Scope, Methodology, and Current Knowledge

By Zhiliang Zhu, Benjamin M. Sleeter, Terry L. Sohl, Todd J. Hawbaker,
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Chapter 1 of

Baseline and Projected Future Carbon Storage and Greenhouse-Gas Fluxes in Ecosystems of the Eastern United States

Edited by Zhiliang Zhu and Bradley C. Reed

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Chapter 1. Scope, Methodology, and Current Knowledge

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1.1. Scope and General Methodology

This is the third in a series of reports produced by the U.S. Geological Survey (USGS) for a national assessment of carbon sequestration and greenhouse-gas (GHG) fluxes in ecosystems. The first two reports covered ecosystems of the Great Plains (Zhu and others, 2011) and Western (Zhu and Reed, 2012) regions of the United States. This report covers ecosystems in the Eastern United States, an area of about 3.05 million square kilometers (Mkm^2; fig. 1–1) that extends from the Great Lakes, the Mississippi flood plains, and the Appalachian Mountains to the plains of the coasts of the Atlantic Ocean and the Gulf of Mexico.

The Eastern United States is a region largely dominated by forests. Conifer and deciduous forests span the Northeast and the areas near and around the Great Lakes, and plantation-style forestry is prevalent in the southern coastal region. In the Southeast, forest land use is dynamic and involves management and short harvest cycles. In other regions of the Eastern United States, the pattern of forest lands decreasing in area because of urbanization but gaining in area from abandoned agricultural lands is prevalent. There is a substantial amount of agriculture in the Eastern United States; at the same time, the region is highly urbanized in areas along the eastern seaboard and around the southern coast of the Great Lakes. Some of the major population centers within the United States are in the East, and these centers are proving to be a key driver of land-use change from forest and agriculture. Wetlands have a large presence along the Atlantic and the gulf coasts as well as in the Great Lakes region, representing the majority of wetland areas in the conterminous United States.

This assessment of carbon stocks and sequestration and GHG fluxes was part of a national assessment required by the Energy Independence and Security Act of 2007 (EISA; U.S. Congress, 2007), which mandated that the U.S. Department of the Interior provide estimates of (1) the amount of carbon stored in ecosystems, (2) the capacity of ecosystems to sequester carbon, (3) the rate of GHG fluxes in and out of the ecosystems, and (4) the effects of the natural and anthropogenic processes that control ecosystem carbon balances and GHG fluxes. The GHGs considered in this assessment were carbon dioxide (CO_2), carbon monoxide (CO, from wildland fires only), dissolved inorganic carbon (DIC), methane (CH_4), and nitrous oxide (N_2O).

This regional assessment was conducted to (1) contribute to the EISA mandate for a national assessment of carbon sequestration and GHG fluxes and (2) help improve the understanding of carbon cycling at a regional scale by focusing on different ecosystems and their relations with natural and anthropogenic controlling processes (such as climate change, land use, land management, and wildland fires). To meet these objectives, the assessment was designed to provide answers to questions including the following: How much carbon was stored in ecosystems of the Eastern United States and how may it change over space and time? How might the stored carbon and carbon fluxes be affected by the natural and anthropogenic processes that control their storage and release in the ecosystems of the Eastern United States? Results and analyses provided in this report, as well as the previous two reports covering the Great Plains (Zhu and others, 2011) and Western (Zhu and Reed, 2012) regions of the United States, pertain to the first question and parts of the second question (because not all processes were exhaustively analyzed and presented). Results pertaining to the natural vegetation change under future climate change are not within the purview of this report.

The major ecosystems evaluated in this study are classified as terrestrial (forests, wetlands, grasslands/shrublands, and agricultural lands) or aquatic (rivers, lakes, estuaries, and coastal waters). The thematic definitions of the ecosystems and their spatial boundaries are outlined in table 1–1 and in Zhu and others (2010). The definitions are largely based on the National Land Cover Database (NLCD; Vogelmann and others, 2001; Homer and others, 2007), which was the primary source of initial land-use and land-cover (LULC) data for this assessment. The LULC data, derived from Landsat remote sensing data, were used to define the spatial boundaries of the ecosystems that were assessed in this study. Because the remote-sensing data allowed for complete coverage of the Eastern United States, the resulting spatially and temporally explicit data products provided a convenient and comprehensive basis for deriving carbon and GHG estimates.

Within the NLCD database, land-use (for example, mechanically disturbed classes (that is, forest clearcuts)) and land-cover (for example, forests) classes were mapped using data acquired from Landsat satellites. Because of the input data and the remote sensing methods used, areas in urban centers with significant tree cover, as determined by the NLCD, were treated as forest cover in this study. LULC change refers to changes between the LULC classes, including land conversions (such as from forest to developed lands) and cover change as the result of forest clearcuts.

