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Carbon sequestration in the U.S. forest sector from 1990 to 2010

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Abstract

Forest inventory data supplemented with data from intensive research sites and models were used to estimate carbon stocks and sequestration rates in U.S. forests, including effects of land use change. Data on the production of wood products and emission from decomposition were used to estimate carbon stocks and sequestration rates in wood products and landfills. From 1990 through 2005, the forest sector (including forests and wood products) sequestered an average 162 Tg C $year^{-1}$. In 2005, 49% of the total forest sector sequestration was in live and dead trees, 27% was in wood products in landfills, with the remainder in down dead wood, wood products in use, and forest floor and soil. The pools with the largest carbon stocks were not the same as those with the largest sequestration rates, except for the tree pool. For example, landfilled wood products comprise only 3% of total stocks but account for 27% of carbon sequestration. Conversely, forest soils comprise 48% of total stocks but account for only 2% of carbon sequestration. For the tree pool, the spatial pattern of carbon stocks was dissimilar to that of carbon flux. On an area basis, tree carbon stocks were highest in the Pacific Northwest, while changes were generally greatest in the upper Midwest and the Northeast. Net carbon sequestration in the forest sector in 2005 offset 10% of U.S. CO_2 emissions. In the near future, we project that U.S. forests will continue to sequester carbon at a rate similar to that in recent years. Based on a comparison of our estimates to a compilation of land-based estimates of non-forest carbon sinks from the literature, we estimate that the conterminous U.S. annually sequesters 149–330 Tg C $year^{-1}$. Forests, urban trees, and wood products are responsible for 65–91% of this sink.
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Keywords: Carbon budget; Forest ecosystem; Carbon sink; Carbon sequestration; Land use change

1. Introduction

Globally, concentrations of CO_2 in the atmosphere are rising by only 3.2 Pg C $year^{-1}$, while fossil fuel emissions release 6.3 Pg C $year^{-1}$, implying the existence of a large carbon sink of 2.7–3.1 Pg C $year^{-1}$ (Prentice et al., 2001; Gurney et al., 2002). Identifying the location and mechanism for this sink is necessary to improve understanding of the global carbon cycle and to guide national and international policy and management efforts. Based on the inversion of atmospheric transport models in the TransCom3 project, North America is responsible for 60% of the terrestrial carbon sink (Gurney et al., 2002). Forests in the conterminous U.S. probably are responsible for much of the North American sink, because Canadian forests are estimated to have been a small net source of carbon in recent years (Chen et al., 2000; Goodale et al., 2002; Gurney et al., 2002), and because non-forest sinks are smaller than forest sinks (Pacala et al., 2001; Goodale and Davidson, 2002; Jackson et al., 2002; Ogle et al., 2003). Because of its probable large size, it is important to make the best possible estimates of the net carbon flux in forests in the conterminous U.S.

One method of estimating the net carbon flux in forests is to begin with forest inventory data collected from statistically-based surveys and then estimate carbon stocks using relationships between inventory variables and carbon stocks augmented with models for pools that are not sampled (Intergovernmental Panel on Climate Change, 1997, henceforth IPCC). Although this method does not directly measure carbon fluxes, it is useful in areas or countries with systematic forest inventories because of the large number of sampling points where forest attributes are measured directly and because carbon is directly related to some measured forest attributes. In the U.S., data collected by the U.S. Department of Agriculture (USDA) Forest Service Inventory and Analysis program (FIA) have been used by our research group and others to estimate carbon stocks and net fluxes in forests (Birdsey, 1992; Birdsey and Heath, 1995; Hoover et al., 2000;

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Martin et al., 2001; Goodale et al., 2002; Ney et al., 2002). Forest inventory data are a useful basis for estimating carbon stocks and net fluxes for the sampled area. However, not all forest carbon pools are represented well by attributes measured in forest inventories, and so there is a need to augment survey data with data from intensive research sites and models (Birdsey and Heath, 1995; Smith and Heath, 2002, 2004; Heath et al., 2003; Smith et al., 2003).

This paper describes the approach we used to develop estimates of greenhouse gas emissions and sequestration by U.S. forests and in wood products (i.e., the forest sector). Such estimates are used to meet U.S. reporting commitments under the United Nations Framework Convention on Climate Change (UNFCCC). Annual estimates are presented because annual estimates from the base year of 1990 to the present are required under the UNFCCC. Estimates are also presented for 2010 to indicate a likely trajectory of net carbon flux in forests over the next several years. This study improves on previous inventory-based estimates of forest carbon stocks and net fluxes (Birdsey and Heath, 1995; Turner et al., 1995a, 1995b) in several ways. We used new inventory data, particularly new data and revised estimates included in the 2002 Resources Planning Act Assessment (RPA) forest inventory database (http://fia.fs.fed.us/rpa.htm). We also used data from intensive research sites to improve estimates of forest carbon pools such as the forest floor that have not been not measured in most forest inventories (Smith and Heath, 2002). Improvements have also been made in estimating carbon on public forest lands (Smith and Heath, 2004). Estimates of tree carbon stocks were improved by using new biomass equations derived from a comprehensive literature review and analysis (Jenkins et al., 2003; Smith et al., 2003). The latest version of the FORest CARBon model (FORCARB) model, FORCARB2, was used to project future forest carbon stocks and stock change. New estimates of land use change effects on forest floor and soil carbon stocks were developed based on historical data using gross (two-way) land use transitions. Finally, the actual survey year was used rather than the nominal reporting year for RPA forest inventory databases.

At the national, continental, and global scale, more robust estimates of terrestrial carbon sources and sinks will depend on reconciling estimates derived from different methods such as atmospheric inversion modeling, inventory-based approaches, ecosystem modeling, and land use change modeling (Houghton, 2003a, 2003b; House et al., 2003; Pacala et al., 2001). We improve upon the summary of U.S. terrestrial carbon sinks presented by Pacala et al. (2001), to help determine the role of forests, urban trees, and wood products in the U.S. carbon balance.

2. Methods

For estimating net carbon flux, carbon in forest ecosystems can be divided into the following five storage pools.

- *Trees*: trees greater than 2.54 cm in diameter, including the coarse roots, stems, branches, and foliage of living trees, and standing dead trees (fallen dead trees are included in the ‘‘down dead wood’’ pool).
- *Understory vegetation*: including herbs, shrubs, bushes, and trees less than 2.54 cm in diameter, including the roots, stems, branches, and foliage.
- *Down dead wood*: including logging residue and other coarse dead wood 7.5 cm in diameter or greater on the ground, and stumps and roots of stumps.
- *Forest floor*: organic carbon (litter, duff, humus, and fine woody debris) above the mineral soil including woody fragments with diameters of up to 7.5 cm.
- *Soil*: including all organic material in soil to 1 m in depth, except coarse living roots of trees and roots of understory vegetation.

The net change in forest carbon is not equivalent to the net flux between forests and the atmosphere because timber harvests do not cause an immediate flux of carbon to the atmosphere. Instead, harvesting transfers carbon to a ‘‘product pool.’’ Once in a product pool, the carbon is emitted over time as CO_2 and other gases when the wood product combusts or decays. If wood products are disposed of in landfills, the carbon contained in the wood may be released many years or decades later, or may be stored almost permanently in the landfill.

