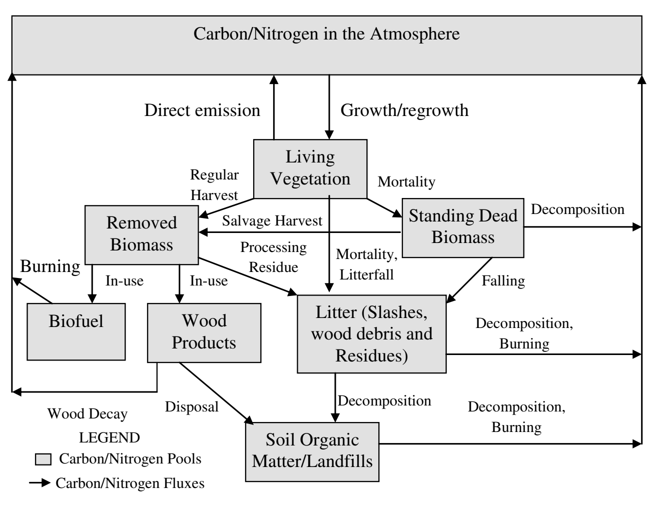

Figure 4. Carbon and nitrogen flows in DLEM forest management and disturbance module (CWD: coarse woody debris).

Table 1. Model Basic Parameters Related to the Disturbance Module in the Dynamic Land Ecosystem Model (DLEM)

Parameters	Description	Evergreen Needle Leaf Forest	Deciduous Broadleaf Forest	Units	References/Note
Vcmax25	The maximum rates of carboxylation at 25°C	33	40	μ mol m^{-2} s^{-1}	Calibrated
Dstart	Age when forest NPP decline starts	50	50	years	*Bellassen et al.* [2010]
Dend	Age when forest NPP decline ends	200	200	years	Calibrated
Dmax	Age-related maximum decline in photosynthesis rate	0.9	0.95		*Bellassen et al.* [2010]
CWD_fast	Proportion allocated to fast decomposition coarse woody debris pool	0.6	0.6		Calibrated[a]
CWD_slow	Proportion allocated to slow decomposition coarse woody debris pool	0.4	0.4		Calibrated
Agemax	Max stand age for obtaining random forest harvest and calculating natural mortality	300	300	years	*Pan et al.* [2011]
Midage	Forest canopy closure age or midrotation age	15	15	years	*Fox et al.* [2007]
Rotationage	Rotation age for plantation forest	35	50	years	*Foley* [2009]
Vegcmax	Maximum vegetation carbon after maturity	15,000	15,000	g C m^{-2}	*Smith et al.* [2006]
Mortmax	Maximum natural mortality rate for tree	0.04	0.03		*Smith et al.* [2009]
Ext_coef	Light extinction coefficient at canopy	0.5	0.5		*White et al.* [2000]
SLA	Specific leaf area	15	25	m^2 kg C^{-1}	*White et al.* [2000]
Salvrate[b]	Salvage logging after disturbance and harvest	0.6	0.6		*Smith et al.* [2006, 2009]
Alloc_root	Allocation of photosynthetic products to root	0.3	0.25		Calibrated
Alloc_stem	Allocation proportion to stem	0.4	0.4		Calibrated
Alloc_leaf	Allocation proportion to leaf	0.3	0.35		Calibrated

[a]These parameters are tuned to fit the inventory CWD and litter C data in 1997 from Forest Inventory and Analysis (FIA) [*Smith et al.*, 2009; *Birdsey and Lewis*, 2003].
[b]Salvage rate for stem alone. This value is an average over the harvest rates induced by both disturbance and regular harvest events according to the inventory data from FIA.

(g C/m^2), living vegetation biomass (g C/m^2), and mortality rate (%) for plant organ i (i.e., 1: leaf, 2: fine root, 3: coarse root, 4: stem), respectively. The remaining standing live biomass is calculated as the difference between the total and dead biomass.

2.3.3. Changes in Forest Structure and Recovery

[13] In DLEM, the magnitude of leaf area index (*LAI*) is dynamically simulated according to photosynthetic product allocation to the leaf, while the daily *LAI* pattern is controlled by the daily leaf phenology data averaged over 10-year Moderate Resolution Imaging Spectroradiometer (MODIS) *LAI* products. When forest mortality occurs, the canopy coverage (or crown density) and *LAI* will be changed in the meanwhile. The effect of disturbance on *LAI* is calculated as follows:

$$LAI = LAI_0 \times (1 - Mort_1). \tag{2}$$

where LAI_0 is the LAI before forest disturbance and $Mort_1$ is leaf mortality rate due to disturbance. The stand age was estimated using the following equations:

$$Age = INT(Age_0 \times (1 - Mort_4)). \tag{3}$$

where Age_0 is the overall forest age before disturbance, $Mort_4$ is the forest stem mortality rate due to disturbance, and *INT* is the function to round the age to the nearest integral value. If the existing fraction of stems after disturbance is less than 10% (default), this forest ecosystem will be restarted at forest age 0 with the forest type being the same as the previous one. Otherwise, forest age will be proportionally decreased with mortality rate.

[14] Changes in structure will in turn instantly influence canopy light and water interception, photosynthesis, litter quality, and thus ecosystem C, N, and water cycles. Except for instant impacts, the legacy effects (or footprints) of forest disturbance on C, N, and water cycles may last for a long period (e.g., 50 or 100 years) [*Houghton and Hackler*, 2000]. The LAI recovery after disturbance is estimated based on the DLEM allocation mechanisms for photosynthetic C products. The C allocation to different organs of tree is dynamically determined by the available water, light, and labile N (including N uptake from soil and labile/storage N within the tree). One of the advantages of a process-based model, such as DLEM, is its capability to dynamically track the footprints of disturbance effects and at the same time consider the interactive effects between forest disturbance and multiple environmental factors (e.g., land use change, climate change, changes in atmospheric composition).

Table 2. Parameters for the Fates of Different Tree Components After Tree Mortality

Tree Components	Fates[a] Removed Fraction	Slash Burning	Remaining on the Site
Leaf	0	0.4	0.6
Root	0	0.1	0.9
Stem[b]	0.6	0.1	0.3

[a]Source: Data are reorganized based on *Smith et al.* [2006, 2009].
[b]Stem includes branches, boles, and barks.

Table 3. Disposition Parameters for Harvested Softwood and Hardwood to Different Middle Uses

Products[a]	Logwood	Pulpwood	Fuelwood	Others	Processing Losses
Softwood	0.56	0.37	0.01	0.06	0.05
Hardwood	0.43	0.42	0.13	0.02	0.18

[a]Data source: Values for the south-central region in *Smith et al*. [2009].

2.3.4. Age-related NPP Decline and Forest Coverage

[15] Many observations and field experiments indicated that the net primary productivity (NPP) and gross primary productivity (GPP) may decline with increasing forest age [*Gower et al*., 1996; *Bellassen et al*., 2010]. In the DLEM management and disturbance module, we adopted the same modeling algorithms as the ORCHIDEE model [*Bellassen et al*., 2010] to simulate impacts of forest age on photosynthesis.

$$\textit{If Age} > D_{start} : \mathrm{V_{cmax}} = \mathrm{D_{factor}} \times \mathrm{V_{cmax0}}. \tag{4}$$

$$\mathrm{D_{factor}} = \max\left(\mathrm{D_{max}}, \frac{\mathrm{Age} - \mathrm{D_{start}}}{\mathrm{D_{end}} - \mathrm{D_{start}}}\right). \tag{5}$$

where V_{cmax} is the maximum rates of carboxylation, D_{factor} is the age-related decline factor for GPP, V_{cmax0} is the standard parameter value for V_{cmax}, *Age* is the age of the stand, D_{max} is the maximum age-related decline factor, D_{start} is the age at which age-related decline starts, and D_{end} is the age at which age-related decline ends. The parameter values are listed in Table 1.