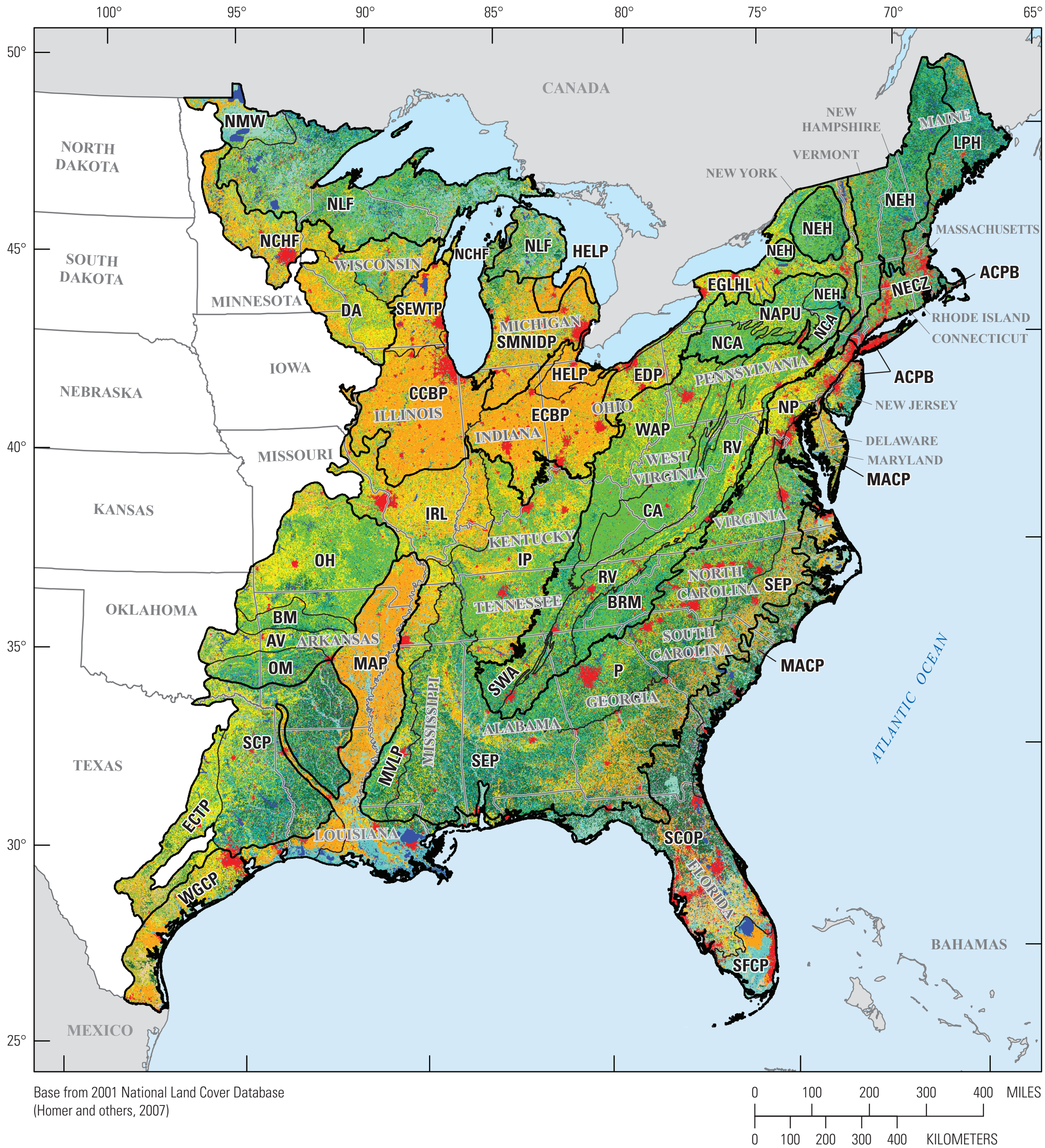
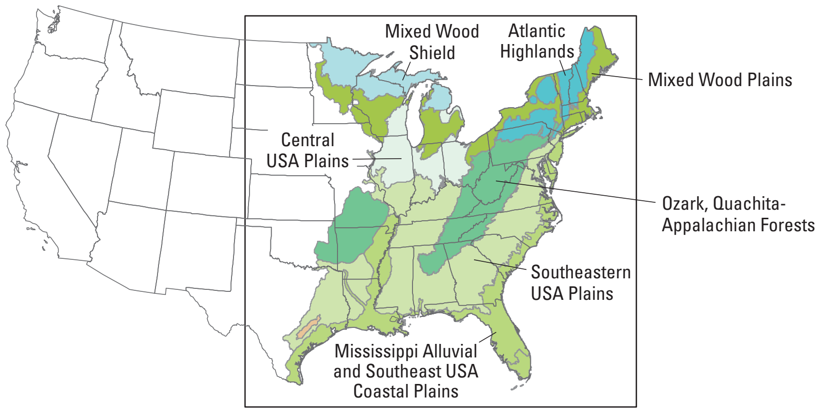


Figure 1–1. Map showing the spatial extent of the assessment of carbon storage and fluxes in the Eastern United States. The region consists of seven level II ecoregions (modified from U.S. Environmental Protection Agency, 2013a). The total area of the Eastern United States is about 3.05 million square kilometers (table 2–2). The land-use and land-cover classes shown on the map represent conditions that existed in 2005, the year that was chosen as the baseline for this assessment.



Index map of Level II ecoregions in the Eastern United States

EXPLANATION

Land cover

- Water
- Developed
- Mechanically disturbed national forest
- Mechanically disturbed other public land
- Mechanically disturbed private land
- Mining
- Barren
- Deciduous forest
- Evergreen forest
- Mixed forest
- Grassland
- Shrubland
- Agriculture
- Hay/pasture
- Herbaceous wetland
- Woody wetland
- Ice/snow

Ecoregion boundary

- Level II
- Level III

Atlantic Highlands

NAPU Northern Appalachian Plateau and Uplands
NCA North Central Appalachians
NEH Northeastern Highlands

Central USA Plains

CCBP Central Corn Belt Plains
ECBP Eastern Corn Belt Plains
HELP Huron/Erie Lake Plains
SEWTP Southeastern Wisconsin Till Plains

Mississippi Alluvial and Southeast USA Coastal Plains

ACPB Atlantic Coastal Pine Barrens
MACP Middle Atlantic Coastal Plain
MAP Mississippi Alluvial Plain
SCOP Southern Coastal Plain
SFCP Southern Florida Coastal Plain [Everglades]
WGCP Western Gulf Coastal Plain [Texas-Louisiana Coastal PLain]

Mixed Wood Plains

DA Driftless Area
EGLHL Eastern Great Lakes and Hudson Lowlands
EP Erie Drift Plain
LPH Laurentian Plains and Hills
NCHF North Central Hardwood Forests
NECZ Northeastern Coastal Zone
SMNIDP Southern Michigan/Northern Indiana Drift Plains

Mixed Wood Shield

NLF Northern Lakes and Forests
NMW Northern Minnesota Wetlands

Ozark, Quachita-Appalachian Forests

AV Arkansas Valley
BRM Blue Ridge Mountains
BM Boston Mountains
CA Central Appalachians
OH Ozark Highlands
OM Ouachita Mountains
RV Ridge and Valley
SWA Southwestern Appalachians
WAP Western Allegheny Plateau

Southeastern USA Plains

ECTP East Central Texas Plains
IP Interior Plateau
IRL Interior River Lowland
MVLP Mississippi Valley Loess Plains
NP Northern Piedmont
P Piedmont
SCP South Central Plains
SEP Southeastern Plains

Figure 1–1.—Continued

Table 1–1. Land use and land cover in the Eastern United States.

