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Land use and carbon dynamics in the southeastern United States from 1992 to 2050

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Abstract

Land use and land cover change (LUCC) plays an important role in determining the spatial distribution, magnitude, and temporal change of terrestrial carbon sources and sinks. However, the impacts of LUCC are not well understood and quantified over large areas. The goal of this study was to quantify the spatial and temporal patterns of carbon dynamics in various terrestrial ecosystems in the southeastern United States from 1992 to 2050 using a process-based modeling system and then to investigate the impacts of LUCC. Spatial LUCC information was reconstructed and projected using the FOREcasting SCEnarios of future land cover (FORE-SCE) model according to information derived from Landsat observations and other sources. Results indicated that urban expansion (from 3.7% in 1992 to 9.2% in 2050) was expected to be the primary driver for other land cover changes in the region, leading to various declines in forest, cropland, and hay/pasture. The region was projected to be a carbon sink of 60.4 gC m^{-2} yr^{-1} on average during the study period, primarily due to the legacy impacts of large-scale conversion of cropland to forest that happened since the 1950s. Nevertheless, the regional carbon sequestration rate was expected to decline because of the slowing down of carbon accumulation in aging forests and the decline of forest area.

Keywords: land use and land cover change (LUCC), carbon fluxes, carbon stocks, carbon sequestration, process-based ecosystem model

1. Introduction

There is a widespread consensus that terrestrial ecosystems play a key role in sequestering anthropogenic CO_2 emissions and mitigating global climate change (e.g., Pacala *et al* 2001, Janssens *et al* 2003, Piao *et al* 2009), and the magnitude of terrestrial carbon sink has been weakening at least since 2000 (Denman *et al* 2007, Canadell *et al* 2007, Houghton 2007, Le Quéré *et al* 2009). However, the regional patterns, magnitude, and driving mechanisms of terrestrial carbon sinks and sources are uncertain and likely vary across regions. There are large uncertainties in the estimates of carbon fluxes in and out of terrestrial ecosystems, and land use and land cover change (LUCC) is one of the main contributors (Canadell 2002, Ramankutty *et al* 2007, Houghton 2010, Liu *et al* 2011b, Baccini *et al* 2012). Understanding LUCC-induced carbon exchange between the terrestrial biosphere and the atmosphere is critical for more accurate estimates of regional carbon budgets, which can provide helpful information for policy and management implementation to mitigate climate change (Canadell *et al* 2007, Stone 2009). Unfortunately, the lack of detailed LUCC databases (e.g., 250 m or higher resolution) and appropriate models capable of dynamically assimilating LUCC information into simulations over large areas make quantifying the net flux of carbon between the terrestrial biosphere and the atmosphere induced by LUCC a challenge (Strassmann *et al* 2008, Zhao *et al* 2009, 2010a, 2010b).

Land cover and land use in the southeastern United States have experienced rapid changes since the 17th century (Delcourt and Harris 1980, Hansen *et al* 2010, Sleeter *et al* 2012). Earlier studies have indicated that LUCC plays a critical role in controlling ecosystem carbon balance in the region (Delcourt and Harris 1980, Liu *et al* 2004a, Binford *et al* 2006, Zhao *et al* 2010b, Tian *et al* 2012). However, most of these earlier studies lacked detailed treatment on LUCC. For example, Tian *et al* (2012) recently put together an excellent effort in quantifying the carbon dynamics in the southern United States from 1895 to 2007. Still, their model simulations were performed with a pixel size of 8 km × 8 km, and forest management practices such as timber harvesting were not considered. After quantifying carbon dynamics in four counties in the southeastern United States with detailed LUCC information, Zhao *et al* (2010a) found a threshold of 1 km for characterizing LUCC, and LUCC information at coarser spatial resolution introduced significant biases to the estimated carbon balance, its interannual variability and spatial patterns, and attribution of driving forces.

The goal of this study was to quantify the spatial and temporal changes of carbon dynamics in terrestrial ecosystems in the southeastern United States from 1992 to 2050 and to assess the carbon sequestration capacity and the impacts of LUCC. We first constructed a consistent historical and future LUCC database that described the yearly dynamics of LUCC in the southeastern United States from 1992 to 2050 at 250 m resolution using a combination of remote sensing and modeling approaches. Then, a biogeochemical model used this LUCC information to simulate the spatiotemporal changes of ecosystem carbon balance. Finally, the impacts of LUCC (e.g., urbanization, forest clearcutting) on carbon dynamics and sequestration were analyzed.