[16] In addition to LAI, forest canopy coverage will also increase with forest age and arrives at maximum canopy coverage at the midrotation forest age [*Hurtt et al*., 2004]. The previous version of DLEM assumes that trees can use all the resources (e.g., light, water and nutrients) in a grid cell, which may be correct for a mature forest stand. However, during the recovery of disturbed forest stands, the regenerated trees can only use part of the available resources in a grid cell since the trees cannot occupy all the land area in a grid cell (i.e., large bare land without tree establishment) before a certain age. After the stand development arrives at a stage (e.g., midrotation age), the trees can occupy all the bare land area, and the resources become available for trees. Therefore, a scalar (*Forcov*; ranges from 0.1 to 1.0) is added in DLEM to constrain the resource use by forests. DLEM simulates changes in forest canopy coverage with age using a modified modeling mechanism from the ORCHIDEE model [*Bellassen et al*., 2010]:

$$\textit{Forcov} = \max\left(0.1, \min\left(\sqrt{\frac{\mathrm{Age}}{\mathrm{Midage}}}, 1\right)\right). \tag{6}$$

where 0.1 is a default minimum forest coverage (initial forest coverage), *Age* is the stand forest age, and *Midage* is the midrotation age for a specific PFT, at which the forest stand has the highest canopy density (can be adjusted for different PFTs) (Table 1).

2.3.5. Natural Mortality

[17] In addition to the mortality induced by disturbance, DLEM also calculates the natural/background forest turnover/mortality ($Mort_{nat}$) due to increasing forest age. The mortality induced by natural turnover is generally a small portion of the forest stand and thus is not monitored by the Landsat images, which is estimated with equation (7):

$$Mort_{nat} = 0.2 \times Mort_{max} \times \frac{1 - \frac{Veg_{max} - Veg}{Veg_{max} + Veg}}{365} + 0.8 \times Age \times \frac{1}{Age_{max}} \times Mort_{max} \times \frac{1 - \frac{Veg_{max} - Veg}{Veg_{max} + Veg}}{365}. \tag{7}$$

where $Mort_{max}$ is the maximum tree natural mortality rate (Table 1), Veg_{max} is the maximum vegetation C of a forest type, and *Veg* is the current vegetation C.

2.3.6. Disposition of Harvested Biomass

[18] The dead biomass will be partly removed from the local ecosystem by man (Figure 4). Removed biomass due to regular or salvage harvest is first allocated to three pools: slash, roundwood, and fuelwood. The roundwood will then be disposed to different wood product pools, the slash will be allocated to different litter pools, and fuelwood will be burnt as energy with C and N being emitted immediately into the atmosphere. The fuelwood may be used to replace fossil fuel as energy, thereby partially reducing C emissions from fossil fuel. The fates of wood products are tracked in detail in the DLEM wood products module, while the slash will be added into different existing litter pools as defined by DLEM (Figure 3):

$$\textit{When } 1 \le k \le 3, LT_{ijk} = \textstyle\sum_{i,j,k} HB_{ik} \times fLT_{ijk}. \tag{8}$$

$$\textit{When } k = 4, CWD = \textstyle\sum_{i,j,k} HB_{ik} \times fLT_{ijk}. \tag{9}$$

where *i* denotes the litter pool from two sources (1: aboveground litter, 2: belowground litter pool), *j* denotes the litter pools with different decomposition rate (1: labile, 2: middle, and 3: resistant litter pools), *k* denotes the disposition fraction of different components of removed tree biomass (1: leaf; 2: fine root; 3: coarse root; 4: stem) to litter pools with different decomposition rates, HB_{ik} is the disposition proportion of harvested biomass of component *k* to litter pool i, and

Table 4. Disposition Parameters for Harvested Biomass to Different Middle Product Uses

	Middle Product Uses[a]			
Materials	Sawnwood	Boards	Paper	Fuelwood
Logwood	0.8	0.15	0.05	0
Pulpwood	0	0.1	0.9	0
Removed slash	0	0	0	1

[a]Source: *Skog and Nicholson* [2000] and *Skog* [2008].

Table 5. Harvested Wood Disposition to Different Half-Life Span Product Pools[a]

Products	Long Term (40 years)	Medium Term (15 years)	Short Term (1 year)
Sawnwood	0.5	0.3	0.2
Boards wood	0.3	0.5	0.2
Paper and fuelwood	0	0.1	0.9

[a]Note: The disposition parameters were modified from *Schelhaas et al.* [2004] and *Skog* [2008].

Table 6. Disposition Parameters for the End Products

Products	Recycling	Energy	Landfill
Long term	0.1	0.8	0.1
Medium term	0.1	0.8	0.1
Short term	0.2	0.75	0.05

fLT_{ijk} is the total disposition proportion of organ k to below- and above-ground litter pool i with a different decomposition rate j.

[19] The DLEM classifies three types of litter pools in terms of decomposition rates: labile (decomposes very fast), middle (decomposes relatively fast), and resistant (decomposes slowly) litters. Leaves and fine roots are disposed to these three types of litter pools according to a fixed proportion, coarse roots are only disposed to middle and resistant pools, and stems (including branches) that are not disposed to product pools will be allocated to coarse woody debris (CWD). In DLEM, two types of CWD pools are further differentiated according to their decomposition rate: fast decomposing CWD (CWD_fast; including small size branches and barks) and slow decomposing CWD (CWD_slow; including boles and large size branches).

[20] The harvested roundwood will enter into different product pools:

$$PROD_{ij} = HB_{ij} \times (1 - fLT_i). \tag{10}$$

where $PROD_{ij}$ is the disposition of harvested tree organ i to product pool j (three half-life end-use product pools: long term, medium term, and short term), HB_{ij} is the disposition proportion of harvested biomass of component i to product pool j, and fLT_i is the total disposition proportion of organ i to litter pools.

2.3.7. The Life Cycle of Wood Products

[21] The products module of DLEM tracks the C and N fates after the removed biomass is disposed into product pools. This module was developed based on the CO2FIX Model [*Schelhaas et al.*, 2004] and the concept models of *Skog and Nicholson* [2000] and *Heath et al*. [2003]. In the same year as forest disturbance events take place, the wood products will be first disposed to different usages, then to corresponding end product pools, and finally, part of them will be released to the atmosphere. The product module distinguishes three categories of end products: long-term, medium-term, and short-term products. The wood product is distributed over these end product categories. When the end products are discarded at the end of their lifespan, they may be either recycled, or deposited in landfills, or used for energy [*Schelhaas et al.*, 2004].

[22] The half-life span could be different when used in different regions. Generally, the simple exponential decay function is used to track the decay processes of different end products (including end products at landfill and mill site) [*Skog and Nicholson*, 2000; *Schelhaas et al.*, 2004; *Heath et al*., 2003; *UN FCCC*, 2005].

$$P_{i,t+1} = P_{i,t} \times (1 - ln2 \div HL_i). \tag{11}$$

where $P_{i,t}$ is the amount of C or N in product types i at time t (years), $P_{i,t+1}$ is the amount of C or N in product types i at time $t+1$, and HL_i is the half life for product type i.

[23] The parameter values of roundwood dispositions to different middle wood products and end-use products are listed in Tables 2–6.

