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# Carbon stocks on forestland of the United States, with emphasis on USDA Forest Service ownership

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**Abstract.** The U.S. Department of Agriculture Forest Service (USFS) manages one-fifth of the area of forestland in the United States. The Forest Service Roadmap for responding to climate change identified assessing and managing carbon stocks and change as a major element of its plan. This study presents methods and results of estimating current forest carbon stocks and change in the United States for public and private owners, consistent with the official 2010 U.S. greenhouse gas inventory, but with improved data sources for three states. Results are presented by National Forest System region, a major organizational management unit within the Forest Service, and by individual national forest. USFS forestland in the United States is estimated to contain an average of 192 Mg C/ha (megagrams carbon per hectare) on 60.4 million ha, for a total of 11,604 Tg C (teragrams C) in the year 2005. Privately-owned forestland averages 150 Mg C/ha on 173.8 million ha, with forestland of other public owners averaging 169 Mg C/ha on 43.1 million ha. In terms of change, private and USFS ownerships each sequester about a net 150 Tg $CO_2$/yr, but an additional 92 Tg $CO_2$/yr is stored in products from private harvests compared to about 3 Tg $CO_2$/yr from harvest on USFS land. Emissions from other disturbances such as fires, as well as corresponding area estimates of disturbance are also important, but the needed datasets are not yet available. Recommendations are given for improving the estimates.

**Key words:** carbon density; carbon in HWP; forest carbon accounting; Forest Inventory and Analysis; greenhouse gas inventory; National Forest System; uncertainty analysis.

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## INTRODUCTION

Forty-four percent of the area of forestland of the United States is in public ownership. The Federal Government controls one-third of all U.S. forestland, with the USDA Forest Service (USFS) managing one-fifth of all U.S. forestland, making it the primary owner of Federal forestland in the United States (Smith et al. 2009). Thus, management of these forests can substantially affect the total forest carbon stocks and change in the United States. Recognizing this, the second of four strategic goals of the 2010–2015 USDA strategic plan (USDA 2010) is to ensure national forests and private working lands are conserved, restored, and made more resilient to climate change, including mitigation considerations. To help implement this plan, the USFS roadmap for responding to climate change (USDA FS 2010*a*) identified assessing and managing carbon stocks and change as a major element of its plan. Joyce et al. (2008) discuss potential adaptation approaches and mitigation tradeoffs that the USFS might adopt to help achieve its goals, but carbon estimates are not included.

Estimates of carbon stocks and change are also important for other ownerships. The USDA Strategic Plan (USDA 2010) includes the idea of an "all-lands" approach to U.S. forest management, which means considering the context of other ownerships across the landscape when making management decisions on USFS land. It has long been known that forest conditions can differ significantly by ownership, and that landowner behavior will continue to affect future conditions (e.g., Nabuurs et al. 2007), including forest carbon stocks and change. Ownership may also play a factor in carbon finance, with a popular discussion treating publicly owned land differently than private (e.g., Olander et al. 2010).

The goal of this study is to derive and present estimates of forest carbon stocks and change in the United States by major ownership, with a focus on USFS forestland to help meet the needs of the USFS climate change roadmap. The estimates are consistent with the 2010 official U.S. greenhouse gas (GHG) inventory, which is important because having several sets of "official" estimates raises doubts about their accuracy. The U.S. GHG inventory is published annually by the U.S. Environmental Protection Agency (USEPA) for all sectors including the forest sector (e.g., USEPA 2010). For forests, these inventories include forest carbon stocks in units of carbon, as well as net sequestration in units of carbon and also in units of carbon dioxide equivalent. The inventories have been required since the United States ratified the United Nations Framework Convention on Climate Change in the early 1990s. By signing, the United States agreed to provide an annual inventory of carbon stocks and carbon change, with base year 1990. The protocols and guidance have evolved over time (IPCC 2003, 2006) based on experience, evolving policy interests, and new technology and scientific information. For more information about the overall U.S. GHG forest inventory, also see Heath et al. (*in press*) or USEPA (2010).

Older state-level estimates are available (e.g., USDA 2008), but estimates have not been derived previously by major ownership by major USFS organizational unit. Forest carbon stocks for USFS forestland can be calculated using the COLE suite of web tools (Van Deusen and Heath 2010*a*), such as reported in Ingerson and Anderson (2010). However, COLE uses a different algorithm for statistical analysis (Van Deusen and Heath 2010*b*) than that currently used in the official GHG inventories, and the tool does not yet provide change estimates and uncertainties. The USFS Forest Inventory and Analysis (FIA) program also has tools (USDA FS 2010*b*) which can provide forest carbon stocks by individual national forest unit. These tools also do not produce needed estimates because they include newer algorithms that have not been incorporated into the official GHG inventories such as biomass equations by Heath et al. (2008), do not include carbon change for all states, or focus on annualized data so that not all needed data are included.