[For the National Land Cover Dataset, see Vogelmann and others (2001). Vegetation Change Tracker is a product of Landscape Fire and Resource Management Planning Tools Project (LANDFIRE; Rollins, 2009); see Huang and others (2010)]

LULC class	Ecosystem	Area, in percent of total	Source
National Land Cover Dataset			
Barren	Other lands	0.1	Bare rock, sand, and clay
Cultivated crop	Agricultural lands	13.9	Row crop; small grains; fallow
Deciduous forest	Forests	23.7	Deciduous forest
Evergreen forest	Forests	16.4	Evergreen forest
Grassland	Grasslands/shrublands	0.6	Grassland and herbaceous
Hay/pasture	Agricultural lands	17.9	Pasture and hay
Herbaceous wetland	Wetlands	0.4	Emergent herbaceous wetlands
Ice/snow	Other lands	0.0	Perennial ice and snow
Mining	Other lands	0.1	Quarries, strip mines, and gravel pits
Mixed forest	Forests	12.6	Mixed forest
Open water	Other lands	2.0	Open water
Shrubland	Grasslands/shrublands	0.5	Shrubland
Urban/developed	Developed	3.5	Low- and high-intensity residential; commercial, industry, and transportation; urban and recreational grasses
Woody wetland	Wetlands	5.6	Woody wetlands
Landscape Fire and Resource Management Planning Tools Project			
Mechanically disturbed, national forest	Forests	0.1	Vegetation Change Tracker
Mechanically disturbed, other public land	Forests	0.0	Vegetation Change Tracker
Mechanically disturbed, private land	Forests	2.6	Vegetation Change Tracker

Within the LULC classes, land-management activities were defined as those actions that were aligned with the LULC classes and modified the way land was used, but did not change the LULC classes. Forest clearcuts were mapped as a LULC change class but were treated as a management activity when deriving and analyzing carbon estimates. Input data describing land-management or ecosystem disturbances were developed in addition to the classifications in the NLCD; these additional data are described in chapters 3 and 4. As a result, forest clearcuts and thinning were land-management activities included in the assessment, as were several agricultural management activities described in chapter 7. Ecosystem disturbances are defined as those natural disturbances that altered the production of carbon or other functions in an ecosystem. For this assessment, wildland fire was the only natural disturbance that was considered; natural disturbances such as persistent drought and insect-driven forest defoliation (such as gypsy moth) or mortality (such as spruce budworm epidemics) were not included.

The assessment was conducted based on a methodology framework that (1) collected and used existing data, including various biophysical data derived from remote sensing, inventories of biological resources and soil properties, climate histories and future projections, and measurements made by a national network of streamgages; (2) linked land-use, land-management, and climate data with statistical and process-based methods and models to generate spatially and temporally explicit carbon storage and GHG flux estimates; and (3) applied a set of future LULC and climate change scenarios to the assessment to project a range of estimates for carbon stock and sequestration and GHG flux in ecosystems. The major components of the assessment methodology and their roles and relations are listed in table 1–2 and shown in figure 1–2, with corresponding chapters of this report indicated in the boxes along with the methodological details described in the chapters.

The methodology framework shown in figure 1–2 is spatially and temporally explicit. The spatial and temporal framework is described in chapter 2. Based on this framework, the ecosystems were mapped or modeled, and all pixels from the mapping effort were partitioned into LULC and LULC-change classes, using the landscape LULC model described in chapter 3. The resulting digital maps, described in chapters 3 through 7, have a nominal spatial resolution of 250 meters. Because the assessment was conducted at national and broad regional scales, the resulting information and data products should be applied only at the regional scale or broader.

In this report, the term "region" is often used in a general sense, depending on the context, whereas the term "ecoregion" refers to the U.S. Environmental Protection Agency (EPA) ecoregion mapping hierarchy (U.S. Environmental Protection Agency, 2013a). In total, seven level II EPA ecoregions

Table 1–2. Main features of the assessment methodology of carbon storage and fluxes in the Eastern United States.

[EPA, U.S. Environmental Protection Agency; FIA, Forest Inventory and Analysis National Program (USDA); FORE–SCE, forecasting scenarios of future land cover; LANDFIRE, Landscape Fire and Resource Management Planning Tools Program (Rollins, 2009); LULC, land use and land cover; IPCC, Intergovernmental Panel on Climate Change; MTBS, Monitoring Trends in Burn Severity Project; NASA, National Aeronautics and Space Administration; NHD, National Hydrography Dataset; NLCD, National Land Cover Dataset (Vogelmann and others, 2001); NOAA, National Oceanic and Atmospheric Administration; NWIS, National Water Information System; RESSED, Reservoir Sedimentation Database; SRES, Special Report on Emissions Scenarios; USDA, U.S. Department of Agriculture; USGS, U.S. Geological Survey; VCT, vegetation change tracker (a product of LANDFIRE; Huang and others, 2010)]

Methodology feature	Input data	Chapters
Maps of baseline and projected future LULC classes, forest age, and ecosystems at 250-meter resolution using a set of LULC change scenarios and FORE–SCE landscape model	NLCD, VCT, FIA data, and LULC change history from USGS Land Cover Trends project, the IPCC SRES scenarios, and references from literature	2, 3
Baseline and projected future wildfire areas, severity and emissions using an integrated fire prediction and behavior model. Derived data produced at 250-meter resolution	Fire data from MTBS, LANDFIRE fuel data, downscaled weather and future climate data	4
Baseline carbon transport, emissions, and burial by inland aquatic ecosystems derived using empirical methods (tabular data only)	Surface water areas derived using the USGS NHD, and measured variables from the USGS NWIS, the USGS RESSED, and the EPA national lakes assessment	5
Baseline and projected future fluxes of nutrients and sediments to estuarine and coastal waters, and resulting terrestrial component of coastal carbon storage. Products are digital maps at 250-meter spatial resolution	LULC data from chapters 2 and 3; historic water-quality data from USGS NWIS; USGS SPARROW model output; coastal bathymetric and estuary parameter data from NOAA; remote sensing data for chlorophyll and suspended sediment from NASA	6
Baseline and projected future carbon stock and flux using three models: a spreadsheet model, CENTURY, and EDCM. Simulations were run at 1 percent systematic sample (full-resolution maps subsequently produced at 250-meter resolution). A total of 3 simulations were run at annual steps for baseline and 21 for future projections	Biomass and land-management data derived from resource inventories (FIA agricultural data), soil organic carbon from national soil databases, future climate projections, and the baseline and future projected LULC, forest age, ecosystems, and fire data from chapters 2, 3, and 4	7