The key steps in calculating carbon flux in trees, soil, and forest floor are summarized in Fig. 1. In general we used a stock change approach to estimate net fluxes in carbon pools defined above. In this approach, carbon stocks are estimated at two or

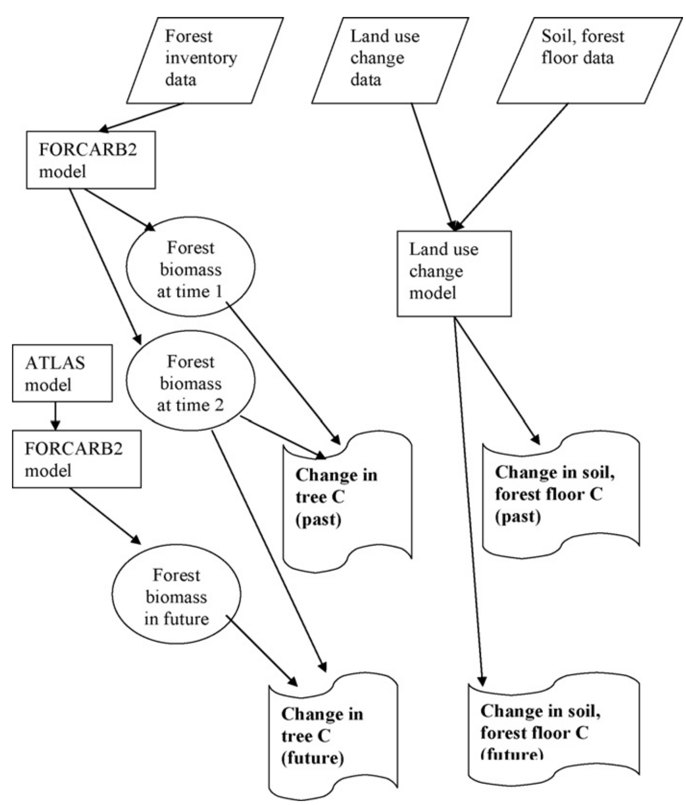

Fig. 1. Key steps in calculation of carbon flux in forest biomass, forest floor and soil. Steps are not shown for wood products. See text for further information about all carbon pools.

more different times, and net annual carbon flux is estimated by subtracting one stock estimate from the other and dividing by the number of years between stock estimates. Estimates of carbon stocks on forest lands in the conterminous U.S. during recent decades were based on periodic forest inventories conducted by the USDA Forest Service, augmented with data from the literature and models. As shown in Fig. 1, projections of current and future forest carbon stocks were made with the FORCARB2 model, based on predicted future forest inventory from the aggregate timberland assessment system (ATLAS) model (Mills and Kincaid, 1992). Estimates of changes in forest floor and soil carbon stocks were developed by accounting for the effect of past land use transitions. Estimates of carbon fluxes from harvested wood were developed by accounting for the variable rate of decay of harvested wood according to its disposition pool (e.g., product-in-use, landfill, combustion). Different data sources and/or methods were used to estimate the carbon stocks and net flux in (1) live and dead trees, understory, and down dead wood, (2) forest floor and soils, and (3) harvested wood products. Therefore, methods for calculating stocks and stocks changes or net fluxes for these pools are described separately below.

2.1. Tree, understory, and down dead wood carbon stocks

2.1.1. Forest inventory data

Forest inventory data in the United States were obtained from three FIA RPA databases. These databases contain records for between 146,302 (1987) and 174,401 (2002) individual forest plots throughout the U.S. These databases were developed in support of RPA reports of forest condition throughout the U.S. based on the most recent available data for each State. Summaries of these databases were published for the nominal reporting years of 1987 (Waddell et al., 1989), 1997 (Smith et al., 2001), and 2002 (Smith et al., 2004b). We used the FORCARB2 model to estimate of carbon stocks in the tree, understory, and down dead wood pools were at the level of individual forest plots, and then aggregated to individual states based on the area represented by each plot.

The actual survey dates of individual forest inventory plots are always older than the nominal RPA reporting year, particularly earlier when surveys were conducted periodically in each State. For this reason, the phrase ''reporting year'' is used to distinguish between the RPA reporting year and the actual survey year during which data were collected. Forest inventory data for each State were selected from the three RPA databases for each periodic inventory that occurred between 1991 and 2002, and for the most recent inventory prior to 1991. We calculated the average field survey year from the inventory plot field survey dates for each State for each periodic survey. The average survey years for each State are shown in appendix Table A1, as is the RPA database from which each State survey was selected. For carbon estimation, key FIA data elements include growing stock volume, age, forest type (see appendix Table A2), and ownership group of the plot. The effect of using the survey year rather than the reporting year is shown in Fig. 2 and this issue is addressed further in Section 4.

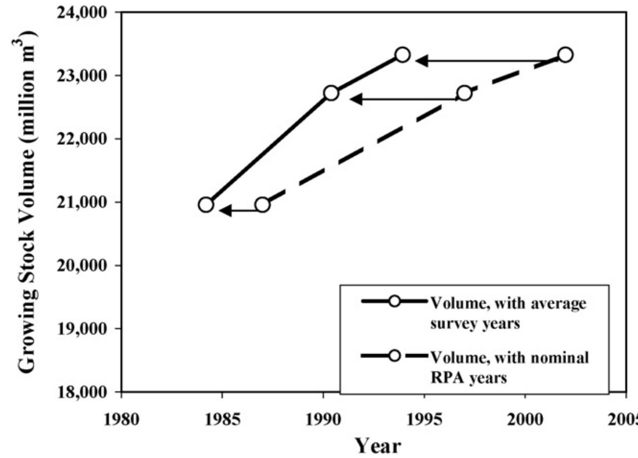

Fig. 2. Effect of using survey years on estimates of growing stock volume of trees on timberland. Using the average survey years shifts each stock estimate back for several years, as shown by the arrows. See text for description of FIA data.

Historically, the main purpose of the FIA program has been to estimate timber supply: forest area, volume of growing stock, timber products output, and utilization factors. Growing stock is a classification of timber inventory that includes live trees of commercial species that meet specified standards of quality (Smith et al., 2001). Timber products output refers to the production of industrial roundwood products such as logs and other round timber generated from harvesting trees, and the production of bark and other residue at processing mills (Haynes, 2003). Utilization factors relate inventory volume to the volume cut or destroyed when producing roundwood (May, 1998). We used all of these data to estimate carbon stocks or fluxes in forest or wood product pools. For more information about using forest inventory data to estimate carbon stock change, see Birdsey and Heath (2001), Smith and Heath (2004), and Smith et al. (2004a, 2004b).

2.1.2. Forest sector modeling system

As summarized in Fig. 1, projections of forest carbon stocks for the year 2010 were made by linking the FORCARB2 model to ATLAS (Mills and Kincaid, 1992) model projections of future forest inventory. ATLAS is one model of a compilation of models that collectively represents the forest sector modeling system used for USDA Forest Service RPA timber assessments from the late 1980s to the present (Haynes, 2003). The system includes area change (Alig, 1986; Alig et al., 2003), timber demand and supply (TAMM; Adams and Haynes, 1980), pulp and paper demand and supply (NAPAP; Ince, 1994) and an inventory model based on FIA data (ATLAS; Mills and Kincaid, 1992). Many of these models are econometric and are designed to project the demand and supply and prices in the forest sector. Results of the modeling system include growing stock volume, forest areas, harvests, and primary product production. The assumptions and results of this modeling system are described by Haynes (2003).