2. Study area and methods

2.1. Study area

The study area covers 1247 034 km^2 of the southeastern United States, including all or portions of 13 states (figure 1). The region has high potential productivity and favorable climatic conditions that range from a temperate subtropical climate in the north to a warm humid tropical climate in the south. In 2012, the landscape consisted of 48% forest, 24% cropland and hay/pasture, 10% woody wetlands, 5% urban areas, and 13% other lands (e.g., open water, herbaceous wetlands, and barren). Major forest types include industrial pine forests, mixed forests, and hardwood forests. Slash pine and longleaf pine forests are intensively managed for timber production in the region with a rotation of 25–30 years. Most of the non-managed hardwood and mixed forests are middle aged and result from large-scale abandonment of agricultural lands in the 1950s (Delcourt and Harris 1980, Tian *et al* 2012).

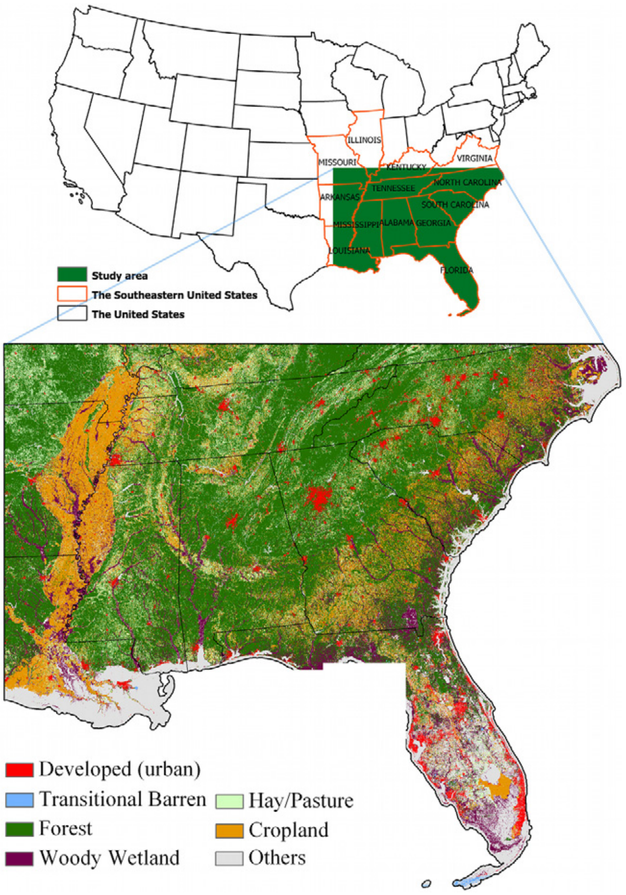

Figure 1. Location of the study area and map of land cover distribution in 1992 from the FORE-SCE model.

2.2. LUCC databases

Consistent and spatially explicit LUCC databases at 250 m resolution from 1992 to 2050 for the study area were developed using the FOREcasting SCEnarios of future land cover (FORE-SCE) model (Sohl *et al* 2007, 2012, Sohl and Sayler 2008). FORE-SCE can backcast historical and project future land use changes based on historical land cover change trends, spatial characteristics of recent land cover change, and probability-of-occurrence surfaces for each unique land cover type. The scenario for FORE-SCE projection was an extrapolation of the USGS Land Cover Trends data (Loveland *et al* 2002, Sleeter *et al* 2012), which characterized land cover change activities across the conterminous United States using a historical archive of 1973–2000 Landsat data. In addition, model parameterization of FORE-SCE relied heavily on the results from the Land Cover Trends project.