were used for the assessment: (1) Mixed Wood Shield, (2) Atlantic Shield, (3) Mixed Wood Plains, (4) Central USA Plains, (5) Southeastern USA Plains, (6) Ozark, Ouachita-Appalachian Forests, and (7) Mississippi Alluvial and Southeast USA Coastal Plains (which includes the Everglades and the Texas-Louisiana Coastal Plain ecoregions for the purposes of this assessment; Zhu and others, 2010, fig. 3–1).

All the models used in this assessment were parameterized, and the results were calibrated and validated on the basis of these ecoregions. The major terrestrial and aquatic ecosystems are analyzed within these ecoregions. The use of the ecoregions and the NLCD LULC classes chosen for the ecosystems in this assessment suggest that the reported results are meaningful within the defined ecoregion and ecosystem definitions and may not be directly comparable with other national- or regional-level estimates because of the different boundary definitions. Further discussion of the ecoregions and ecosystems may be found in Zhu and others (2010).

The temporal foundation of the assessment was twofold and included a baseline and a range of future projections, as described in chapter 2. Baseline is defined as the average contemporary annual conditions to be assessed. Different components of the assessment have different ranges of baseline years stemming from considerations for data availabilities: LULC are assessed from 1992 through 2005; wildland fires, from 2001 through 2008; terrestrial carbon and GHG fluxes, from 2001 through 2005; and aquatic carbon fluxes, from the 1920s through 2011. A range of future LULC scenarios projecting from the time after the end of the baseline period through 2050 were developed by incorporating rationales and criteria of a set of GHG emission trajectories used in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES; Nakićenović and others, 2000), ensuring consistency of globally available climate and land-use data with the LULC scenarios developed for this assessment at the national and regional scales.

Based on the spatial and temporal frameworks, changes in LULC and forest age were mapped (and modeled) in annual steps using a spatially explicit landscape model (chap. 3). Fire areas, severity, and combustion emissions also were estimated and mapped, using a coupled statistical and landscape simulation model (chap. 4). The derived LULC, forest age, and fire data, along with other available data (including national soil databases, biomass growth curves, available land-management activity data (such as partial forest cutting in forests and the use of fertilization in agriculture), and future climate projections), were incorporated into a modeling task using three process-based ecosystem models (described in chap. 7) to estimate the current and projected future carbon stock, carbon flux, and GHG flux in four terrestrial ecosystems (forests, grasslands/shrublands, agricultural lands, and wetlands). Three general carbon pools were represented (live biomass, soil organic matter, and dead biomass (including litter and woody debris)). Ecosystem processes represented

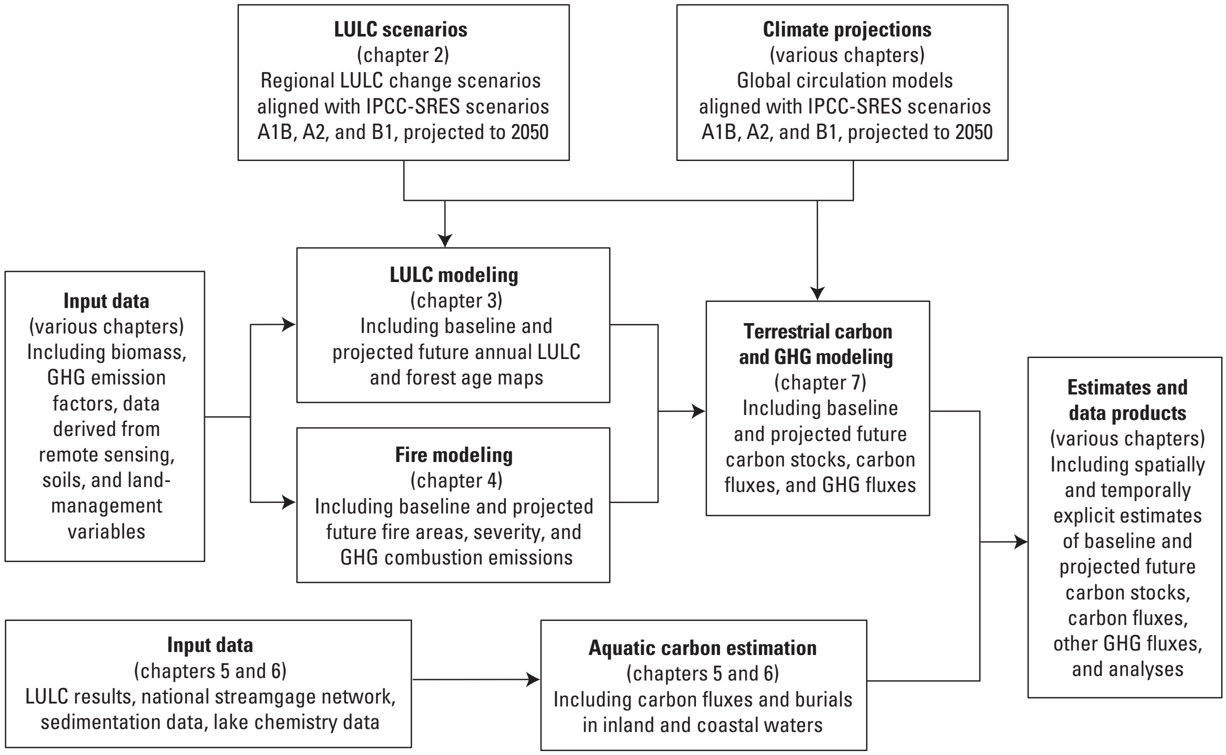


Figure 1–2. Flow diagram showing the general framework of the methodology used in the assessment of carbon storage and fluxes in the Eastern United States. The heading in each box represents a major component of the assessment. The chapter numbers indicate where in this report those components are discussed. Arrows show relations between components. GHG, greenhouse gas; IPCC–SRES, Intergovernmental Panel of Climate Change Special Report on Emissions Scenarios (Nakićenović and others, 2000); LULC, land use and land cover.