The FORCARB model (Heath and Birdsey, 1993; Plantinga and Birdsey, 1993; Heath et al., 1996; Heath and Birdsey, 1997) uses forest inventory data on growing stock volume, forest areas, and harvests, or projections of such information from the ATLAS model to estimate carbon in live and dead trees using biometrical relationships between carbon and live tree growing stock volume. FORCARB also estimates carbon stocks in all other forest storage pools including soils (Birdsey and Heath, 1995). The most recent version of FORCARB is FORCARB2 (Heath et al., 2003). The model WOODCARB (Skog and Nicholson, 1998) uses data and methods reviewed above to estimate carbon in harvested wood. The most recent version of the WOODCARB model is WOODCARB II (Skog et al., 2004).

The FORCARB2 model can make projections for multi-State regions of the conterminous U.S. based on ATLAS model projections of future inventory. To estimate forest carbon stocks for individual states for the year 2010, we disaggregated the regional model projections into individual states based on the relative proportion of carbon in forests in each State estimated as described above from the most recent available forest inventory data.

2.1.3. Live and standing dead trees

The minimum-sized tree included in FIA data is 2.54 cm diameter at breast height (1.3 m). We estimated the biomass of live trees by applying equations that convert growing stock volume from the plot-level FIA data to total live tree dry biomass for a number of forest types (Smith et al., 2003). In some cases, separate equations are used for different forest ownerships (public or private) and for different regions of the country (Smith et al., 2003). We then divided biomass estimates by two to obtain estimates of carbon in living trees (i.e., it was assumed that dry biomass is 50% carbon). A similar approach was used to estimate the biomass of standing dead trees using equations specifically developed for standing dead trees (Smith et al., 2003).

2.1.4. Understory vegetation

The understory contains only a small portion of the total carbon stocks in forests. To estimate the carbon density in understory vegetation for each average survey year in each State, we used equations based on Birdsey (1996) applied to the plot-level FIA data. These equations use the estimated tree carbon density, the region, and the forest type to predict the amount of carbon in the understory. There was assumed to be a maximum carbon content in the understory when only small trees were present, with a subsequent decline to a minimum as the stand matures. The maximum understory carbon density is predicted to occur when the plot contains no trees greater than 2.54 cm in diameter, and ranges from 1.8 to 4.8 t C ha^{-1}, depending on forest type. The minimum understory carbon density values are predicted to be 0.5% of the tree carbon density; this minimum occurs in mature stands with high tree carbon density.

2.1.5. Down dead wood

We estimated down dead wood carbon using a procedure similar to that used for estimating carbon in understory vegetation. For each average survey year in each State, we made estimates for each forested plot from the RPA databases using predictions of pulses of down dead wood after harvest with harvests based on the ATLAS model (Mills and Kincaid, 1992). Down dead wood carbon was estimated for each major forest type in each region by multiplying the ratio for the forest type and region shown in appendix Table A2 by the live tree carbon density for the plot. These ratios implicitly account for the pulse of down dead wood after harvest in that some down dead wood is predicted to be present in young stands.

2.1.6. Forest floor and soil carbon

We assumed that changes in land use are the main factor causing carbon emission or sequestration in the forest floor and soil, so that lands that had not undergone a transition in land use during the 20th century had no net flux of carbon from the forest floor or soil pools. Changes in these pools due to land use change were estimated by means of a ‘‘book-keeping’’ type model that predicts the effects of land use transitions from 1907 to the present (Woodbury et al., 2006). For historical land use transitions, data have recently been extracted and summarized from USDA Forest Service publications, U.S. Department of Commerce publications, USDA Natural Resources Conservation Service National Resources Inventory (NRI) reports and other sources (Birdsey and Lewis, 2003). Historical data on the area of forestland in the U.S. have been summarized by Smith et al. (2001). Our land use change model uses historical data on gross (two-way) transitions between forest, pasture, plowed agriculture, and urban lands, along with equations describing changes in carbon over many decades, for each type of land use change (Woodbury et al., 2006). Aggregated changes in the forest floor and soil carbon pools are estimated in different forest types for large regions of the U.S. (see Fig. 3). Use of gross rather than net land use transition data is important because afforestation causes a gradual gain in carbon stocks for many decades, while deforestation causes a much more rapid loss in carbon stocks. In the model, a transition matrix

Fig. 3. Regions in U.S. used for model projections and estimates of changes in down dead wood. Similar regions were used for estimate of changes in forest floor, and soil carbon pools, except that all Pacific regions were combined, both Rocky Mountains regions were combined, and the Northern Lakes and North Central regions were divided into Great Plains (ND, SD, NE, KS) and North Central regions (remaining states).

represents the area of land undergoing each type of transition for each forest type for each time period. To model this system, changes in forest floor carbon stocks and soil carbon stocks must be estimated separately for each type of land use change for each date; that is, for each cell in the transition matrix. Because soil and forest floor carbon stock estimates depend on the length of time since a land use transition, each transition is treated as a separate ''cohort'' and its carbon stock is tracked separately from other cohorts. Because the model predicts that it will take many decades for soil carbon to reach a new equilibrium after afforestation, all such transition cohorts are tracked separately from the year of the land use transition until the end of the model run. Equations representing changes in forest floor carbon are based on the model of Smith and Heath (2002) and equations representing changes in soil carbon are based on data from the literature (Woodbury et al., 2006) and data on soil carbon density by forest type. Following deforestation to plowed agriculture, soil carbon is assumed to decrease 25%, with most of the decrease in the first decade. After afforestation of plowed agricultural land, soil carbon is assumed to increase slowly to a characteristic level for each forest type, with most of the increase occurring by 75 years. Data on soil carbon density were obtained from the national State Soil Geographic Data Base (STATSGO) spatial soils database (USDA, 1994). These data were combined with FIA data on the location and area of different forest types to estimate soil carbon density for all forest types (Johnson and Kern, 2003).

2.1.7. Harvested wood carbon

We estimated carbon stock changes in wood products and wood discarded in landfills based on the methods described by Skog and Nicholson (1998). Carbon stocks in wood products in use and wood products stored in landfills were estimated from 1910 to 2010 based on several sets of historical data from the USDA Forest Service. These data include estimates of wood product demand, trade and consumption (Hair and Ulrich, 1964; Ulrich, 1989; Howard, 2001). In addition to these historical data, projections from the forest sector modeling system were used. Annual estimates and model projections of the production of wood products were used to divide consumed roundwood into wood product, wood mill residue, and pulp mill residue. To estimate the length of time that products remain in use before disposal, wood and paper products were divided into categories, each with an estimated product half-life (Skog and Nicholson, 1998). After disposal, an estimate of the amount of waste that is burned was made. For products entering dumps or landfills, the proportion of carbon emitted as CO_2 or CH_4 was estimated. By following the fate of carbon from the wood harvested in each year from 1910 onward, the change in carbon stocks in wood products, the change in carbon stocks in landfills, and the amount of carbon emitted to the atmosphere with and without energy recovery were estimated for each year through 2010. To account for imports and exports, the production approach was used: carbon in exported wood was counted as if it remained in the United States, and carbon in imported wood was not counted (Heath et al., 1996). From 1990 until the present, the amount of carbon in exported wood averaged 6 Tg C year^{-1}, with little variation from year-to-year. For comparison, imports (which were not included in the harvested wood net flux estimates) increased from 7.2 Tg C year^{-1} in 1990 to 13 Tg C year^{-1} in 2002. Further description of this methodology is presented by Skog and Nicholson (1998).