2.3.8. Site Preparation

[24] After harvest and before regeneration of new seedlings in many forests, the harvested sites will be prepared to establish new plant species. Slash burning, fertilization, and slash fragmentation are often used before new vegetation establishment. The C and N in the aboveground litter, soil organic matter, and even the belowground litter will be released to the soil or the atmosphere. Burnt C and N for different pools resulting from slash burning are calculated as follows:

$$BC_i = \textstyle\sum_{j=1}^{4} \left(LT_{ij} \times BR_{ij}\right). \tag{12}$$

$$BN_i = \textstyle\sum_{j=1}^{4} \left(LT_{ij} \times BR_{ij}\right). \tag{13}$$

$$BC = \textstyle\sum_{i=1}^{3} BC_i. \tag{14}$$

$$BN - \textstyle\sum_{i=1}^{3} BN_i. \tag{15}$$

where BC_i and BN_i are the burnt C and N from source i, respectively (three sources: aboveground litter, belowground litter, and SOM). LT_{ij} is the litter biomass for j litter pool subject to decomposition (four litter pools: CWD, labile litter, middle litter, and resistant litter pools). BR_{ij} is the burning intensity (percent of the burnt litter) for litter pool j. Litters include both previous litters on the forest floor or in the belowground soil and the slash left on the site after disturbance/harvest/thinning.

[25] Some of the burnt C and N can be released as trace gases (e.g., CH_4, CO_2, CO, N_2O, and NO) or returned back to the soil C and N pools through ash deposition. The

Table 7. The C and N Gas Emission Factors After Slash Burning for Forests[a]

Litters or Residues	C Gas Emission Factors After Burning				N Gas Emission Factors			
	E_{CO2}	E_{CH4}	E_{CO}	E_{NMHC}	E_{N2O}	E_{NOy}	E_{NH3}	E_{N2}
Hardwood	3484	10.7	236	12.7	0.26	3.0	1.4	3.1
Softwood	3484	10.7	236	12.7	0.26	3.0	1.4	3.1

[a]From *Andreae and Merlet* [2001].

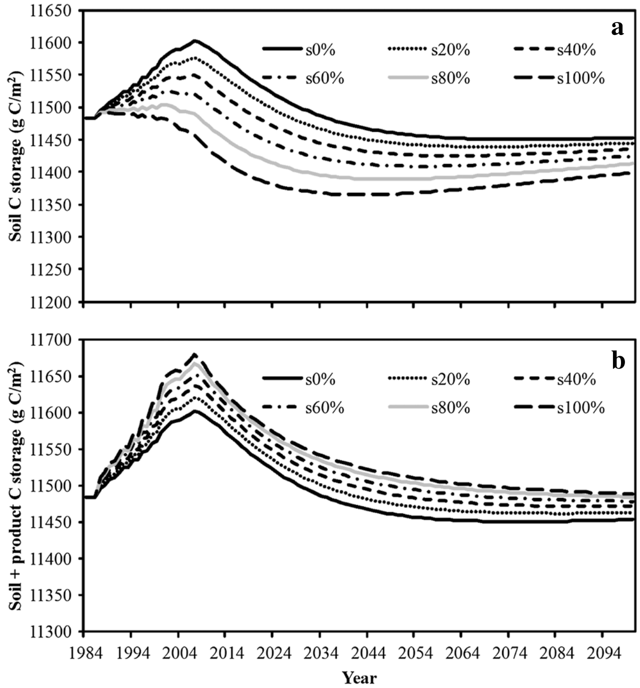

Figure 5. Sensitivities of (a) soil organic C storage and (b) soil + in-use product C pool to different wood salvage rates (i.e., salvage harvest after disturbances) after a disturbance event (50% mortality rate). Different wood salvage rates s0%, s20%, s40%, s60%, s80%, and s100% indicate that 0%, 20%, 40%, 60%, 80%, and 100% dead stems are removed as wood products after a disturbance event, respectively. The lower the wood salvage rate, the faster is the soil organic C to restore to its predisturbed status.

allocations of burnt C to different pools are calculated as [referenced from *Andreae and Merlet*, 2001]

$$BC_m = BC \times Em \times \frac{12}{W_m}. \quad (16)$$

$$BN_n = BC/0.45 \times E_n. \quad (17)$$

$$LEFTC = BC - \sum_{m=1}^{4} BC_m. \quad (18)$$

$$LEFT = BN - \sum_{n=1}^{4} BN_n. \quad (19)$$

where m is the C-related gas type emitted from slash burning (four types of C-related gases: 1, CO_2; 2, CH_4; 3, CO; and 4, NMHC); W_m is the molecular weight of C-related gas m; E_m is the C emission factor for species m (g kg^{-1} C); n is the N-related gas type from slash burning (four types: 1, N_2O; 2, NO_y; 3, NH_3; and 4, N_2); and E_n is the emission factor for N-related gas n. N-related gas emissions are related to the burnt dry matters (*BC*/0.45, DLEM assumes that C concentration in dry matter is 45%) as suggested by *Andreae and Merlet* [2001]; BC_m and BN_n are released C and N for gas types m and n, respectively; *LEFTC* and *LEFTN* are C and N that have not been emitted into the atmosphere but return to the soil or litter pools. *LEFTC* will enter the resistant litter C pool, while *LEFTN* will enter the soil available N pools.

[26] The N that has not been emitted as N gases (*LEFTN*) returns to the soil as ashes with a format of NH_4-N. Therefore, the soil available N pools are changed to the following:

$$AV_{NH4}+ = LEFTN. \quad (20)$$

where AV_{NH4} is the soil available NH_4-N. According to this equation, site preparation will cause a sudden increase in soil available N. However, due to lower vegetation coverage, higher leaching, and accelerated N immobilization due to increased litter inputs, soil available N may decrease soon.

[27] The parameter values related to site preparation were listed in Table 7.

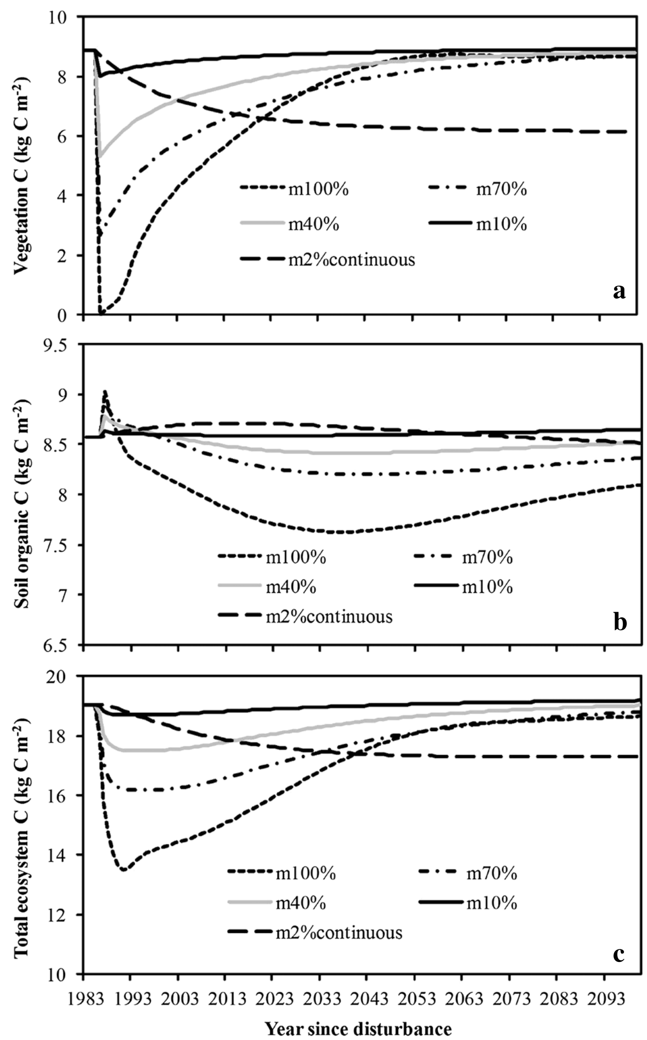

Figure 6. Sensitivities of (a) ecosystem vegetation C, (b) soil organic C, and (c) total C (i.e., soil organic C + vegetation C + litter C + in-use product C) to different disturbance rates. Disturbance rates m10%, m40%, m70%, m100%, and m2%continuous indicate 10%, 40%, 70%, 100% (only one time in 1986), and 2% (per year since 1986) mortality rates, respectively.