in the modeling task included transitions between the LULC and ecosystem classes, net primary production (NPP), heterotrophic respiration (HR), harvested wood (HWD; only accounting for carbon removed from landscapes from clearcuts and partial cuts), long-term effects of wildland fire, and available land-management activities (detailed in chap. 7). Estimates of carbon transport through riverine systems, emissions and burial by all inland water bodies, and flux and burial in estuaries and coastal waters were calculated separately and were based on a series of methods and models detailed in chapters 5 and 6. The results represent a baseline and a range of potential carbon sequestration rates by the ecosystems under a range of projected climate and land-use conditions, which is a requirement of the EISA.

Flux refers to emissions of GHG (such as carbon) to the atmosphere and to uptake by ecosystems. In presenting the results of terrestrial carbon flux assessment, net flux and net ecosystem carbon balance (NECB) are used interchangeably in this report to refer to the net rate of the change in carbon storage in ecosystems. For a given ecosystem and GHG, net flux and NECB are the same as net ecosystem exchange (NEE). However, the use of net carbon flux or NECB is conventional in large-area, land-based studies, such as this assessment. The terms used in calculating NECB and (or) net flux include net ecosystem production (NEP, which is the difference between the NPP and the HR), combustion and long-term emissions from wildland fires, and biomass harvesting. When reporting losses or gains in carbon storage, a negative number indicates carbon uptake, carbon sequestration, or a carbon sink; a positive number indicates a carbon emission or a carbon source. These conventions are used throughout this report unless noted. The usages follow standard conventions found in the literature on this topic (for example, Chapin and others, 2006; U.S. Environmental Protection Agency, 2012) and are consistent with the terms used in the assessment reports for the Great Plains (Zhu and others, 2011) and Western (Zhu and Reed, 2012) regions of the United States. In addition to assessing carbon storage and fluxes in ecosystems, the fluxes or emissions of other GHGs (such as CO_2, CH_4, CO, DIC, and N_2O) were also assessed. Fluxes or emissions of the other GHGs are reported as CO_2-equivalent values and flux estimates were calculated based on their respective global warming potential factors. The units of measurement used in this report also follow previous usages. The total amount of carbon stored in the three major carbon pools (live biomass, soil organic matter, and dead biomass) for a given region is reported in teragrams of carbon. When reporting carbon stock per unit of area, the values are given in kilograms of carbon. When reporting the carbon flux per unit of area, the values are given in grams of carbon.

Whenever possible, the estimates are provided as a range of values, in addition to mean values, in order to represent the spread of variability in assessment results. The ranges of values were presented depending on chapters or components of the report. For variables of wildland fires (chap. 4), estimates were presented for the 5th and 95th percentile values, as well as median, mean, minimum, and maximum values, using Monte Carlo simulations. For the inland water component (chap. 5), the range of values was derived from the 5th and 95th confidence intervals of Monte Carlo simulations. Range values from the coastal water chapter reflected 10th and 90th confidence intervals using Monte Carlo simulations. Range values of terrestrial carbon and GHG estimates (chap. 7) refer to the minimum and maximum of annual mean values by model runs in the baseline and by model runs in LULC scenarios and future climate projections.

The spread of variability in the assessment results, as represented by the range values, covers a major portion of uncertainties in the resulting estimates. Uncertainties in this assessment were related to two general sources: the use of various input data and methods and models (in the baseline and future projections) and the use of LULC scenarios (future projections only). Monte Carlo simulations were used to quantify uncertainties and produce a range of estimated results related to the input data and the methods in the fire and aquatic assessments. For terrestrial carbon and GHG modeling (chap. 7), the Monte Carlo method was not used to estimate the uncertainties in the final results due to constraints of computation intensity and time. However, because model structure and parameterization are often a major source of uncertainty, multiple ecosystem models (as described in chap. 5) were used to produce ranges of terrestrial carbon results. The LULC scenarios were a primary foundation of projecting future potential carbon estimates, including stock and fluxes. By design, multiple scenarios were used to allow analysis of the effects of a range of potential choices and to bound the overall uncertainties in the projected results (Zhu and others, 2010). As a result, the ranges of results presented in this assessment for terrestrial carbon and GHG estimates represent a major part of the overall uncertainties. The methodology, design rationales, and technical specifications are detailed in Zhu and others (2010).

1.2. National and Regional Studies of Carbon Sequestration and Greenhouse-Gas Flux

The Eastern United States has seen the most active LULC change swings in the country, including pressure to expand urban or suburban infrastructure (development pressure), cropland expansion and contraction, increased timber harvesting activities in recent decades, and a continued recovery from deforestation of the 19th century (chaps. 2 and 3; Claggett and others, 2004; Chen and others, 2006; Auch and others, 2012). LULC change, particularly the rate of land conversions to developed lands, and land-management activities, particularly forest harvesting (clearcutting) of plantation forestry, in the Eastern United States in recent decades have been rapid and more active than in any other region in the Nation (Sleeter and others, 2013). The rapid LULC changes have significant hydrological and biogeochemical consequences, including carbon fluxes and sequestration (Houghton and others, 1999; Milesi and others, 2003; Birdsey and others, 2006; Chen and others, 2006; Woodbury and others, 2006; Houghton, 2010; Michalak and others, 2011; Williams and others, 2012; Robinson and others, 2013).