2.2. Annual carbon stock change estimates

After estimation of all forest carbon stocks, the final step was to estimate the annual net carbon stock change for each forest carbon pool. For forest floor, soil, and harvested wood, annual estimates of stock change were made as described above.

For the live and standing dead tree, understory, and down dead wood carbon pools, carbon stocks were estimated as described above for the latest survey year prior to 1990 and all survey years since 1990 (typically one or two, appendix Table A1). We made regional estimates for the year 2010 using the FORCARB2 model and disaggregated into estimates for individual states as described above. We estimated carbon stocks in all other years from 1990 to 2005 for each State by linear interpolation between survey years or between the most recent survey year and the model projection for 2010. Then we calculated annual carbon stock changes by subtracting carbon stocks in the subsequent year from those in the current year (because stocks are estimated as of 1 January, and because an increase in stocks is given a negative sign). Annual carbon stocks and stock changes for each pool were then summed over all states in the conterminous U.S. to derive a national estimate for each year.

3. Results

3.1. Current carbon stocks

Substantial regional variation was found in the density of carbon in forests on an area basis. Fig. 4 shows the average carbon density in live and standing dead trees by State estimated for 2005. In this figure, abrupt changes occur at State boundaries, because a single estimate of tree carbon stocks was made for each State. Carbon density in live and dead trees is

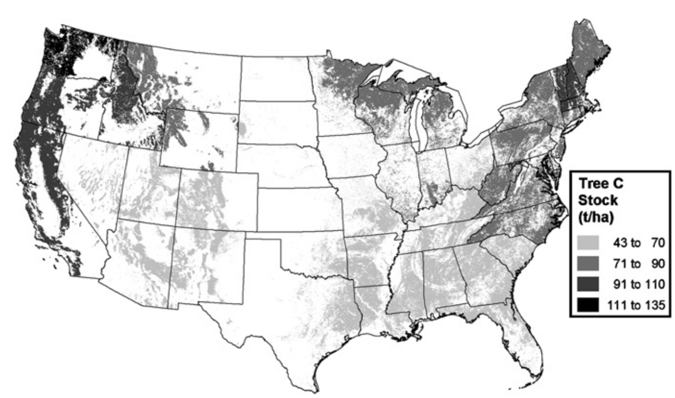

Fig. 4. State-wide average carbon stocks in live and dead trees in 2005.

Table 1
Annual net changes in carbon stocks in forest and harvested wood from 1990 to 2010

	Year																
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2010
Tg C																	
Trees	−97	−83	−80	−65	−81	−99	−127	−109	−84	−75	−79	−78	−78	−78	−78	−78	−78
Down dead wood	−9	−9	−8	−8	−9	−12	−17	−17	−16	−17	−18	−18	−18	−18	−18	−18	−18
Understory	0	1	−2	−2	−2	−2	−1	0	0	1	1	1	1	1	1	1	1
Forest floor	0	0	0	0	0	0	0	−3	−3	−3	−4	−4	−4	−4	−2	−2	−2
Forest soils	−2	−2	−2	−2	−2	−2	−2	−3	−3	−3	−4	−4	−4	−4	−4	−4	−4
Forest sub-total	−108	−94	−93	−78	−95	−115	−148	−133	−106	−98	−104	−103	−103	−103	−101	−101	−100
Wood products	−13	−11	−13	−15	−17	−15	−15	−16	−14	−17	−16	−16	−16	−16	−16	−16	−16
Landfilled wood	−44	−43	−43	−41	−41	−41	−41	−42	−42	−42	−41	−42	−42	−42	−42	−42	−42
Wood sub-total	−57	−54	−55	−56	−57	−55	−57	−58	−56	−59	−57	−58	−58	−58	−58	−58	−58
Total	−165	−148	−149	−133	−153	−171	−204	−191	−163	−156	−162	−161	−161	−161	−159	−159	−159

two-fold greater in the Pacific Northwest than in Southwestern states, Alabama, and Florida (Fig. 4). Carbon density in live and dead trees is also somewhat greater in the Northern Rocky Mountains, California, the Lake States, and Northeastern region than in the South-Central and Southeastern regions (Figs. 3 and 4).

3.2. Current carbon net fluxes

Table 1 presents the carbon stock change estimates for forest and harvested wood carbon pools from 1990 to 2010, with annual estimates from 1990 to 2005. Note that a negative sign indicates removal of carbon from the atmosphere or net carbon sequestration. In 2005, 49% of the total forest sector annual net carbon stock change of 159 Tg C year^{-1} was in live and dead trees, 27% was in wood products in landfills, 11% was in down dead wood, 10% was in wood products in use, and 2% was in forest soil and 1% in the forest floor (Tables 1 and 2). It is notable that the pools with the largest carbon stocks are generally not the same as those with the largest carbon stock change on an annual basis, with the important exception of the tree pool. The tree pool stocks are the second largest of any pool (after soils), and the annual stock change for the tree pool is the largest (Table 2). The next largest contribution to the annual stock change is landfilled wood products, which are only 3% of the total stocks. These large relative differences between stocks and stock changes for individual pools are possible because the annual stock change is such a small percentage of the total stocks—less than 1% in 2005.

Table 2
Comparison of stocks and fluxes for each forest carbon pool in 2005

Pool	Stocks (%)	Net change
Trees	35	49
Down dead wood	3	11
Understory	1	0
Forest floor	8	1
Forest soils	48	2
Wood products	2	10
Landfilled wood	3	27

Substantial regional variation was found in the annual carbon stock change in forests on an area basis. Fig. 5 shows the average carbon stock change in live and standing dead trees by State estimated for 2005. As for the corresponding figure of carbon stocks in the tree carbon pool, abrupt changes occur at State boundaries because a single estimate was made for each State. The regional pattern of changes in carbon stocks among states is not the same as the pattern for carbon density (Figs. 4 and 5). The states with the greatest rates of carbon sequestration in the tree pool on an area basis were Minnesota, New York, Maine, and Florida. Differences among states in carbon sequestration in trees are not strongly correlated with total carbon stocks ($r^2 = 0.11$), carbon stocks per area ($r^2 = 0.00$), or changes in forest area ($r^2 = 0.01$). Rather, differences among states may be due to combinations of many factors, including ongoing effects of prior land use change, management, and disturbance, current management including harvests, and also differences in averaging periods due to surveys occurring in different years.