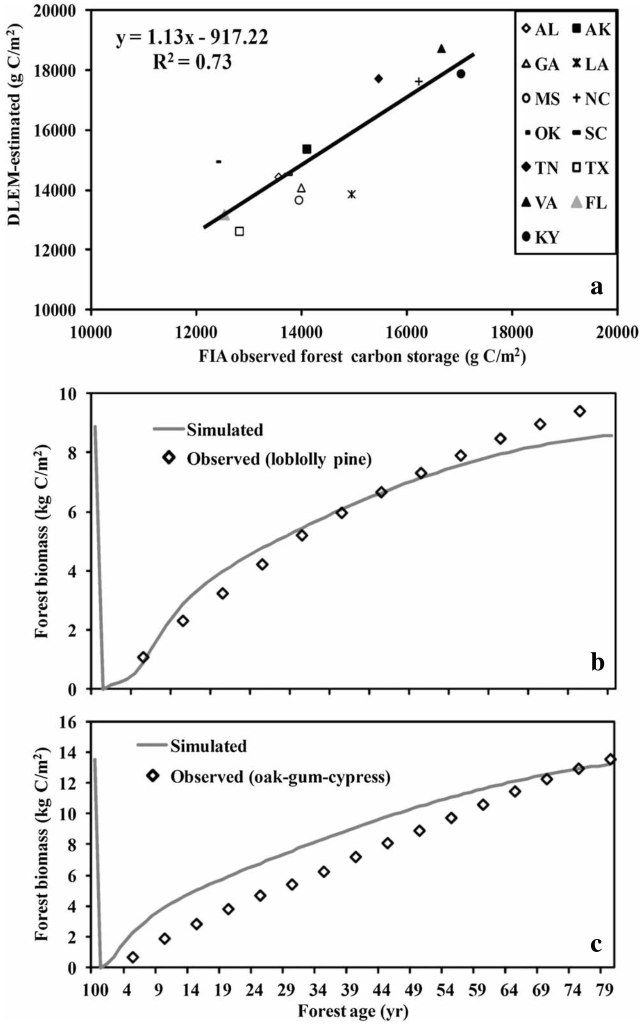

Figure 7. Model performance evaluations for estimating (a) state-level forest C storage (observational data from *Birdsey and Lewis* [2003]) and species-level (b) Loblolly and shortleaf pine and (c) oak-gum-cypress (observation *data from Smith et al.* [2006]) biomass accumulation with stand age after disturbance.

2.4. Model Sensitivity to Forest Disturbance

[28] To evaluate the model behaviors to forest disturbance, model sensitivity to key variables was tested. The two most important variables were selected: wood salvage rate after disturbance and forest disturbance rate.

2.4.1. Sensitivity to Wood Harvest/Salvage Rates

[29] Wood salvage (i.e., the disposition proportion of harvested biomass to different wood products) rates after forest disturbance could greatly influence forest floor litter C and soil C. Six levels of wood salvage rates (i.e., 0%, 20%, 40%, 60%, 80%, and 100%) were designed to evaluate model sensitivity to wood salvage harvest. Under all salvage rates, soil C increased right after a disturbance event (50% mortality rate) and then soon decreased (Figure 5a). After a certain time span, soil organic C began to increase. This time span for soil C recovery was influenced by wood salvage rates. The less wood salvage, the faster the restoration of the soil C to predisturbance level. However, combining total C storage in soil and wood products, higher wood salvage rates could maintain forest sector C stock for a longer period and even elevate it (Figure 5b). This is because products decay more slowly than the effective average turnover time for C molecules in the forest.

2.4.2. Sensitivity to Mortality Rates

[30] Forest disturbance, such as partial harvest, hurricane, and insect disturbance, can cause partial tree mortality in a stand. To test DLEM sensitivity to different mortality rates and frequency at stand level, five forest mortality rates were designed: 10%, 40%, 70%, 100% (only once), and continuous 2% (2% mortality per year). The results indicated that vegetation C gradually recovered to its predisturbance level, and recovery rate was faster for smaller disturbance rates (Figure 6a); however, if repeated disturbance occurred (e.g., 2% mortality per year), vegetation was not able to recover to its predisturbed level in the short term, implying that repeating disturbance events could result in more C losses in vegetation in the long term. Soil C storage decreased faster for higher disturbance rates and took longer to recover (Figure 6b). One-time smaller disturbance events (e.g., 10%) did not significantly change total ecosystem C storage, while higher disturbance rates could significantly decrease total ecosystem C storage. Even after as long as 100 years, the clear-cut forests could not recover to its predisturbed level. Consecutive partial disturbance events could reduce ecosystem C storage more than that of a 100% one-time disturbance rate (Figure 6c), suggesting that repeated disturbance events on stand scale could result in larger C emissions and thus should not be ignored in simulating ecosystem C storage. The repeating repeated disturbance events caused the forests to reach a quasi-static status with relatively lower total C storage in the long term.

2.5. Model Evaluation

[31] The DLEM-simulated net carbon exchange (NCE) rate, C stocks, and GPP for different types of forests with various stand ages have been compared to multimodel simulations and observational data in North America [see *Schwalm et al.*, 2010; *Sulman et al.*, 2012; *Huntzinger et al.*, 2012; *Schaefer et al.*, 2012; *Tian et al.*, 2010a, 2010b, 2012; *Zhang et al.*, 2010; *Chen et al.*, 2012] and China [*Tian et al.*, 2011a, 2011b; *Ren et al.*, 2011; *Lu et al.*, 2012]. These previous evaluations indicated that DLEM could better model the daily, seasonal, and interannual patterns of ecosystem GPP and NPP dynamics but slightly underestimated the net ecosystem production

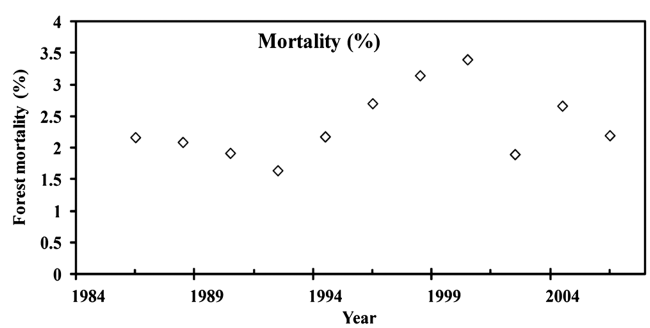

Figure 8. Mean forest disturbance rate (%) for Alabama and Mississippi during 1984–2007.