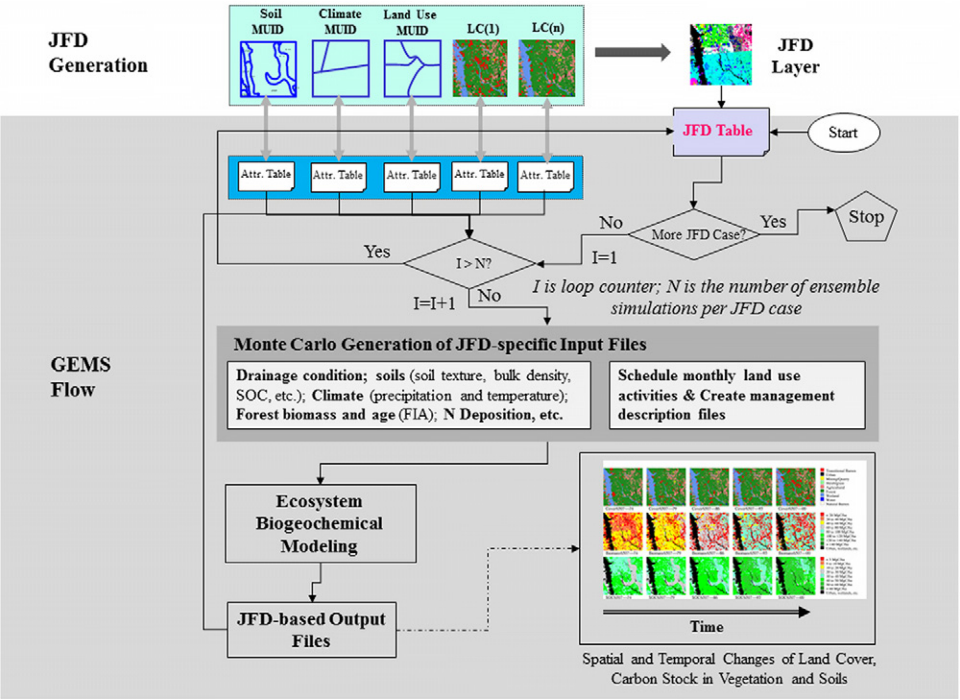

Figure 2. Flowchart of the generation of the joint frequency distribution (JFD) table and the modeling processes within the general ensemble biogeochemical modeling system (GEMS). A JFD grid can be generated via overlay operations of multiple geospatial data layers that might be organized by map unit identification (MUID) symbols. A JFD table is exported from the JFD grid and then used to drive the GEMS and provide keys to retrieve relevant information from the attribute tables of the geospatial data layers. Ensemble model simulations can be used to quantify input data uncertainties from the attribute tables. LC(1) and LC(n) represent land cover maps at time 1 and n, respectively.

Land Cover Trends results from 1992 to 2000 provided annual 'prescriptions' for key variables (e.g., the rates of change for individual land cover types, likelihood of specific land cover transitions, and basic characteristics of patch size) required by FORE-SCE. Logistic regression was used to develop probability-of-occurrence surfaces for each land cover type based on biophysical and socioeconomic drivers related to land use type at a given location. Individual patches of new land cover were placed on the landscape in an iterative process until the annual scenario prescriptions were met. Patch sizes were uniquely assigned to each new patch by approximating the historical distribution of patch sizes for each land cover type. The process continues with yearly iterations, with variable tracking age classes for forest and other classes. A more detailed description of the model and application in the study area can be found in Sohl and Sayler (2008).

2.3. Model simulations

The general ensemble biogeochemical modeling system (GEMS) was used to quantify the impacts of LUCC on regional carbon sources and sinks (figure 2). GEMS was developed to upscale carbon stocks and fluxes from sites to regions with explicit incorporation of the detailed LUCC processes (Liu *et al* 2004a, 2011a, Zhu *et al* 2011). It relies on a site-scale biogeochemical model, the Erosion–Deposition-Carbon Model (EDCM) (Liu *et al* 2003), to simulate carbon dynamics at the local scale. The spatial deployment of the site-scale model EDCM in GEMS is based on the spatial and temporal joint frequency distribution (JFD) of major driving variables (e.g., LUCC, climate, soils, disturbances, and management) (Liu *et al* 2004a). The JFD was generated by overlaying these geospatial data layers with a common grid size of 250 m × 250 m. Model simulation units were the unique combinations of these data layers with varying sizes and the finest simulation unit being one grid cell (i.e., 250 m × 250 m). The uncertainties of data layers at coarser resolutions (such as agricultural census data on management practices at the county or state level) were incorporated into GEMS simulations via a Monte Carlo approach. This approach embedded in GEMS maximally uses information from different sources and scales without compromising the quality of the finest information contained in some data layers (LUCC database in this study, for example) while taking advantage of the other coarser resolution data layers via downscaling with representation of corresponding uncertainty. A more detailed description of the model can be found in Liu *et al* (2004a, 2004b), Liu (2009) and Liu *et al* (2011a).

2.4. Other data sources

Monthly minimum and maximum temperatures and precipitation were obtained from the parameter-elevation regressions on independent slopes model (PRISM) group (1992–2007) and the World Climate Research Programme's (WCRP's)

Table 1. Transition table, in ha, of land cover classes from 1992 to 2050 in the southeastern United States.

		2050						
		Urban	Cropland	Transitional barren	Forest	Hay/pasture	Woody wetlands	Others
1992	Urban	4 618 643	18	31	6	0	0	62
	Cropland	1319 787	15 803 568	63 218	1 196 200	20 668	6	187 993
	Transitional barren	145 100	28 481	8 268	418 456	22 787	35 225	35 231
	Forest	3 440 487	1 021 312	411 087	54 154 462	968 618	68	816 837
	Hay/pasture	1 058 631	23 837	61 793	1 978 587	9 524 756	0	134 906
	Woody wetlands	398 550	8 493	48 337	1 287	12	11 563 343	8 212
	Others	532 381	35 012	19 537	68 862	37 931	0	13 995 643

Coupled Model Intercomparison Project phase 3 (CMIP3) A1B (business as usual) scenario (2008–2050). Initial soil properties were based on the State Soil Geographic (STATSGO) Database. Soil properties used included soil texture (sand, silt, and clay fractions), bulk density, organic matter content, wilting point, and field capacity. Soil drainage classes from excessively well drained to very poorly drained were indicated by the Compound Topographic Wetness Index (http://edna.usgs.gov/Edna/datalayers/cti.asp). Forest species composition, forest age, and biomass distribution data were obtained from the Forest Inventory and Analysis National Program (http://fia.fs.fed.us/tools-data/default.asp). Cropping practices, including shares of various crops and rotation probabilities, were derived from the National Resources Inventory (NRI) database developed by the Natural Resources Conservation Service, US Department of Agriculture (www.nrcs.usda.gov/technical/NRI/). Total atmospheric nitrogen deposition from wet and dry sources was obtained from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/).