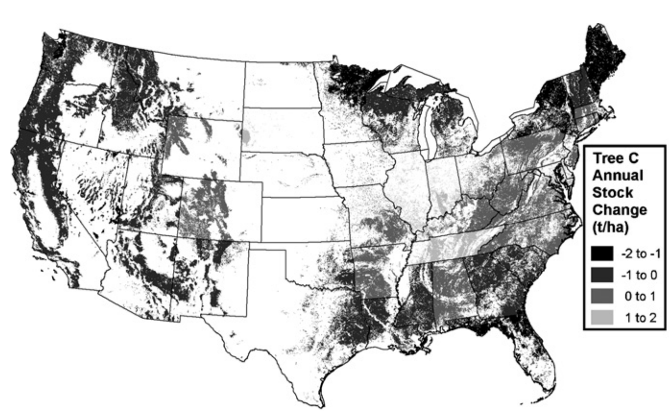

Fig. 5. Changes in State-wide average carbon stocks in 2005 in live and dead trees in the conterminous U.S. (negative values indicate sequestration).

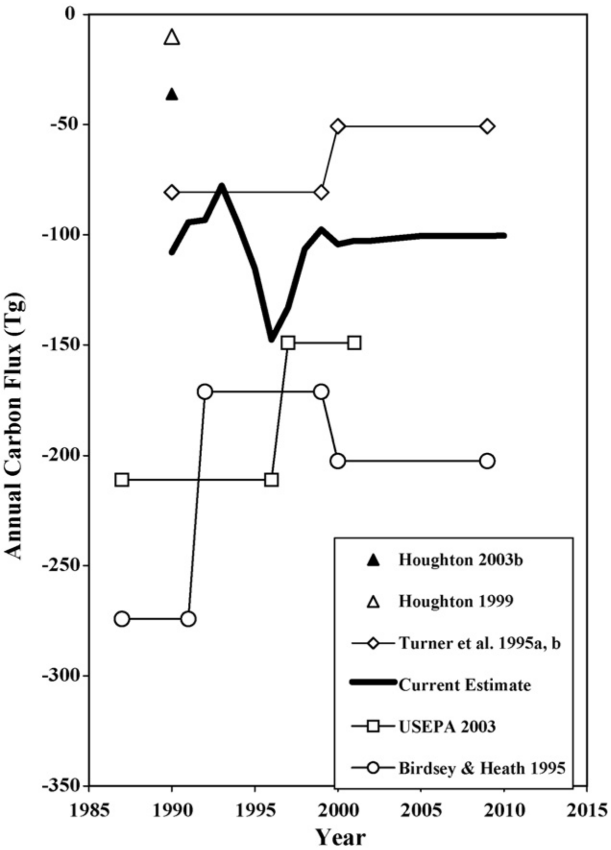

Fig. 6. Net changes in forest carbon stocks from 1990 to 2010: comparison with previously published estimates (does not include wood products, negative values indicate sequestration).

3.3. Trends over time

Changes in carbon stocks in U.S. forests and harvested wood were estimated to account for an average annual net flux of −162 Tg C year^{-1} over the period 1990 through 2005 (Table 1 and Fig. 6). Net sequestration occurred because of forest growth and increasing forest area over this period, particularly before 1997, ongoing effects of prior land use change, and net accumulation of carbon in wood products in use and wood products in landfills. The variation among years in net sequestration is due primarily to variation in tree carbon stocks (Table 1). For individual states, tree carbon stock change varies only in years when surveys were conducted, because estimates in non-survey years are interpolated between survey years. However, there is inter-annual variation in the national estimates because the survey years differ among states. Current trends in stocks and stock changes are predicted by the FORCARB2 model to continue to 2010, so carbon stock changes in 2010 are predicted to be very similar to those in 2005.

4. Discussion

Estimates of forest carbon stocks and stock changes are important because 33% of the U.S. land area is forested (Smith et al., 2001), and carbon removed from the atmosphere by forests can reduce the rate of increase of CO_2 in the atmosphere. We estimated that net annual carbon flux during 2005 in forests was −101 Tg C, and that in wood products and landfills an additional −58 Tg C. This net sequestration offset 10% of total U.S. CO_2 emissions from fossil fuels based on projected emissions for 2005 from the U.S. Department of Energy (http://www.eia.doe.gov/oiaf/aeo/index.html#carbon). The proportion of CO_2 emissions sequestered in prior years was generally greater than that in 2005 because total emissions have been increasing since 1990.

4.1. Comparison with previous forest stock estimates

Our estimates of carbon stocks in the conterminous U.S. are substantially higher than previously published estimates based on forest inventory data. As shown in Fig. 7, our estimate for 2003 is 30% greater than that of Birdsey and Heath (1995), and a similar difference is observed from 1990 to 2010. Our estimate is also 36% greater than that of Turner et al. (1995a, 1995b), which was based on inventory and growth modeling for timberland only (Fig. 7). Timberland is the most productive type of forest land, growing at a rate of 1.4 m^3 ha^{-1} year^{-1} or more. In the conterminous U.S., 79% of forests are classed as timberland (Smith et al., 2001). Other estimates of forest carbon stocks based on inventory data have been made only for

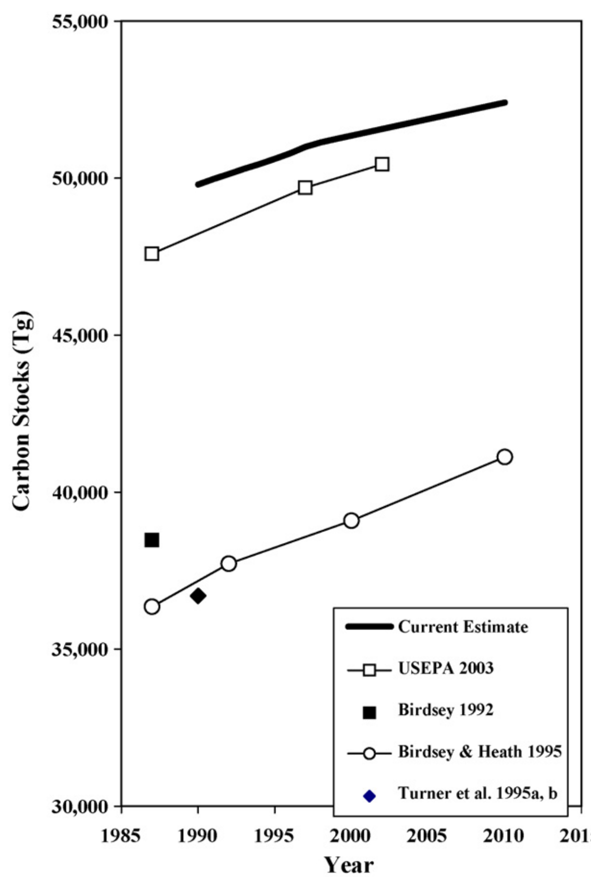

Fig. 7. Forest carbon stocks from 1990 to 2010: comparison with previous estimates (does not include wood products).