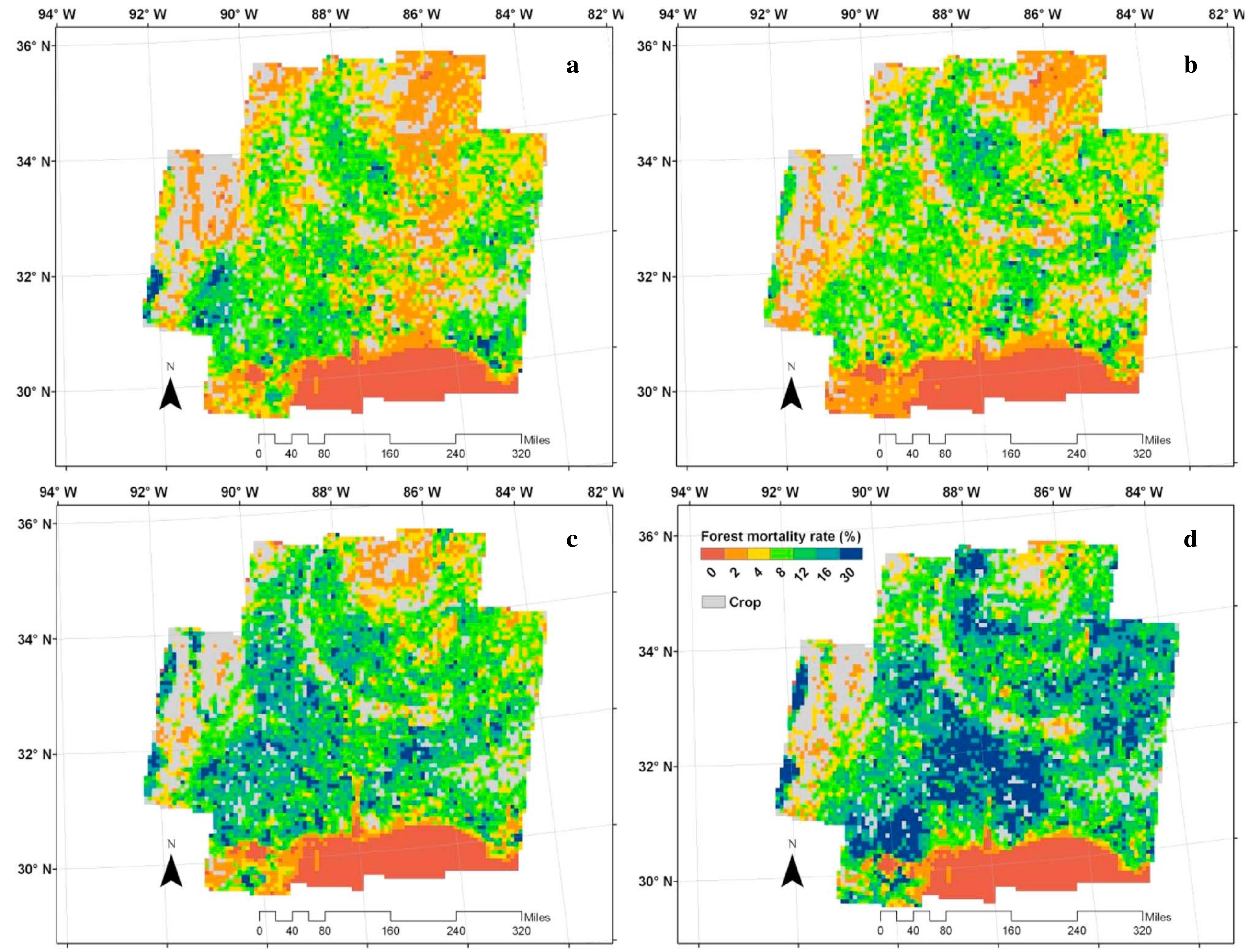

Figure 9. Spatial distribution of forest mortality rate (%) for different periods during 1985–2007: (a) 1985–1989, (b) 1990–1994, (c) 1995–1999, and (d) 2000–2007.

(NEP) as compared to site and regional observations. During these site simulations, DLEM did not use the disturbance information as input, which may be one of the reasons for lower NEP. In this study, we further evaluated DLEM-simulated state-level total forest C storage (vegetation + soil + litter C) in 1997 with the observational data from FIA [*Birdsey and Lewis*, 2003] for the southern United States (see Figure 7a). The results indicate that DLEM well matched (slope = 1.13; $R^2 = 0.73$; $P < 0.01$) the state-level forest ecosystem C storage in the southern United States but slightly underestimated this for Mississippi. Based on the inventory data from *Smith et al*. [2006], we evaluated DLEM-simulated forest biomass accumulation with stand ages for evergreen needleleaf forest (loblolly and shortleaf pines, two major pine species in the region) and deciduous broadleaf forest (Oak-gum-cypress). The comparison indicated that DLEM could capture (slope = 1.103, $R^2 = 0.98$ for pine forest; slope = 1.19, $R^2 = 0.98$ for broadleaf forest; $P < 0.01$) the annual accumulation pattern for biomass after clear-cut harvests (Figures 7b and 7c). DLEM simulation tend to bias more compared to observed biomass after tree maturity (i.e., after 50 years for pine and 70 years for broadleaf forests), which might be because of the model mechanisms for increasing natural turnover rate and declining NPP with stand age in DLEM. This suggested that current model mechanisms might slightly underestimate C storage for old growth forests. The FIA-observed [*Smith et al*., 2006] forest biomass relationships with stand age were based on stands at different locations and using the method of space-for-time substitution, which might also result in some uncertainties. Nonetheless, the model evaluation, although not very thorough, does lend confidence to its utility for C balance assessments as reported in this work.

2.6. Model Parameterization, Initialization, and Simulation Experiments

[32] Before running DLEM, the parameters related to the forest management and disturbance module were calibrated against field measurement or observational data for each forest type in Mississippi and Alabama (see Tables 1–7). The major forest types in this region include temperate needleleaf evergreen forest (TNEF), temperate broadleaf deciduous forest (TBDF), mixed needleleaf and deciduous forest (MF), and forested wetland (Figure 1). We further classified all four types of forests into two groups (i.e., TNEF/softwood and TBDF/hardwood) for the disturbance-specific calibration. DLEM was first run to an equilibrium state using 30 year mean (1895–1924) climate data and other