2.5. Analysis

Carbon sequestration (sink or source) was calculated as the difference between the current year's and the previous year's ecosystem carbon stock, which was equal to net biome productivity (NBP) using the carbon cycle concepts and terminology of Chapin *et al* (2006). Ecosystem carbon sequestration included the amount of net carbon accrued in live biomass, the forest floor, and the soil. Positive values represent uptake, and negative values indicate carbon loss from the biome. Although the amount of wood harvested was simulated by GEMS, the off-site fate of the harvested wood, largely dependent on the type of wood products, was not tracked because of its complexity (Skog 2008). Therefore, carbon sequestration estimated from this study only included the carbon storage increment in natural ecosystems and did not include the carbon storage change in wood products.

3. Results

3.1. Land use and land cover change

The spatial distributions of various land cover classes in 1992 are shown in figure 1. Figure 3 compares the land cover composition in 1992 and 2050 in the study area. Forest is the major land cover class, covering roughly 47–49% of the land area, followed by cropland, woody wetlands, and hay/pasture. These land covers together accounted for about 80% of the land area. Major land cover and land use change was expected in the region primarily driven by urban expansion (table 1). Urban area was projected to expand from 4.62 Mha (million hectares) in 1992 to 11.52 Mha in 2050, an increase of 150% largely at the cost of forest (a decrease of 3.48 Mha), hay/pasture (a decrease of 2.27 Mha), cropland (a decrease of 1.72 Mha), and woody wetlands (a decrease of 0.46 Mha). However, urban expansion was not responsible for all these losses as other miscellaneous land cover classes also experienced small increases (1.03 Mha). The transitional barren, used to refer to a forestland that has experienced harvesting or clearing (Loveland *et al* 2002, Sleeter *et al* 2012), remained relatively stable during the study period at about 1.1% of the forested area. Forest harvesting refers to the activity of harvesting wood from a forest without converting the forest to another use, and clearing suggests conversion to another use after harvesting.

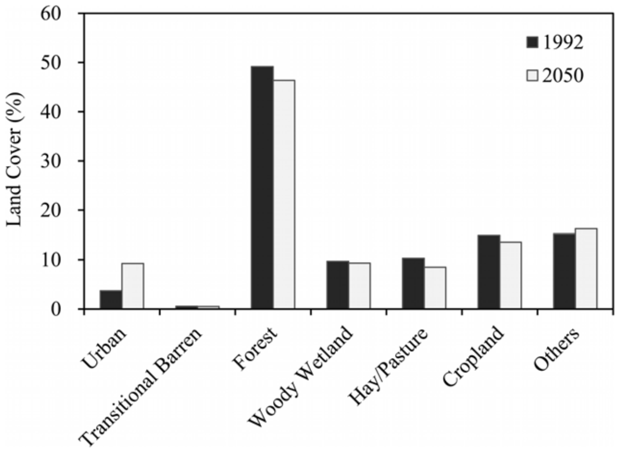

Figure 3. Comparison of land cover composition between 1992 and 2050.

3.2. Comparison of NPP from GEMS and MODIS

NPP is one of the critical variables for estimating carbon sequestration. The spatial pattern of the forest NPP simulated

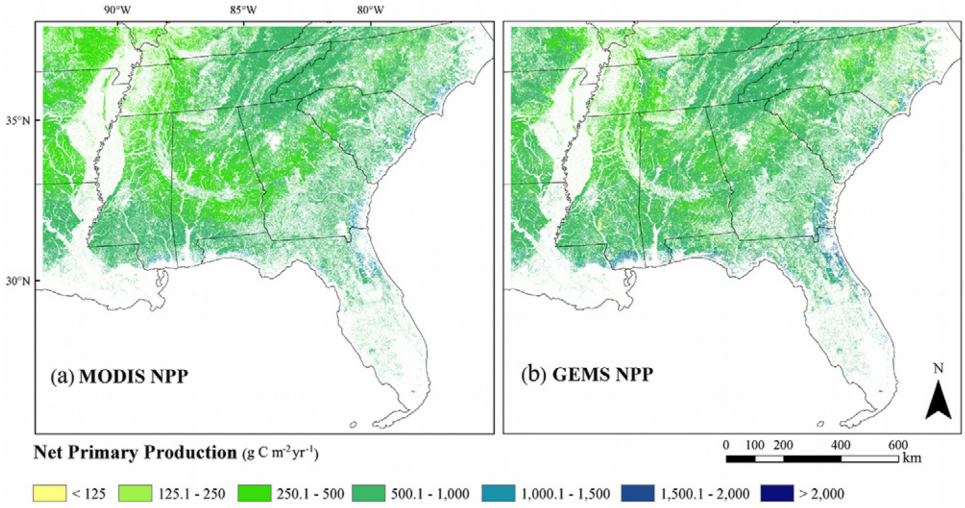

Figure 4. Comparison of the spatial patterns of forest NPP observed from MODIS and simulated by GEMS in 2006.