Table 3
Comparison of our estimates with previously published forest inventory-based estimates of carbon fluxes for each forest carbon pool in 1990 (negative values indicate sequestration)

Pool	Turner et al. (1995a)	Birdsey and Heath (1995)	Our estimate
Tg C year^{-1}			
Trees	−65	−96	−97
Down dead wood	−8		−9
Understory	2	−2	0
Forest floor	−8	−21	0
Forest soils		−155	−2
Wood products		−12	−13
Landfilled wood		−15	−44
Total	−79	−301	−165

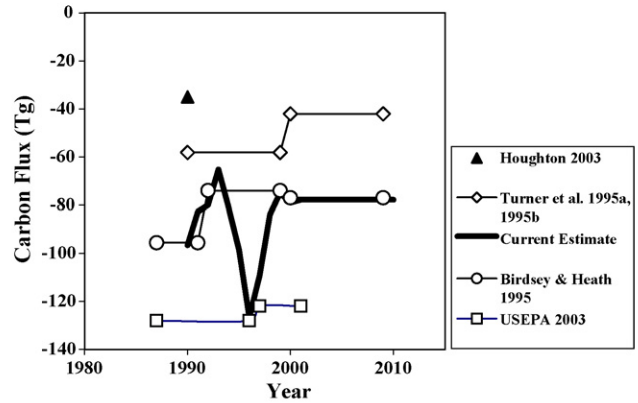

Fig. 8. Comparison of tree carbon flux with previous estimates (negative values indicate sequestration).

portions of the conterminous U.S., and are thus not directly comparable with our national estimates (Schroeder et al., 1997; Brown and Schroeder, 1999; Ney et al., 2002). A comparison of some aspects of our analysis with those of Brown and Schroeder (1999) has been published previously (Smith et al., 2003).

Our carbon stock estimates for conterminous U.S. forests are higher than previous estimates based on forest inventory data for a number of reasons. In comparison to the estimates of Birdsey and Heath (1995), our carbon stock estimates are substantially greater for all pools except wood products in use and wood products in landfills, which are substantially lower. Because they are the largest pools, most of the difference is in soil and tree pools. For soil carbon, this difference was due to the use of new estimates of soil carbon by forest type derived from the STATSGO database (Heath et al., 2002, 2003; Johnson and Kern, 2003,). For tree carbon, the difference was due partly to the use of new allometric equations for calculating total tree carbon mass from individual tree diameter data (Jenkins et al., 2003; Smith et al., 2003), but also to the use of actual survey years rather than nominal RPA reporting years (Fig. 2).

4.2. Comparison with previous net flux estimates

As shown in Fig. 6, our estimate of the net carbon flux in forests (not including wood products) is smaller than most previous estimates based on inventory data, including that of Birdsey and Heath (1995) and the estimate developed by us for the annual USEPA Greenhouse Gas Inventory report published in 2003 (USEPA, 2003). One major difference between our estimates of net carbon flux and previous ones is the use of land use change data to predict changes in soil and forest floor carbon stocks. For example, we estimated the soil in 1990 to be sequestering 2 Tg C year^{-1}, while Birdsey and Heath (1995) estimated 155 Tg C year^{-1} (Table 3). For the forest floor, our estimate was 0 Tg C year^{-1} while that of Birdsey and Heath (1995) was 21 Tg C year^{-1} (Table 3). As discussed in Section 1, our estimates of carbon stocks in trees differ from previous estimates because we used new allometric equations and because we used survey years rather than nominal reporting years (appendix Table A1). Because the actual survey year was several years prior to the nominal RPA reporting year for most states, using the average survey date removed a source of bias in the year. Since there is a trend of increasing carbon stocks in forests over time, removing this bias reduced estimates of forest net carbon fluxes because the previously reported increases in carbon stocks now occur at earlier dates. Thus a higher proportion of the total carbon stock change is now estimated to have occurred prior to 1990, reducing the average annual stock change since 1990. This shift can be seen when examining how using the actual survey year changes estimates of growing stock volume, as shown in Fig. 2. Estimates of growing stock volume are the key data element from the USDA Forest Service FIA inventory data used to derive estimates of biomass and carbon in trees.

Our methodology also estimates greater variation in the forest carbon net flux, because averages are calculated between different years in different states (Figs. 6 and 8). For example, in Fig. 8, there is an unusually large net flux estimated for 1996. This value is not due to a large change for any particular State or to a greater than average number of new survey data from that year, but rather is due to the accumulated interpolated net flux values for all states. Such apparent inter-annual variation thus most likely reflects the timing of data collection rather than a biophysical response to year-to-year variation in climate.

As shown in Fig. 6, our estimate of net carbon flux for forest land (not including wood products) is higher than previous estimates (Houghton, 1999, 2003a, 2003b). Our estimates differ from these previous estimates because they are based on the land-use model of Houghton. The Houghton model is based on reconstructions of net land use change and modeled forest growth whereas our estimates are based on gross (two way) land use changes and growth rates derived from hundreds of thousands of inventory sample plots. As shown in Table 4, our estimate for wood products is more than double that of Houghton (2003a), and falls within the range summarized by Pacala et al. (2001). Additionally, the land-use model of Houghton does not include an estimate of net flux in urban forests, which has been estimated at −16 Tg C year^{-1} (Nowak and Crane, 2002; USEPA, 2004).

Table 4
Land-based estimates of carbon sinks (Tg C $year^{-1}$) in the conterminous USA in 1990 (negative values are removals from the atmosphere)

Category	Pacala et al. (2001)		Birdsey and Heath (1995)	Houghton (2003b)	Non-forest from literature		Current forest estimate[a]	USA total	
	Low	High			Low or only	High		Low	High
Forest trees	−110	−150	−96	−46[b]			−97	−82[c]	−111
Urban and suburban trees							−16[d]	−12[e]	−20
Other forest organic matter	−30	−150	−180	10			−11	−10[c]	−13
Wood products	−30	−70	−30	−27			−57	−32[f]	−69
Woody encroachment	−120	−130		−61	0[g]	−61[h]		0	−61
Landfilled yard trimmings					−7[i]			−7	−7
Cropland soil, including manure, sludge, liming	0	−40		0	3[j]	−9		3	−9
Reservoirs	−10	−40						−10[k]	−40
Fixed in U.S., but exported by rivers	−30	−40						−30[k]	−40
Exports minus imports of food, wood	−40	−90						−40[k]	−90
Total apparent sink (not including net exports)	−370	−710						−219	−460
Total sink	−300	−580						−149	−330
Percentage of total in forests, urban trees, and wood products	57	64						91	65

[a] Forest land includes most land in the U.S. with full or partial forest cover including urban and suburban lands, but does not include lands with woody shrubs and no trees (Smith et al., 2001; Nowak and Crane, 2002).
[b] Sum of forest and Western pine "thickening" due to fire prevention, which occurs on forest land.
[c] This uncertainty range is from an earlier investigation with the FORCARB model and does not include all sources of uncertainty (Smith and Heath, 2000; Heath and Smith, 2000).
[d] Nowak and Crane (2002) presented a gross sequestration rate of 22.8 Tg $year^{-1}$, and based on this same research the net sequestration value shown above is presented in USEPA (2004), Table 7-2.
[e] This uncertainty estimate accounts for only sampling uncertainty, not all sources of uncertainty (USEPA, 2004; Nowak and Crane, 2002).
[f] Based on (1) an updated estimate from a manuscript in preparation (personal communication, Ken Skog) and (2) additional uncertainty of 20% based on Skog et al. (2004).
[g] Based on studies in Kansas (McCarron et al., 2003; Smith and Johnson, 2003), and Colorado, New Mexico, and Texas (Jackson et al., 2002).
[h] From Houghton (2003a, 2003b). Note that this value was calculated by dividing a previous estimate by two, because he considered the previous estimate to be a maximum value. We chose this lower estimate as maximum value because of new information on woody encroachment, see footnote g above.
[i] From USEPA (2004) Table 7-14. Note that the corresponding estimate for 2002 is only 2.8 due to increases in municipal and home composting.
[j] From USEPA (2004) and Ogle et al. (2003). The uncertainty range from Table 7-13 was converted from Tg CO_2 equivalents and applied to 1990 flux from Table 7-11.
[k] Both low and high values are from Pacala et al. (2001).