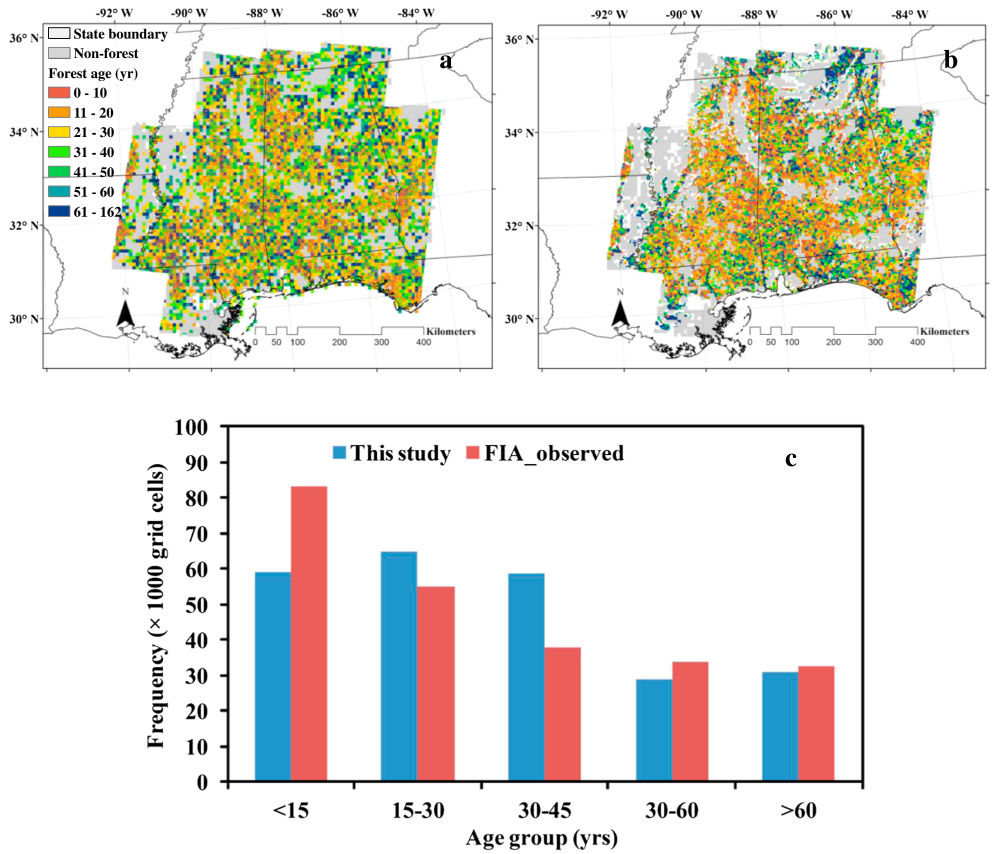

Figure 10. (a) Simulated (unit: years) and FIA observed [*Pan et al.*, 2011a] (b) forest age structure and (c) frequency distributions (unit: grid cell numbers) in 2002 at a spatial resolution of 1 km.

input data (i.e., land use, N deposition, and atmospheric CO_2 concentration) in 1895 to develop the simulation baseline for C, N, and water pools. Then, a 90 year spin-up simulation was conducted using the detrended climate data to stabilize unusual fluctuations caused by simulation mode shifts from equilibrium to transient. Due to lack of forest disturbance information before 1984, we used the average forest rotation age (50 years for TBDF and 40 years for TNEF according to *Winjum and Lewis* [1993] and *Foley* [2009]) to clear-cut all forest in each grid cell. A random scheme was implemented to select grid cells for harvest during 1895–1984. After 1984, the random harvest scheme was closed and replaced by the transient forest mortality data.

[33] For model transient runs during 1984–2007, three simulation experiments were designed to achieve the objectives: (a) no forest disturbance—only transient environmental data (i.e., nitrogen deposition, climate, and atmospheric CO_2 concentration) drive the model, while keeping other input data as constants; (b) forest disturbance and environment—both transient environmental data and forest mortality data were used to drive the model, while keeping other input data as constants; and (c) forest disturbance only—only transient forest mortality data were used, while average environmental data in 1984 was used and kept constant during

Table 8. Changes in Different C Pools Caused by Forest Disturbance in Alabama and Mississippi From 1983 to 2007 (Tg C, 1 Tg = 10^{12} g)

Carbon Pools	Litter C	SOC	Vegetation C	Product C	Total
1984	260.51	2362.08	1765.62	423.48	4811.69
2007	265.84	2380.10	1510.63	516.20	4672.77
2060	254.67	2357.70	1755.13	447.14	4814.64
Difference	5.33	18.02	−255.00	92.73	−138.92
(2007–1984)	(2.04%[a])	(0.76%)	(−14.44%)	(21.90%)	(−2.89%)
Difference	−5.84	−4.38	−10.50	23.66	11.59
(2060–1984)	(−2.24%)	(−0.19%)	(−0.59%)	(5.59%)	(−0.79%)

[a]Change rate compared to C pools in 1984.

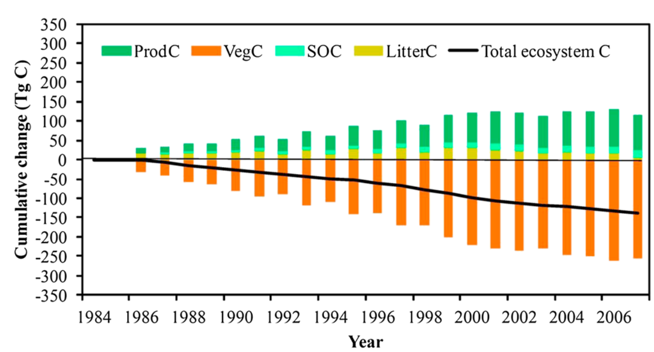

Figure 11. Changes in different C storage pools (Tg C, 1 Tg = 10^{12} g) caused by forest disturbance in Alabama and Mississippi from 1984 to 2007. Positive values indicate a C sink, whereas negative values indicate a C source. ProdC: Wood product C; VegC: Living vegetation C; SOC: soil organic C; LitterC: litter C including fine litters and coarse woody debris (CWD).

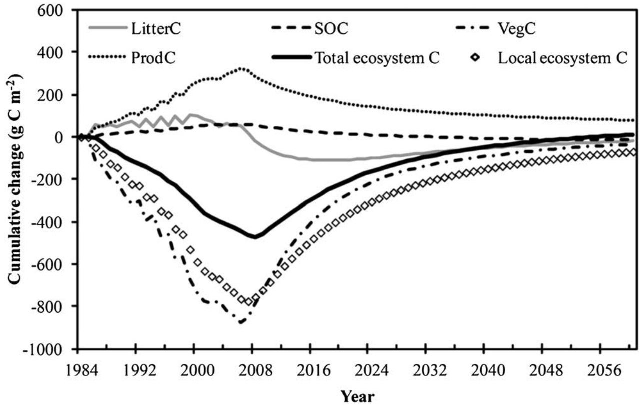

Figure 12. Legacy effects of forest disturbance on different C pools (g C/m^2) in Mississippi and Alabama. Note: Total ecosystem C includes vegetation, litter, soil organic, and in-use wood product C, while local ecosystem C excludes wood product C. We assume that no forest disturbance occurred after 2007.

the simulation period. The difference between these two simulation experiments (b – a) was the effects of forest disturbance on C fluxes. Experiment c (i.e., forest disturbance only) was used to represent the C pools under the influence of disturbance alone.

3. Results and Analyses

3.1. Forest Mortality Rate and Resultant Forest Age During 1984–2007

[34] Annual mean forest mortality rate induced by disturbance was about 2.37% in Alabama and Mississippi, and the highest was 3.40% during 1999–2000 (Figure 8). Forest mortality showed an increasing trend from 1980s to 2000s, indicating that forest disturbance accelerated during the recent period. At the spatial scale, the highest mortality was seen in the coastal area, with smaller disturbance in the north of the study region (Figure 9). The maximum forest mortality rate occurred during the period of 2000–2007, which could be upward to 50% in some areas. The study region is located in the Gulf of Mexico and suffers from severe impacts of hurricanes and storms, such as Hurricane Ivan in 2004 and Hurricane Katrina in 2005, causing tremendous forest mortality during this period.

[35] The disturbance events created fragmented landscapes and thus a complex forest age structure in Alabama and Mississippi (Figure 10). The oldest forest stands (>60 years) were generally located in the northern region (Figure 10a). Age for most forests was less than 15 years and showed a decreasing tendency in distribution frequency with increasing forest age (Figure 10c). The spatial and frequency distribution patterns of forest age derived from Landsat TM/ETM$^+$ disturbance data were generally consistent with FIA-observed forest age [*Pan et al.*, 2011a] in the study region (Figures 10b and 10c). Less younger (i.e., 0–15 years old) forest stands but more older (i.e., >15 years old) forest stands were estimated using the disturbance data.