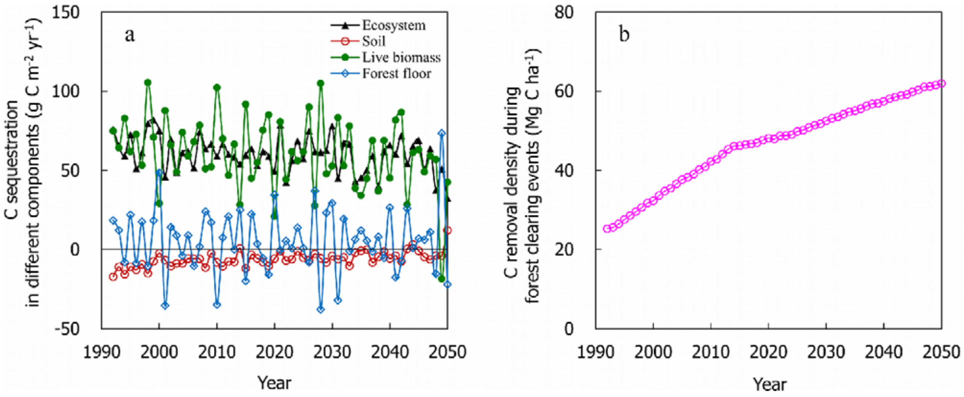

Figure 5. Temporal changes of C sequestration in different components (a) and C removal density during forest clearcutting events on average (b) from 1992 to 2050 in the southeastern United States. Ecosystem C sequestration is the sum of C accrued in live biomass, forest floor, and soil.

by GEMS agreed well with MODIS satellite observations (figure 4). Our NPP estimate for the forests in the study area varied from 620 to 800 gC m^{-2} yr^{-1} from 1992 to 2050, comparable with other studies. For example, Mickler *et al* (2002) gave an estimate of 645–712 gC m^{-2} yr^{-1} (converted from biomass using a factor of 0.5) for NPP of the forests in the southeastern United States. Brown and Schroeder (1999) reported that the NPP in the eastern United States (converted from aboveground NPP assuming it accounted for 65% of the total NPP) was averaged at 746 and 669 gC m^{-2} yr^{-1} for hardwood and softwood, respectively, according to forest inventory data. Tian *et al* (2010) estimated the average NPP of broadleaved and coniferous (including mixed) forests in the southern United States was 679 and 715 gC m^{-2} yr^{-1}, respectively.

3.3. Temporal patterns of carbon sequestration

Annual changes of the mean regional carbon sequestration are shown in figure 5(a). The terrestrial ecosystem in the southeastern United States has been sequestering carbon from 1992 to 2050, with an average rate of 60.4 gC m^{-2} yr^{-1} and a decreasing capacity of carbon sequestration over time. We partitioned the ecosystem carbon sequestration into the carbon accrued in live biomass, the forest floor, and the soil. The amount of carbon accrued in live biomass is the sum of net carbon accumulation in ecosystem live components, including leaf, fine root, fine branch, trunk, and coarse root. The amount of carbon accrued in the forest floor is the sum of net carbon accumulation in fine and coarse woody debris, and surface litter. The amount of carbon accrued in the soil is the net accumulation of organic carbon in the top 20 cm of soil. The results demonstrated that carbon accrued in live biomass accounted for most of the carbon sequestration for the southeastern United States (figure 5(a)). From 1992 to 2050, the average contributions of carbon accrued in live biomass, the forest floor, and the soil to ecosystem carbon sequestration were 100.5, 9.5, and -10.0%, respectively.