4.3. Implications for forest management

During the last decade, there has been increasing interest in the U.S. and elsewhere in managing forests for carbon sequestration. Although the Kyoto Protocol has not been ratified by the U.S., there has been substantial interest in documenting how U.S. forests help reduce the buildup of atmospheric CO_2. Such interest has stimulated increasing efforts during the last decade to estimate carbon sequestration in U.S. forests (Birdsey, 1992; Birdsey and Heath, 1995; Brown and Schroeder, 1999; Martin et al., 2001). The results presented herein are based on inventories designed to assess forest condition over large areas, and forestry projects that seek to obtain "carbon credits" may need to conduct more detailed local inventories to document management effects on carbon sequestration (Brown, 2002a, 2002b). However, our results have important implications for managing carbon in the forest sector. For example, although the stocks of wood products in use and wood products in landfills are relatively small, they contribute disproportionately to carbon sequestration in the forest sector (Table 2). Wood waste also may be burned with energy recovery, and thus may substitute for fossil fuel use. Methane may be captured from landfills and burned for energy, reducing total greenhouse gas emissions and substituting for fossil fuels. We have not provided estimates of these potential benefits, but they may be substantial (Skog and Nicholson, 1998).

Another approach to sequestering additional carbon is to increase the rate of tree growth, for example in managed plantations, and to increase the use of long-lived wood products. Our results suggest that increases in the tree pool are currently the most important single component of carbon sequestration by the forest sector (Tables 1 and 2). If management techniques for increasing soil carbon stocks in plantations can be developed, such as burial of stumps and slash during site preparation, additional carbon could be sequestered in plantations at least for many years. However, it must be noted that even with optimal management, forests can provide only a partial solution to reducing the buildup of greenhouse gases in the atmosphere due to fossil fuel combustion.

4.4. Uncertainty and comparison to total U.S. net flux

Our methodology does not explicitly include annual effects of wildfire, insect damage, and other stressors on forest carbon sequestration. However, such effects will be captured in forest inventory statistics over decadal time scales. The forest inventory data that form the basis of our estimates of forest carbon stocks are based on a statistical sampling technique designed to represent the wide variety of growth conditions present over large territories. However, forest inventory data that are currently available generally exclude timber stocks on most forestland in Alaska, Hawaii, and U.S. territories. For this reason, our estimates were restricted to the conterminous U.S. Within the conterminous U.S., the USDA Forest Service mandates that forest area data are accurate within 3% at the 67% confidence level (one standard error) per 405,000 ha of forest land (Miles et al., 2001). For larger areas, the uncertainty in area is concomitantly smaller. For volume data, the accuracy is targeted to be 5% for each 28,300 m^3 at the same confidence level.

Recent studies have begun to quantify the uncertainty in national-level forest carbon budgets based on the methods adopted here. Smith and Heath (2000) and Heath and Smith (2000) report on an uncertainty analysis they conducted on carbon sequestration in privately owned timberlands throughout the conterminous U.S. These studies are not exactly comparable to the estimates presented herein because they used an older version of the FORCARB model and are based on older data. However, the relative magnitudes of the uncertainties are informative. For the period 1990 through 1999, the true mean net carbon flux was estimated to be within 15% of the reported mean at the 80% confidence level. The corresponding true mean carbon stock estimate for 2000 was within approximately 5% of the reported mean value at the 80% confidence level. Uncertainty in the estimates presented herein may be greater than the estimate of Heath and Smith (2000) because their analysis did not include uncertainty in growing stock volume data and was only for timberland, not all forest land. Of conterminous U.S. forests, 7% are reserved (unavailable for timber harvest) and 14% are not considered suitable for harvest due to very slow growth or other site factors. Until very recently, non-timberlands have not been surveyed as thoroughly as timberlands, and there are larger uncertainties for estimating stocks and stock changes on them.

Table 4 puts our estimates of forest net carbon flux in context of total U.S. annual net carbon flux estimates for 1990, and is an update of a similar table presented by Pacala et al. (2001). In addition to the estimates presented above, this table includes recent estimates from the literature for urban trees, woody encroachment (increase of shrub density on non-forest land), landfilled yard trimmings, and croplands. Overall, we estimate the terrestrial carbon sink to be 149–330 Tg C $year^{-1}$, which is much lower than the range of 300–580 Tg C $year^{-1}$ estimated by Pacala et al. (2001). There are substantial differences in most of the carbon pools, with the largest differences in woody encroachment, forest trees, and forest soil (included in ‘‘other forest organic matter’’). Further details of our estimates are presented in the footnotes to Table 4. The new estimates suggest that forests, urban trees, and wood products are responsible for approximately 65–91% of the U.S. sink, with the remainder mostly in exports of food and wood, exports in rivers to the ocean, and storage in reservoirs, and for the 65% estimate also due to woody encroachment.

The land-based estimates summarized in Table 4 can also be compared with recent estimates from ecosystem models and atmospheric inverse modeling efforts. The NASA—Carnegie Ames Stanford Approach (CASA) simulation model based on satellite observations of vegetation cover suggests that mean annual net carbon fluxes for North America averaged between −200 and −300 Tg C $year^{-1}$ from 1982 to 1998, with a similar pattern from 1990 to 1998 (Potter et al., 2003). A prediction of −76 Tg C $year^{-1}$ for the conterminous U.S. from 1990 to 1995 was made with a new version of terrestrial ecosystem model (TEM) model that incorporates soil thermal dynamics (Zhuang et al., 2003). An analysis based on satellite observations (AVHRR) and inventory data estimated annual storage in U.S. forests to be −142 Tg C $year^{-1}$ for the period from 1981 to 1999 (Myneni et al., 2001). Overall, our total land-based estimates shown in Table 4 are thus similar to those of these ecosystem models, except for the TEM estimate.

The TransCom3 project addressed many choices involved in inverse modeling by using 16 different transport models and investigating different methods of data selection (Gurney et al., 2002, 2003; Law et al., 2003). For temperate North America, predicted annual net carbon fluxes from these models for 1992–1996 ranged from -160 ± 550 to -1770 ± 330 Tg C $year^{-1}$ (Gurney et al., 2003), with additional uncertainty due to site selection (Law et al., 2003). Overall, our land-based estimates of net carbon flux are near the lower end of the broad range predicted by the TransCom3 inversion analysis.

5. Conclusions

In summary, there are remaining uncertainties in land-based estimates of net carbon flux in the U.S., such as effects of woody encroachment in the arid West. Despite these uncertainties, it is clear that forests, urban trees, and wood products account for most of the U.S. carbon sink—we estimate this proportion to be 65–91%. In recent years, there has been much discussion of a ‘‘missing’’ carbon sink based on differences between atmospheric and land-based estimates of net carbon fluxes. Although not all sources of uncertainty in land-based estimates have yet been fully quantified, our results suggest that land-based estimates for the conterminous U.S. may have substantially smaller uncertainties than those based on atmospheric inversion modeling. The improved inventory-based estimates of forest carbon stocks and net fluxes presented herein and future refinements of these and other land-based estimates should help to constrain projections from ecosystem and atmospheric models.