3.2. Changes in C Storage Following Disturbance

[36] All the forest disturbance events totally resulted in C emission of 138.92 Tg (6.04 Tg C yr^{-1}, Table 8; 1 Tg = 10^{12} g) during 1985–2007, which was about 2.89% of the total forest C storage in 1984 (predisturbed year). If product C is disregarded (since it is removed from the local ecosystem), the total C storage in the forest ecosystem decreased by 231.65 Tg C (10.07 Tg C yr^{-1}), accounting for 4.81% of the total ecosystem C storage. From 1985 to 2007, in-use wood product, soil, and litter (including both below- and above-ground litter) C continuously increased, while vegetation C continuously decreased (Figure 11). Among four C pools, wood product, soil, and litter C pools were C sinks of 92.73, 18.02, and 5.33 Tg, respectively. Vegetation C pool was a C source of 255.0 Tg during 1984–2007 (Table 8). Wood product became the largest C sink under the impacts of forest disturbance, implying a significant role of wood salvage in preserving ecosystem C storage after forest disturbance events. The results indicate that disturbance events had much larger negative effects on forest biomass compared to other C pools.

3.3. Legacy Effects of Forest Disturbance

[37] Forest disturbance may have a strong legacy effect on the forest ecosystem C dynamics due to its long-term impacts on forest structure, C allocation, and nutrient cycles. In this study, a "what-if" simulation experiment was designed to assess the legacy effect of disturbance events on forest C storage. The results indicate that soil organic C, litter C, and in-use wood product C pools will become C sources, while vegetation C will increase quickly after disturbance events stopped (Figure 12). The cumulative changes of soil C storage from 1984 to 2060 is a small C source (14.68 g C/m^2), indicating that disturbance first increases C storage but will decrease it in the long term. Vegetation C pool could only recover to ~94% of the predisturbed level (1984) even after disturbance events stop for 53 years (2060). It is notable that litter C pool recovered very slowly, and it is a C source during 1984–2060. Adding up all four C pools, forest ecosystems in this region will be a small C sink (9.88 g C/m^2) after ~50 years, mainly owing to the increased wood product C; however, if only accounting for local ecosystem C storage (no wood product C), the forest ecosystems will still be a C source (69.36 g C/m^2), indicating a long-term legacy effect or recovery trajectory after forest disturbance, especially for vegetation C.

3.4. Spatial Heterogeneity in C Fluxes Caused by Forest Disturbance

[38] The mean annual mortality rate induced by forest disturbance varied spatially and temporally (Figures 9, 2e, and 2f), resulting in a large spatial variation in total net C exchange during 1984–2007. Generally, higher forest mortality resulted in larger C emission. The cumulative C emission in some 8 km resolution grid cells could be up to 1900 g m^{-2}, which means that about 13% of the total ecosystem C storage (i.e., biomass + litter + soil C pools) was released to the atmosphere during the past 23 years. The largest releases of C occurred in the southern coastal region, where both forest harvest and hurricane events occurred frequently, and the least in the northern Alabama area, where the major disturbance was forest harvest (Figure 13b). Carbon sinks were found in some areas of the north if the wood product C pool is considered as a component of local forest ecosystem C storage (Figure 13a), while most areas were C sources

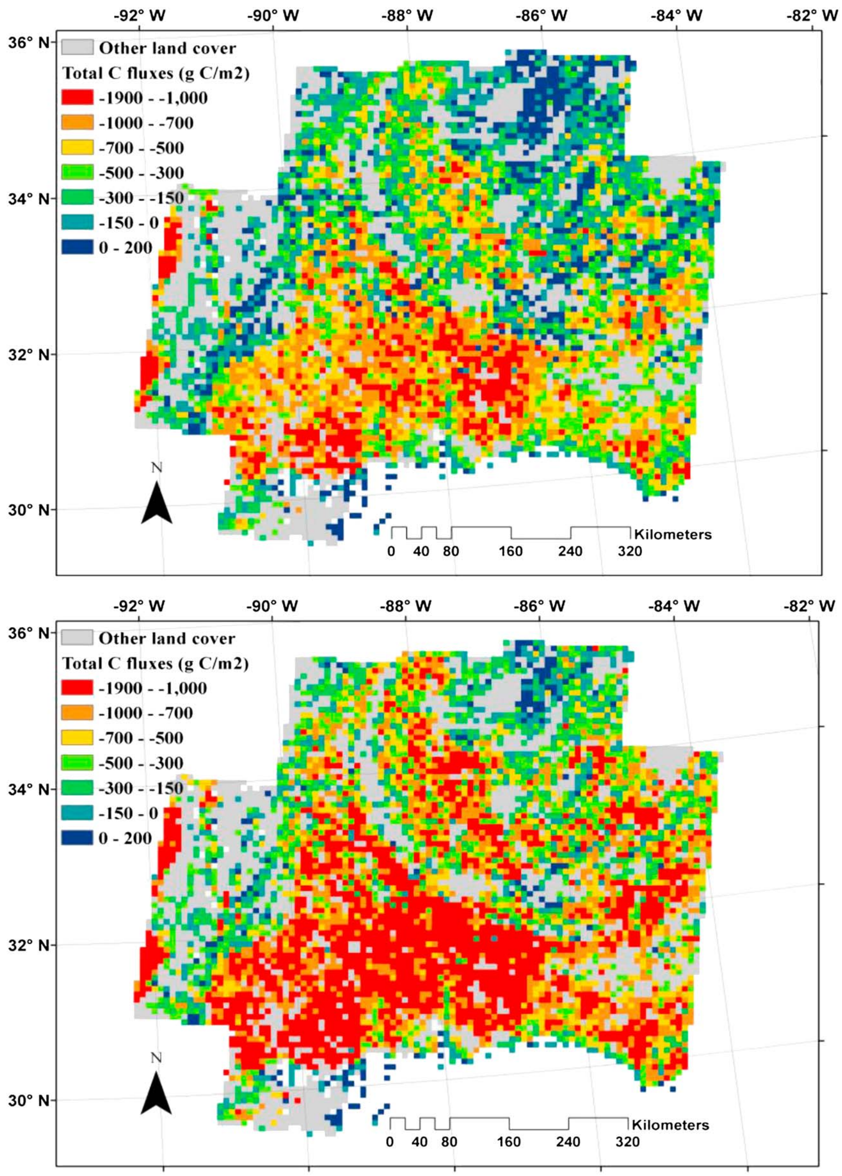

Figure 13. Accumulated net carbon exchange (negative indicates C source, g C m^{-2}) (a) with and (b) without wood product C at a spatial resolution of 8 km in Mississippi and Alabama during 1984–2007.

without wood product C pool (Figure 13b). Comparing Figures 13a and 13b with disturbance intensity data (Figures 2e and 2f), we generally found that the higher mortality rate induced more C emission, which further implied that the forest ecosystem C could not be recovered in the short term especially after consecutive forest disturbance events.