3.4. Spatial patterns of carbon sequestration

Figure 6(a) clearly visualizes the spatial distribution of carbon sources and sinks in the southeastern United States from 1992

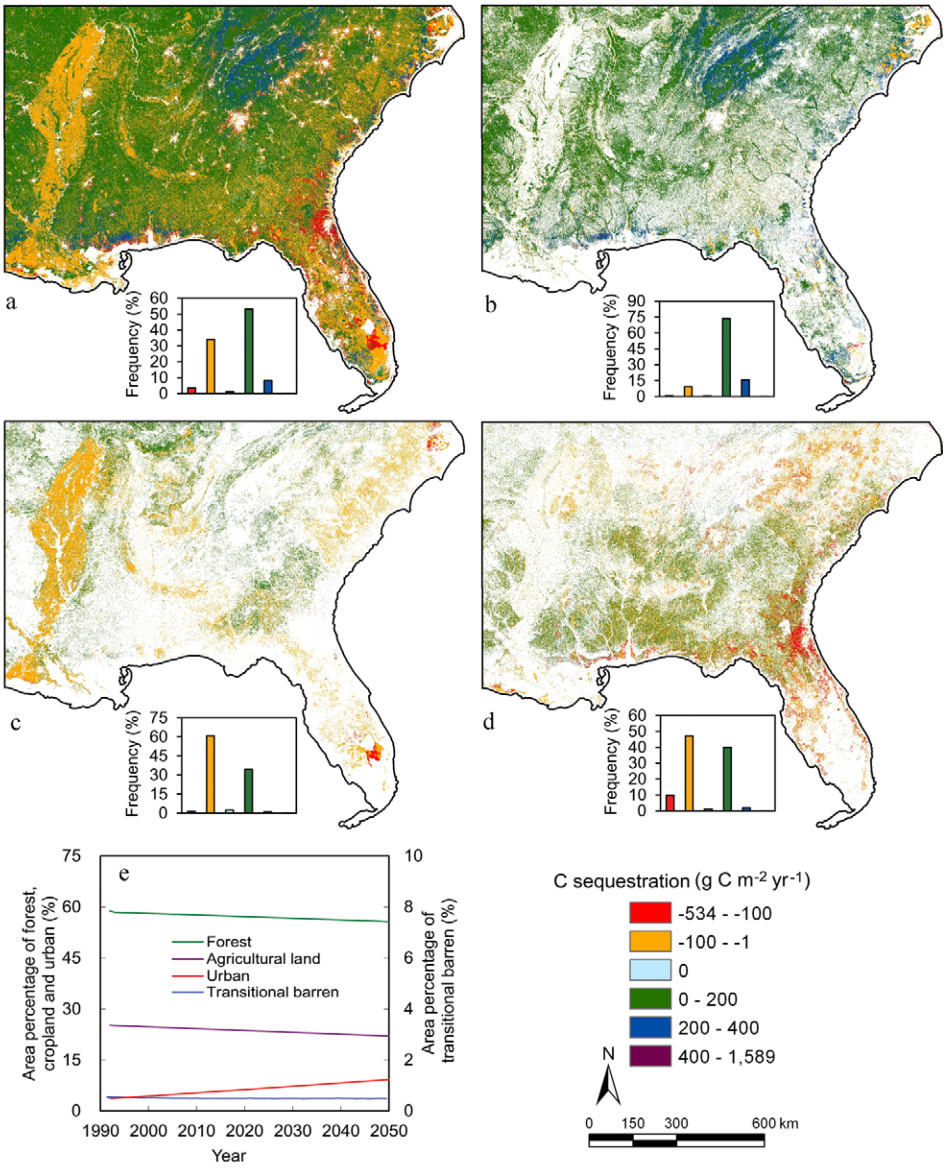

Figure 6. Spatial distributions of ecosystem C sequestration from 1992 to 2050 in the southeastern United States (a), its relationships with undisturbed forest (b), persistent agricultural land (c), forest clearcutting (d), and land cover dynamics for three major land cover types (forest, agricultural land, and urban) and transitional barren (caused primarily by forest clearcutting) (e). The inset graph denotes the area frequency distribution of C sequestration. A negative sequestration represents a movement of C from the biome.

to 2050. Overall, 37.6% of the total land area lost carbon (red and orange), 1.1% was carbon neutral (sky blue), and 61.3% gained carbon (green, dark blue, and purple). Most of the area losing carbon (34.1%) released carbon at a magnitude of less than 100 gC m^{-2} yr^{-1} (orange), and 53.1% of the area gaining carbon sequestered carbon at a magnitude of less than 200 gC m^{-2} yr^{-1} (green).

4. Discussion

Our results indicate that the southeastern United States has been sequestering carbon at an average rate of 65 gC m^{-2} yr^{-1} from 1992 to the present, and the magnitude agreed well with previous studies in the region (Liu *et al* 2004a, Binford *et al* 2006, Zhao *et al* 2010b). Binford *et al* (2006), using four 15 km by 15 km sample areas, studied the effects of land management and wildfire on carbon storage dynamics in the southeastern United States Coastal Plain ecoregion from 1975 to 2001, and they found the carbon accumulation rate averaged 100 gC m^{-2} yr^{-1}. Our previous studies showed that the contemporary carbon sink strength was 89 gC m^{-2} yr^{-1} for the southeastern Plains ecoregion (Liu *et al* 2004a), 76.7 gC m^{-2} yr^{-1} for Fort Benning, a military installation, and 18.5 gC m^{-2} yr^{-1} for the four surrounding counties around Fort Benning (Zhao *et al* 2010b). Figure 6(b) clearly shows the highest carbon sequestration was found in the Appalachian forests, which agreed well with the estimated carbon sequestration rate of 180 ± 60 gC m^{-2} yr^{-1} (Liu *et al* 2006) and the spatial pattern shown in Tian *et al* (2012). However, our estimate here was higher than the 23.7–50 gC m^{-2} yr^{-1} estimated by Tian *et al* (2012) for the southern United States. The lower value from Tian *et al* (2012)