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Appendix A

Summary of average forest inventory survey years for each State and forest types for plot-level tree biomass estimates and dead wood ratios are shown in Tables A1 and A2.

Table A1
Summary of average forest inventory survey years for each State, by RPA Database

State[a]	RPA region[b]	Data source[c,d]		
		1987 RPA	1997 RPA	2002 RPA
AL	South Central		1990.0	1998.7
AR	South Central	1978.0		1995.1
AZ	Rocky Mountain South	1984.4	1991.4	1995.8
CA	Pacific Southwest	1980.4	1992.2	1995.8
CO	Rocky Mountain South			1985.7
CT	Northeast		1985.0	1997.8
DE	Northeast		1986.0	1999.0
FL	Southeast	1987.0		1994.0
GA	Southeast	1982.1		1996.4
IA	Northern Prairie States	1987.0		1989.1
ID	Rocky Mountain North	1982.5		1991.9
IL	Northern Prairie States		1985.0	1997.5
IN	Northern Prairie States	1987.0		1997.3
KS	Northern Prairie States	1987.0		1993.8
KY	South Central			1986.6
LA	South Central	1984.0		1990.9
MA	Northeast		1985.0	1997.1
MD	Northeast		1986.0	1999.0
ME	Northeast	1983.0		1994.7
MI	Northern Lake States	1987.0		1992.3
MN	Northern Lake States			1988.6
MO	Northern Prairie States			1987.8
MS	South Central	1977.0		1993.3
MT	Rocky Mountain North	1984.3		1993.0
NC	Southeast			1989.6
ND	Northern Prairie States	1987.0		1994.0
Northeast	Northern Prairie States	1986.9		1993.9
NH	Northeast		1983.0	1996.5
NJ	Northeast		1987.0	1998.3
NM	Rocky Mountain South	1982.9	1992.4	1997.2
NV	Rocky Mountain South		1985.1	1994.0
NY	Northeast	1985.0		1992.4
OH	Northern Prairie States	1985.0		1991.0
OK	South Central	1986.0		1991.2
ORE	Pacific Northwest Eastside	1983.2		1995.5
ORW	Pacific Northwest Westside	1984.3	1990.7	1995.5
PA	Northeast			1989.3
RI	Northeast		1985.0	1998.0
South Central	Southeast	1986.0	1992.3	1999.5
SDE	Northern Prairie States	1986.7		1994.9
SDW	Rocky Mountain South		1987.2	1997.9
TN	South Central		1989.0	1997.7
TX	South Central	1985.3		1991.8
UT	Rocky Mountain South	1978.2		1993.0
VA	Southeast	1986.0		1990.9
VT	Northeast		1983.0	1996.7
WAE	Pacific Northwest Eastside	1982.7		1993.0
WAW	Pacific Northwest Westside		1989.9	1991.8
WI	Northern Lake States	1987.0		1994.7
WV	Northeast		1989.0	
WY	Rocky Mountain South		1982.5	1993.3

[a] Three states are divided into Eastern and Western parts for estimation purposes: OR, SD, and WA.
[b] For region boundaries, see Fig. 2.
[c] Estimates for each State for the year 2010 are from the FORCARB2 model.
[d] The nominal RPA reporting year is shown in the column heading, see Section 4 and citations in text.The average survey year for each State is shown in the body of the table. The decimal point indicates tenths of a year.

Table A2
Forest types for plot-level tree biomass estimates and dead wood ratios

Region[a]	Forest type group[b]	Dead wood ratio[c] ($Mg\ ha^{-1}$)
Northeast	Aspen-Birch	0.078
	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Maple-Beech-Birch	0.071
	Oak-Hickory	0.068
	Oak-Pine	0.061
	Longleaf-Slash Pine, Loblolly-Shortleaf Pine, and pines other than White-Red-Jack	0.065
	Spruce-Fir and other non-pine conifers	0.092
	White-Red-Jack Pine	0.055
Northern lake states	Aspen-Birch	0.081
	Oak-Gum-Cypress and Elm-Ash-Cottonwood	0.061
	Maple-Beech-Birch	0.076
	Oak-Hickory	0.077
	All pine groups and Oak-Pine	0.072
	Spruce-Fir	0.087
Northern prairie states	All conifer groups	0.073
	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Aspen-Birch	0.069
	Maple-Beech-Birch	0.063
	Oak-Hickory	0.068
	Oak-Pine	0.069
South central	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Aspen-Birch	0.063
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, naturally occurring	0.068
	Oak-Pine	0.072
	Other conifer groups	0.068
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, planted	0.077
	Oak-Hickory and Maple-Beech-Birch	0.067
Southeast	Oak-Gum-Cypress, Elm-Ash-Cottonwood, and Aspen-Birch	0.064
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, naturally occurring	0.081
	Oak-Pine	0.063
	Other conifer groups	0.081
	Longleaf-Slash Pine and Loblolly-Shortleaf Pine, planted	0.075
	Oak-Hickory and Maple-Beech-Birch	0.059
Pacific southwest	Douglas-fir and Hemlock-Sitka Spruce	0.091
	Fir-Spruce-Mountain Hemlock	0.109
	Hardwoods	0.042
	Ponderosa Pine, Lodgepole Pine, and other conifer groups	0.100
	Pinyon-Juniper	0.031
	Redwood	0.108
Pacific northwest	Douglas-fir, Western Larch, and Redwood	0.103
	Fir-Spruce-Mountain Hemlock and Hemlock-Sitka Spruce	0.106
Eastside	Hardwoods	0.027
	Lodgepole Pine	0.093
	Ponderosa Pine and Western White Pine	0.103
	Pinyon-Juniper	0.032
Pacific northwest westside	Douglas-fir and Redwood	0.100
	Fir-Spruce-Mountain Hemlock	0.090
	Ponderosa Pine, Western White Pine, Lodgepole Pine, and other conifer groups	0.073
	Other hardwoods	0.062
	Alder-Maple	0.095
	Hemlock-Sitka Spruce	0.099
Rocky mountain north	Douglas-fir, Western White Pine, Hemlock-Sitka Spruce, Western Larch, and Redwood	0.062
	Fir-Spruce-Mountain Hemlock	0.100
	Hardwoods	0.112
	Lodgepole Pine	0.058
	Other conifer groups	0.060
	Ponderosa Pine	0.087
	Pinyon-Juniper	0.030
Rocky mountain south	Douglas-fir, Western White Pine, Hemlock-Sitka Spruce, Western Larch, and Redwood	0.077
	Fir-Spruce-Mountain Hemlock	0.079
	Hardwoods	0.064
	Lodgepole Pine	0.098
	Other conifer groups	0.060
	Ponderosa Pine	0.082
	Pinyon-Juniper	0.030

[a] For region boundaries, see Fig. 2.
[b] Forest group types taken from the forest inventory and analysis database.
[c] Ratio of the down dead wood to live tree biomass in the plot.

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