4. Discussion

4.1. Long-term Disturbance Events and Forest C Dynamics

[39] Due to lack of high resolution data, it is difficult to study the impacts of forest disturbance on C fluxes at a large scale. However, many researchers have recognized the important role of local-scale disturbance in C fluxes [e.g., *Woodbury et al.*, 2007; *Goward*, 2004; *Birdsey et al.*, 2006; *Pan et al.*, 2011b]. On a large scale such as national or continental, forest disturbance is generally assumed to occur to a large extent and has a long returning interval (e.g., 20 or 30 years), but under most situations, forest disturbance may frequently occur on a local scale, with only a small part of the forest ecosystem that is disturbed. So generally, model simulations with aggregated large-scale forest disturbance data could either underestimate or overestimate C fluxes. The USDA Forest Resource Assessment [*Smith et al.*, 2006, 2009] estimated that the annual timberland harvest proportion was about 3% during 1980–1990 in the south-central United States. If this is transformed to forestland (timberland accounts for about two thirds of forestland; http://www.fs.fed.us/pl/rpa/timber89.htm), about 2% proportion of forests were harvested, which is slightly lower than our reported forest mortality rate (2.37%) in Alabama and Mississippi. Other types of forest disturbance (e.g., fire and hurricane) might explain this difference.

[40] Our estimation found that long-term disturbance events in Mississippi and Alabama could result in a C source

of 231.65 Tg or 10.07 Tg yr^{-1}(without wood products). Based on the USDA Forest Service inventory biomass data, *Han et al*. [2007] estimated that annual forest biomass C sink in Mississippi and Alabama was 16.5 Tg C yr^{-1} during recent years. This implied that forest disturbance had largely reduced forest biomass accumulation rate in these states. We also found that in-use wood product was the largest C pool after disturbance. In some areas of the northern Alabama and Mississippi, disturbance (primarily forest harvest) could result in a C sink if the wood product C was regarded as one of the local ecosystem C pools due to the slow decay rate and long residence of wood product C pool. This implied that wood product C pool should be taken into consideration to make a full accounting in forest C cycles. *Heath et al*. [1996] also noted that wood products should be included in C budgets for the U.S. because this component is significant compared to U.S. forest ecosystem flux estimates.

[41] The forest ecosystems in the United States were reported as a C sink ~0.20 Pg yr^{-1} in recent decades [*Pacala et al*., 2001; *Xiao et al*., 2011; *Pan et al*., 2011a]. If forest disturbance effects were removed, this C sink could be significantly larger [*Williams et al*., 2012]. FAO report [2006] estimated that 104 million ha per year of the world's forests, or 3% of the total area, were disturbed each year by fire, pests, and weather; however, this was a significant underestimate of the disturbance rate because of incomplete reporting by countries. This suggested that accurate estimation of disturbance effects on regional scales could be of importance for accurately estimating C budgets in the United States and globe [*Zheng et al*., 2011; *Pan et al*., 2011a; *Liu*, 2011].

4.2. Changes in C Pools and Legacy Effects Following Forest Disturbance

[42] Forest disturbance (including harvest) could have a strong legacy effect on forest ecosystem C, water, and N dynamics. Since biomass increases with stand age, postponing disturbance to the age of biological maturity may result in the formation of a larger C sink [*Alexandrov and Yamagata*, 2002]. Although productivity could increase due to higher regrowth rate of young forests, forest biomass had greatly decreased after disturbance in Mississippi and Alabama during 1985–2007. A long-term legacy effect following disturbance was also found, especially for forest biomass (even 50 years after a disturbance event), indicating the system could not fully recover to predisturbed levels in the short term.

[43] Through collection of a large number of field experiment data, *Johnson* [1992] and *Johnson and Curtis* [2001] conducted a meta-analysis to further evaluate the relationships between forest harvest and soil C storage. They concluded that soil C could either decrease or increase after forest harvest depending on the harvest intensity and regimes. *Yanai et al*. [2003] revisited the Covington's curve (i.e., forest floor mass declined sharply following harvest, with 50% of forest floor organic matter lost in the first 20 years [*Covington*, 1981]) and the relationships found from *Johnson and Curtis* [2001]. They concluded that forest harvest has a much smaller effect on forest floor and soil C pools than was predicted from early interpretations of Covington's curve. Through analyzing a large collection of observational data from 432 sites in the temperate climatic zone, *Nave et al*. [2010] also pointed out that soil C was not significantly changed after harvesting, while forest floor litter C could be reduced more. In this study, we noted that there was a negligible forest soil C increase of 18.02 Tg C (by 0.76%) resulting from long-term forest disturbance during 1985–2007. This was mainly because of increased litter inputs at the forest floor during a disturbance event and faster litter decomposition due to opening canopy (Figure 12). After a forest disturbance event, litter C was soon depleted and needed a long time to recover, which resulted in decreased soil C storage from 2007 to 2060. This means that soil C may increase in the short term after disturbance events but eventually decrease in the long-term period. We also found that litter C storage (by 4.19%) reduced faster than soil C storage (by 0.94%) from 2007 to 2060.

[44] The different patterns of C pool changes during and after disturbance implied that a static or statistical approach [e.g., *Johnson and Curtis*, 2001; *Yanai et al*., 2003; *Thiffault et al*., 2011], which statistically estimates the changes in different C pools, may not accurately track the C dynamics after disturbance. Reports [e.g., *Xiao et al*., 2011; *Pan et al*., 2011a] showed that the current U.S. forest C sink (~0.2 Pg /yr) was primarily distributed in the southern forests based on static estimation approaches. These studies might overestimate this C sink since in-use forest wood products and long-term disturbance legacy effects were not accounted for in their analyses. Based on long-term model input data, *Tian et al*. [2012] estimated that the southern United States was a larger C sink during recent decades but only a slight C sink in the long-term period (i.e., 1895–2007). It is necessary to dynamically monitor long-term changes in forest structure, C, N, and water cycles.

4.3. Uncertainties and Future Research

[45] Currently, it is still a great challenge to accurately assess disturbance impacts on forest C budgets [*Pan et al*., 2011b]. Two major uncertainties exist: disturbance data accuracy and representative modeling algorithms [*Liu*, 2011]. In this study, the use of ~30 m high-resolution forest mortality data as classified from Landsat TM images could ensure a relatively high input data accuracy. In addition, the DLEM model used in this study has fully coupled ecosystem-level C, water, and N cycles, and a full tracking module for C budget after forest disturbance, which improves the assessment accuracy for disturbance impacts. However, many uncertainties still exist. For example, DLEM assumes trees will regenerate right after a disturbance event and no competition among different biomes during forest succession. Further improvements will be made for this modeling algorithm. In addition, the disposition parameters were assigned based on average conditions in the southern United States for different wood product pools (e.g., 1, 15, and 40 year half-life wood products and landfill), wood product salvage rates, and site preparation intensity (e.g., slash burning portion). Due to lack of enough information, we are unable to separate forest mortality induced by forest harvest from other natural disturbance events (e.g., hurricane, storm, and fire). Instead, we used average parameters for harvested forest biomass allocation and site preparation, which could result in some uncertainties since managed forest accounts for about 20% in this region [*Smith et al*., 2009].

5. Conclusions

[46] Based on high-resolution forest mortality rate data and a process-based biogeochemical model, this study estimated the C storage changes in Mississippi and Alabama following long-term forest disturbance events. Forest disturbance caused large C emission during 1985–2007, which is comparable to the previously reported forest C sink in this region. Litter, soil, and in-use wood product C pools were C sinks during forest disturbance events; however, this effect was negated by more decreases in vegetation C. Due to legacy effect after disturbance events, forest ecosystems need a long period to recover; however, forest disturbance might also result in a C sink in some areas if wood product C pool is considered as a component of local ecosystem C storage due to long residence time of wood product C. Forest ecosystems in the United States were reported as a large C sink during the recent decade; however, forest disturbance may have greatly reduced this C sink size. To accurately assess long-term regional C budgets, it is necessary to estimate the impacts of forest disturbance using a dynamic modeling approach, which fully couples water, C, and N cycles.

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