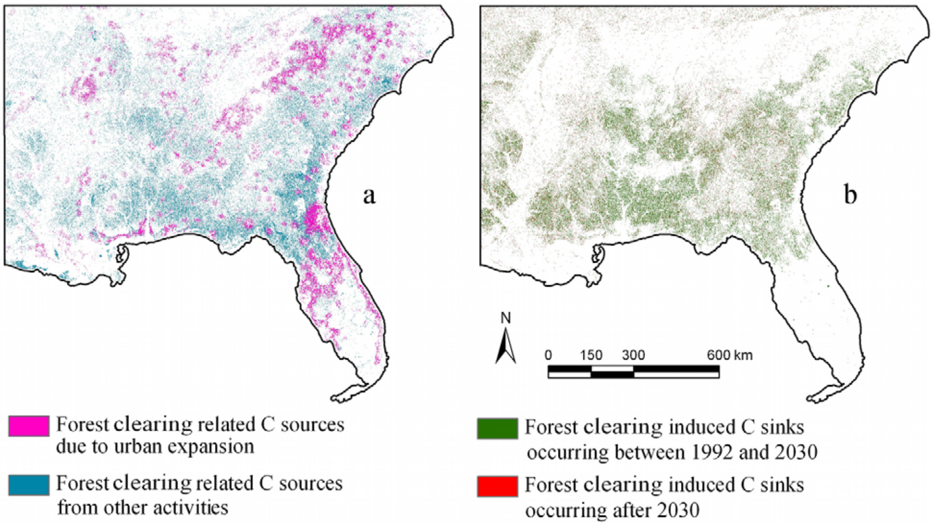

Figure 7. Further partition of forest clearcutting related C sources (a) and sinks (b).

might be explained by the inclusion of the southwestern states such as Texas, which has a much lower carbon sequestration rate. Overall, our estimate of contemporary carbon sequestration in the southeastern United States fell within the range of previous estimates for various areas in the region.

LUCC is critical in determining the distribution, magnitude, and mechanisms of terrestrial carbon sources and sinks at local to global scales (e.g., Watson *et al* 2000, Canadell 2002, Zaehle *et al* 2007, Houghton 2010, Zhao *et al* 2010b). Forest (including forested upland and woody wetlands), agricultural land (including cropland and hay/pasture), and urban are three major land cover types in the region. Transitional barren is a typical disturbed land cover type because of land use activities and is caused primarily by forest clearing in the region. These four land cover types together covered most of the southeastern United States land (87.5–87.9%) (figure 6(e)). We made an in-depth analysis on spatial distributions of ecosystem carbon sequestration (figure 6(a)) and its relationships with undisturbed forest (forest without any change from 1992 to 2050, figure 6(b)), persistent agricultural land (figure 6(c)), and forest clearcutting (figure 6(d)) to understand the possible mechanisms of carbon sources and sinks in the region. The analyses demonstrated that 90% of undisturbed forest acted as a carbon sink (C sequestration > 0) (figure 6(b) and the inset graph), and together they explained 66.5% of the total carbon sink in the region (figures 6(a) and (b)). The other 10% of the undisturbed forests were either carbon neutral or carbon source because of old age and poor site conditions. In contrast, 62.2% of persistent agricultural land acted as carbon sources (figure 6(c) and the inset graph), which accounted for 37.2% of total carbon source in the region (figures 6(a) and (c)). Forest clearcutting can create immediate and various legacy impacts on carbon sources and sinks (figure 6(d) and the inset graph). An immediate carbon source is created when a forest is cleared. Rapid urbanization in the region (figure 7(a)) explained about 36% of the carbon sources related to forest clearing (figure 6(d)). Urban expansion along the coastal zone and around cities, especially in the vicinity of Jacksonville in Florida, was predicted to be one of the major forces for reducing carbon sequestration capacity in the region. Depending on the subsequent land use after forest clearcutting, various legacy impacts can be created. Little carbon gain is expected if the forest is converted to urban. On the other hand, a legacy carbon sink can be created in a few years of recovery after reforestation. For example, eddy covariance flux tower measurements and biometric measurements indicated that slash pine plantations switched from a carbon source to a sink proximately 3–4 years after planting in north Florida because of the increase of leaf area index (LAI) (Binford *et al* 2006, Bracho *et al* 2012). About 84% of carbon sinks induced by forest clearcutting was attributed to harvesting activities that occurred between 1992 and 2030 in this study (figures 6(d) and 7(b)), suggesting forest harvesting activities had created a legacy carbon sink after 20 (2050–2030) to 58 (2050–1992) years of recovery. This agrees with many previous studies that recovery from past disturbances is the dominant driver for some regional terrestrial carbon sinks, contributing to a large portion of the current northern hemisphere terrestrial sink (e.g., Fang *et al* 2001, Goodale *et al* 2002, Kauppi *et al* 2006, Liu *et al* 2011b, Pan *et al* 2011).