Existing estimates of carbon storage and sequestration and GHG fluxes varied widely by ecosystem and region in the Eastern United States. Forests occupy a significant land base in the east, representing about one-half the total area in the region and are the most important carbon sink. The forest inventories that were conducted by the U.S. Department of Agriculture Forest Service indicated that, in 2010, forest lands in the Eastern United States had a combined 24.2 petagrams of carbon (PgC) in forest ecosystems (table 1–3). The carbon inventory estimate of 24.2 PgC stock for the forests in the Eastern United States (Brad Smith, U.S. Department of Agriculture, Forest Service, unpub. data, 2010) was higher than that of the forests in the Western United States by more than 50 percent, whereas the per unit of area carbon stock was also higher compared with that in the forests of the Western United States (15.7 kilograms of carbon per square meter (kgC/m^2) in the east compared with 14.5 kgC/m^2 in the west). Among the seven ecoregions in the Eastern United States, the Southeastern USA Plains contained more stored carbon than any other ecoregion. The most recent Resource Planning

Table 1–3. Total carbon stock from all major pools in the forest ecosystems in the seven ecoregions used in the assessment of carbon storage and fluxes in the Eastern United States.

[Data were derived from the Forest Inventory Database Online (FIDO; U.S. Department of Agriculture, Forest Service, 2012b) and were analyzed by Brad Smith (U.S. Department of Agriculture, Forest Service, unpub. data, 2010). Ecoregions are from Zhu and others (2010) as modified from U.S. Environmental Protection Agency (1999). kg/m^2, kilograms per square meter; TgC, teragrams of carbon]

Ecoregion	Carbon, in TgC	Carbon per unit of area, in kg/m^2
Mixed Wood Shield	3,556.2	23.5
Atlantic Shield	2,815.8	18.6
Mixed Wood Plains	2,845.6	18.5
Central USA Plains	426.2	16.9
Southeastern USA Plains	7,230.5	12.9
Ozark, Quachita-Appalachian Forests	4,646.0	14.0
Mississippi Alluvial and Southeast Coastal Plains[1]	2,660.8	15.5
Eastern United States, total	**24,181.2**	**15.7**

[1]Includes the Everglades and Texas-Louisiana Coastal Plain level II ecoregions for the analysis of this assessment.

Act (RPA) assessment produced by the Forest Service for the conterminous United States and coastal Alaska shows a steady increase of the total carbon stock from 44,643 TgC in 1990 to 48,437 TgC in 2010, and the net annual change varied from 185.7 teragrams of carbon per year (TgC/yr) in 1990 to 248.6 TgC/yr in 2005 (U.S. Department of Agriculture, Forest Service, 2012).

Studies confirm that ecosystems in the United States are a carbon sink (Houghton and others, 1999; Pacala and others, 2001; Pan and others, 2011). There are differences in definitions, boundaries of reporting classes (ecosystems), components, and methods used in these studies. However, results from these studies were useful as references to this assessment. For example, the most recent national GHG inventory report by the EPA covering the conterminous United States suggested a net sink of –246.8 teragrams of carbon (TgC) in 2011 by forests, grasslands/shrublands, agricultural lands, and settled areas, which represented an offset of about 15.4 percent of the total fossil fuel CO_2 emissions in the United States (U.S. Environmental Protection Agency, 2012). Most of the –226.7 TgC/yr (–75.6 grams of carbon per square meter per year (gC/m^2/yr)), as a mean value, of carbon sequestration between 2007 and 2011 came from forest lands. Data from the Forest Inventory and Analysis Program of the Forest Service were the common basis for the EPA report as well as other similar publications. In describing the methodology and analysis using the Forest Service data, Heath and others (2011a,b) estimated that the combined net carbon flux of forest ecosystems and urban trees in the conterminous United States, including pools of soil organic carbon and HWD products, was about –223.5 TgC/yr (–89.8 gC/m^2/yr) in 2002, –244.1 TgC/yr (–97.5 gC/m^2/yr) in 2005, and –241.8 TgC/yr (–95.4 gC/m^2/yr) in 2008.

A net forest carbon flux of –180 TgC/yr in the conterminous United States between 1992 and 2001 was derived (Zheng and others, 2011) by relating forest cover change from the NLCD data with carbon density estimates from the Forest Inventory Analysis (FIA). Carbon removed from forests as a result of wildfire (9.9 TgC/yr) and HWD products (142 TgC/yr) was included in deriving the net forest carbon flux. However, it is not clear from Zheng and others (2011) whether including forest harvesting from the FIA inventory and NLCD forest cover change data resulted in double counting of carbon removed from the landscape. Using a relationship between forest age derived from forest inventory and carbon recovery derived from remote sensing, Williams and others (2012) arrived at a much lower total net forest carbon flux (–47 TgC/yr), together with carbon removed from forest harvest (107 TgC/yr) and wildland fire (10 TgC/yr) for the conterminous United States in 2005.

Three recent studies provided estimates for regional forest carbon flux and balances for areas that approximately correspond to the area of study for this assessment. For two Forest Service regions (the Southern and Eastern regions), Heath and others (2011a,b) reported forests of all ownerships had a net sequestration rate (excluding soil organic carbon) ranging between –132.2 and –42.1 TgC/yr, with a mean value of –88.2 TgC/yr, or about two-thirds the total estimate in the conterminous United States. On a per-unit-area basis using areas of NLCD forest classes in the two regions, the mean carbon sink was about –57.2 gC/m^2/yr (excluding woody wetlands). Turner and others (1995) analyzed regional forest carbon change from the FIA forest survey data collected in the 1990s and estimated regional sink strengths to be –190 gC/m^2/yr for the Northeast region, –290 gC/m^2/yr for the Southeast region, and –250 gC/m^2/yr for the South-Central region. For comparison, Williams and others (2012) provided forest carbon flux estimates for four of several regions in the conterminous United States (Northeast, Southeast, South-Central, and northern States in the Great Lakes region). The total gross forest carbon flux for 2005 was –114 TgC/yr for the four regions before subtracting carbon removal terms, including forest harvesting and wildland fire emission.

In addition to estimates of forest carbon fluxes in recent years, long-term trends and future projections have also been reported. Between 1600 and 1800, forests were in a state of carbon balance. The 19th century saw significant land-use-related carbon emissions due to land clearing, followed by regrowth of forests and resulting carbon sequestration in the 20th century (Birdsey and others, 2006). Projected to future years based on the IPCC emission scenarios (Nakićenović and others, 2000), forest lands in various regions in the conterminous United States could become a net carbon source (U.S. Department of Agriculture, Forest Service, 2012) or weakened carbon sink (Hurtt and others, 2002; Birdsey and others, 2006; Liu and others, 2012b). As a comparison, the projected future forest carbon sink in the Western United States ranged between –10.8 and –100.2 gC/m^2/yr, depending on land-use scenarios, future climate projections, and biogeochemical models used (Liu and others, 2012b).

Carbon sequestration is a function of the biogeochemical exchange between the atmosphere and biosphere, including soils, and is strongly influenced by key controlling processes such as land use, land-management activities, ecosystem disturbances, and climate (Bachelet and others, 2003; Law and others, 2004; Running, 2008). In the Southeastern United States, where the LULC change is the most active in the recent decades, estimation of carbon stocks and fluxes and effects of primary driving processes are of particular importance. Tian and others (2010, 2012) estimated from several related studies covering 13 Southeastern States extending from Texas to Virginia that the total terrestrial ecosystem carbon stock was about 30.2 PgC, with 64 percent as soil organic carbon (SOC). Between 1951 and 2007, there has been a trend of increase in carbon stored in the ecosystems, totaling –2.0 PgC over the 57 years, or a mean uptake of –35 TgC/yr. Among different land and vegetation cover types, the net primary production was 679 gC/m^2/yr by broadleaf deciduous forests, 715 gC/m^2/yr by needleleaf evergreen forests, 676 gC/m^2/yr by herbaceous and woody wetlands, and 520 gC/m^2/yr by agricultural lands. Using LULC change data derived from a sample of Landsat imagery and a biogeochemical model, Liu and others (2004) estimated that, between 1973 and 2000, the Southern region averaged a carbon sink of 89 gC/m^2/yr. Albani and others (2006) analyzed the effects of LULC change and timber harvesting for all terrestrial ecosystems in the Eastern United States and estimated that the net carbon flux ranged from 0.21 petagram of carbon per year (PgC/yr) in the 1980s to 0.25 PgC/yr in the 1990s and 0.26 PgC/yr in 2008; they also projected that the net carbon flux in future years would be about 0.25 PgC/yr.

The specific effects of various controlling processes are difficult to estimate. Land-use change in the Southern United States is often characterized by conversions from forests to agricultural and developed areas and by forestry practices of economically determined rotation ages and planting improved stock, which have led to dynamic cover loss and gain patterns. Woodbury and others (2006) attributed changes in carbon balance to land-use conversions, and estimated that, between 1990 and 2004, carbon gains as the result of afforestation outweighed carbon losses due to deforestation by 49 to 88 TgC. Over a 50-year period, converting marginal pasture lands to southern pine plantations could result in improved sequestration from an average of 8.3 megagrams of carbon per hectare (MgC/ha; 0.83 kgC/m^2) by marginal pastures to 58 MgC/ha (5.8 kgC/m^2) by southern pine plantations (Lee and Dodson, 1996). Tian and others (2012) noted that the strength of the carbon sink in the Southeastern States may be attributed to fertilization by increased CO_2 in the atmosphere and nitrogen deposition in the past five to six decades, although such effects could be easily overestimated if relying on simulation modeling alone (Albani and others, 2006).

Climate is also a major controlling factor in the direction and size of carbon sources or sinks. For example, Chen and others (2012) estimated that the terrestrial ecosystems in the Southeast (the 13 Southeastern States from Texas to Virginia) could be a carbon source (emitting 72.5 TgC/yr) during the driest 10 years in the recent record or a sink (–81.45 TgC/yr) during the wettest 10 years in the recent record. Keenan and others (2012) noted that changes in climate (including lengthening of the growing season) may be responsible for increases in forest growth rates and carbon uptake in eastern North America and specifically the observed increases in NEE in the Harvard Forest in Petersham, Massachusetts, from 1992 to 2009.

The effects of wildland fires on carbon sequestration in ecosystems include (1) the immediate release of GHGs from combustion emissions and (2) the long-term combined effects of decomposing biomass, which releases carbon into the atmosphere, and regenerating vegetation, which increases the uptake of carbon (Law and others, 2004; Hurteau and Brooks, 2011). Hawbaker and Zhu (2012) estimated that the immediate release of GHGs from wildland fires in the Western United States in recent years offset about 10 percent of the total ecosystem carbon sequestration. Although fires of ecosystems in the Eastern United States are less frequent and intense than those of the Western United States and are not expected to affect carbon balance on a comparable scale (chap. 4 of this report), fires in the Eastern United States have had unique and significant effect on individual ecosystems and in specific locations, such as the carbon-rich pocosin peatland soils along the Atlantic coastal regions. Emissions from a fire that burned Pocosin Lakes in North Carolina in 1985, for example, were estimated to range between 1.01 and 3.76 TgC, depending on depth of peat consumed (Poulter and others, 2006). To illustrate the importance of peat fires in the Atlantic coastal ecosystems, this one fire emitted as much as 30 percent of the average annual fire emissions of the ecosystems in the Western United States (Hawbaker and Zhu, 2012).

Development pressure in the Southeastern States has a significant effect on the overall carbon balances, but estimates of the effects of development pressure have been variable. Milesi and others (2003), using remote sensing data, estimated that development in the Southeastern States was responsible for a reduction of 3.04 TgC/yr in NPP by terrestrial ecosystems. However, Zhang and others (2012) estimated the loss of carbon from southeastern ecosystems to be 3.4 TgC/yr between 1945 and 2007 and suggested that whether developed areas were a carbon source or sink is dependent on whether the lands were converted to developed areas from forests or agricultural lands. Forests in established developed areas remain a sizeable carbon sink and are responsible for about 8 to 10 percent of the total forest carbon sequestration in the conterminous United States (Nowak and Crane, 2002; U.S. Environmental Protection Agency, 2012).