Our results also show that the carbon sequestration capacity of the southeastern United States is predicted to decrease from 1992 to 2050, and the general trend agrees well with previous studies (Hurtt *et al* 2002, Liu *et al* 2004a, Zhao *et al* 2010b). Aside from the slowing down of carbon accumulation rate as forests age (Hurtt *et al* 2002), land use and land cover change, especially urban expansion and forest decline, is also a factor for the reduction of carbon sequestration capacity in the region. A total of 3.94 Mha of forests (including wetland forests) was projected to disappear during the study period, which would effectively reduce the net carbon accrued in live biomass of forest as it accounted for most of the carbon sequestration for the southeastern United

States (figure 5(a)). The carbon removal from the biome by forest clearcutting increased over time (figure 5(b)). This was not caused by the increased cutting activities (e.g., expansion of clearcutting area) over time but by the increased amount of carbon removed per unit area. The carbon removal intensity via clearcutting increased from about 25.3 MgC ha^{-1} in 1992 to 61.9 MgC ha^{-1} on average in 2050 for each cutting event. The increased carbon removal intensity resulted from the overall increase of the carbon storage due to carbon accumulation in these growing forests because only less than half of the forests, mostly coniferous, was being rotationally cut in the region and the rest kept growing (Smith *et al* 2000).

Errors and uncertainties, introduced by deficiencies in model structure, parameters, and input data, are an integral part of model simulations (Larocque *et al* 2008). Although errors and confidence limits could not be assigned to the estimated carbon fluxes and stocks in this study, general and qualitative observation of uncertainties can be made along with processes and procedures that can potentially be put in place to reduce these uncertainties. First, LUCC legacy effects on carbon dynamics were not well quantified, especially during the early part of the study period. It would be better if the details of historical LUCC dynamics could be extended and reconstructed back further into the 1700s using FORE-SCE and agricultural census data as LUCC has experienced dramatic changes in the region (Waisanen and Bliss 2002). The agricultural expansion following pioneer cultivation from the 1800s to the 1940s and the subsequent abandonment and conversion of degraded farmlands into forests in the southeastern United States have created LUCC legacy effects on carbon dynamics that can last for tens to hundreds of years (Liu *et al* 2003, Tian *et al* 2012). Therefore, our current study might underestimate LUCC legacy impacts, although great efforts were put in place to constrain model initialization and parameterization using FIA data, STATSGO, and other databases. Extended historical land use records can let the model run for a longer time period to gradually acclimate itself, referred to as spin-up (Thornton and Rosenbloom 2005), and consequently diminish the uncertainties and errors introduced from model initialization and parameterization. The uncertainty related to soil carbon dynamics can be most likely reduced with longer historical land use data as the initial soil carbon database STATSGO still contains large uncertainty. Second, the uncertainty of soil organic carbon (SOC) change rate might be high in this study due to a number of factors: long-lasting LUCC impacts on SOC (Guo and Gifford 2002) that require a long spin-up time, our weak capability to quantify SOC changes in extensive organic soils in the region (e.g., the Mississippi valley, the coastal wetlands and low plains), and not being able to include some of the management practices (e.g., tillage and forest fertilization). For example, according to meta-analyses performed on site-scale studies, conservation practices implemented on croplands can lead to a SOC sequestration of 45 gC m^{-2} yr^{-1}, higher than conventional tillage (Causarano *et al* 2008, Franzluebbers 2010). Overall, our results showed that the soils in the region lose carbon while forest live biomass and floor accumulate carbon, and the magnitude of carbon loss from soils will diminish over time (figure 5(a)). These results might be attributed to (1) a high urbanization process that usually loses carbon due to conversion of natural ecosystems to developments (see table 1), (2) loss of high carbon-bearing wetlands to low carbon-bearing ecosystems, and (3) uncertainty related to soil carbon initialization (from STATSGO), model parameters such as the default soil carbon decomposition rates from CENTURY, and other modeling uncertainties described above. Finally, the SOC accumulation rate in the coastal estuaries can be as high as those in uplands (Loomis and Craft 2010) but was not considered in this study. Apparently, additional observational and modeling studies are required to integrate more processes and ecosystems to really reduce the uncertainty in the estimated carbon dynamics in the region.

Acknowledgments

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