The Eastern United States is a major agricultural region. Agricultural lands account for about 32 percent of the total area in the region, mostly concentrated in the Corn Belt of the Ohio River Valley and the Mississippi Alluvia Plains as well as interspersed throughout the eastern plains. In a synthesis study for tillage practices in the conterminous United States, West and Marland (2002) estimated that the average rates of carbon sequestration in agricultural soils were about 0 gC/m^2/yr in conventionally tilled lands and –37 gC/m^2/yr in no-till lands. West and Marland (2002) further noted that, when taking soil carbon sequestration and farm operation emissions into calculations, the average net carbon flux would be 16.8 gC/m^2/yr for conventional tillage and –20 gC/m^2/yr for no-till practices. However, when considering only SOC balance in farmlands in the Midwest, Christopher and Mishra (2009) found that tillage effects in a whole profile were mixed and there was no significant difference in SOC between no-till and conventional till farming; the two practices yielded an average SOC stock of 4.8 kgC/m^2.

A majority of the freshwater and saltwater wetlands with herbaceous and woody vegetation cover in the conterminous United States are located in the East. As mapped by the NLCD (Vogelmann and others, 2001; Homer and others, 2007), the wetlands in the conterminous United States cover about 312,571 square kilometers (km^2), or 4 percent of the land mass of the conterminous United States. In the Eastern United States, wetlands total 272,442 km^2, representing 8.9 percent of the total area in the region and 87 percent of all wetland areas in the conterminous United States. These wetlands include peat and mineral soil types. Large wetland areas are distributed in the Great Lakes region, particularly in northern Minnesota and Wisconsin, and in the coastal plains of the Atlantic coast and the Gulf of Mexico.

Bridgham and others (2006) synthesized data from published sources to estimate the total rates of carbon stock and sequestration in the wetlands of the conterminous United States to be 19,600 TgC and –17.3 TgC/yr, respectively. Using the total wetland area estimate of 431,000 km^2, these estimates translate to 45.5 kgC/m^2 for the per-unit-of-area of carbon stock and –40.1 $gC/m^2/yr$ for the per-unit-of-area sequestration rate in the conterminous United States. Freshwater peatlands and mineral soil wetlands store most of wetland carbon in the conterminous United States; however, tidal marshes have the highest per-unit-of-area sequestration rate at –220 $gC/m^2/yr$, followed by peatlands (–71 $gC/m^2/yr$) and mineral soil wetlands (–17 $gC/m^2/yr$). Sequestration in estuaries is mostly accomplished as the result of sedimentation (Bridgham and others, 2006). For comparison, Armentano and Menges (1986) estimated a range of soil carbon accumulation rates that ranged from –48 $gC/m^2/yr$ in peatlands in the northern part of the region to –2.25 $gC/m^2/yr$ in peatlands in Florida. Chmura and others (2003) reported carbon accumulation in the coastal tidal marshlands of –136.5 $gC/m^2/yr$ and –296.6 $gC/m^2/yr$ for the Atlantic and the gulf coast areas, respectively. Methane emissions from ecosystems in the conterminous United States were estimated to be about 50.4 teragrams of CO_2-equivalent per year (Bridgham and others, 2006) and were mostly emitted from freshwater mineral-rich soil in wetlands because of the low salinity content of this soil type (Poffenbarger and others, 2011).

The emission, transport, and sequestration of carbon by aquatic ecosystems should be considered when estimating carbon balances in ecosystems (Chapin and others, 2006; Cole and others, 2007; Tranvik and others, 2009). National-scale studies suggest that lateral transport of carbon fixed within the conterminous United States and exported to coastal areas can represent about 10 percent of the total carbon sequestered in forests (trees and soils), croplands, and shrublands (Pacala and others, 2001; Butman and Raymond, 2011; Stackpoole and others, 2012). In addition to the role of aquatic ecosystems in transporting and sequestering carbon, recent global studies have indicated that inland waters can also be sources of carbon emitted into the atmosphere (Cole and others, 2007; Tranvik and others, 2009). In a carbon flux and sequestration assessment for the Western United States (Stackpoole and others, 2012), the mean values of emission of CO_2 from lateral fluxes, water surfaces, and sequestration (burial) in lakes and reservoirs were estimated to be 7.2 TgC/yr, 28.2 TgC/yr, and –2.4 TgC/yr, respectively.

The above-referenced studies produced estimates of net carbon flux that were spatially and temporally variable; however, these estimates also provide a set of reference points against which this assessment may be compared. Estimates for the agricultural lands, forests, and wetlands ecosystems in the Eastern United States from these recent studies are summarized in table 1–4.

Table 1–4. Mean net carbon flux per unit of area from a selected sample of studies for the four major terrestrial ecosystems used in the assessment of carbon storage and fluxes in the Eastern United States.

[The four major terrestrial ecosystems are forests, agricultural lands, grasslands/shrublands, and wetlands. C, carbon; $gC/m^2/yr$, grams of carbon per square meter per year; $kgC/m^2/yr$, kilograms of carbon per square meter per year; SOC, soil organic carbon]

Ecosystem	Geography	Estimates, units, and type of estimate	Source	Timeframe of the sourced work
Agricultural lands	Conterminous United States	1.5 $gC/m^2/yr$, net C flux	U.S. Environmental Protection Agency (2012b)	2007–2011
	Conterminous United States	0 $gC/m^2/yr$, net C flux by conventional tillage	West and Marland (2002)	1990s
	Conterminous United States	–37 $gC/m^2/yr$, net C flux by no-till farming	West and Marland (2002)	1990s
	Midwestern United States	4.8 kgC/m^2, mean SOC stock	Christopher and Mishra (2009)	2006
Forests	Conterminous United States	–84.6 $gC/m^2/yr$, net C flux	Heath and others (2011a,b)	2002, 2005, 2008
	Major Eastern United States	–82.8 $gC/m^2/yr$, net C flux	Williams and others (2012)	2005
	Eastern United States	–243 $gC/m^2/yr$, net C flux	Turner and others (1995)	Early 1990s
Peat wetlands	Northern United States	–37.8 $gC/m^2/yr$	Yu (2012)	1998–2009
Tidal marshlands	Atlantic and gulf coast areas	–136.5 $gC/m^2/yr$ and –296.6 $gC/m^2/yr$	Chmura and others (2003)	1990s
Wetlands	Conterminous United States	–40.1 $gC/m^2/yr$	Bridgham and others (2006)	Various, previous decades