Although baseline forest stock estimates are important, information about the source and fate of harvested wood carbon, such as carbon stored in products or wood burned for energy, can also be important when considering carbon benefits from forests. For instance, Heath et al. (*in press*) note that a recent average 205 teragrams carbon dioxide (Tg $CO_2$) has been emitted from wood burned for energy (see last five years of USEPA GHG inventories). If this wood had been left standing in the forest, forest carbon stocks would increase, but an additional equivalent amount of emissions could have been released instead if more fossil fuel was burned as the substitute source of the needed energy. Studies of future actions to increase carbon mitigation benefits should consider all sectors related to forests, as well as life cycle assessments to inform management actions. Given the lack of baseline forest carbon stock information for National Forest System (NFS) land and recent improvements in methodologies and updates in FIA plot data, in this study we focus on baseline forest carbon stocks and net sequestration, but also provide a rudimentary estimate of carbon contributions from harvested wood products (HWP) for a more thorough understanding of the carbon system. Explicit information about emissions from other disturbances such as fire, and their corresponding area disturbed, are also important, however data sources were not quite yet

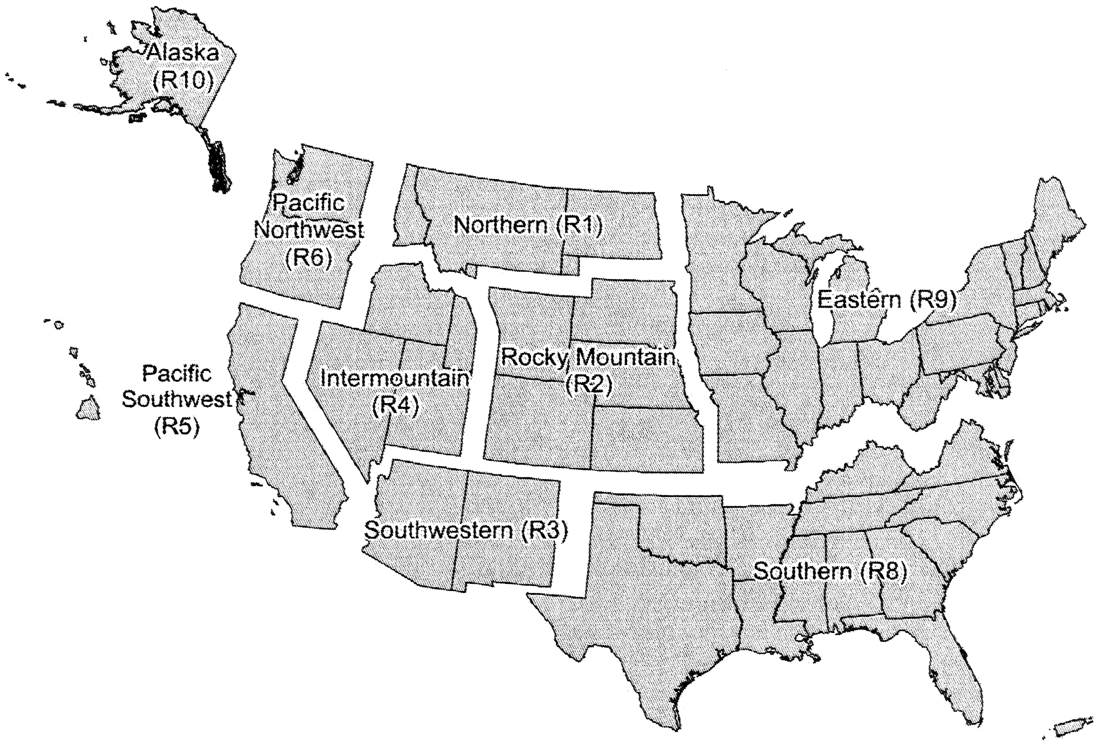


Fig. 1. Map of USDA Forest Service, National Forest System regions.

available for this study.

## Methods

### *Definitions and units*

Forestland as defined here is "Land at least 36.6 meters wide and 0.405 hectare in size with at least 10% cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated" (Smith et al. 2009). All carbon pools on forestland are included (Smith et al. 2006): above- and belowground live tree biomass, understory vegetation, standing dead trees, down dead wood, forest floor, and soil organic carbon to the depth of one meter. (See Appendix A: Table A1 for definitions of component pools.) Carbon in HWP is the sum of changes in products in use, and changes in carbon in landfills. For reporting carbon change, we convert carbon to units of carbon dioxide by multiplying by 44/12 (the molecular weight of $CO_2$/C) because change in greenhouse gas inventories is reported in terms of $CO_2$. Indeed, the GHG inventories use units of carbon dioxide equivalents, $CO_2$e, which is a way to report on emissions for all types of GHGs, but we use the label $CO_2$ for $CO_2$e. In terms of signs, a negative $CO_2$ change means carbon is taken out of the atmosphere and carbon is increased in forests; a positive $CO_2$ change means carbon is added to the atmosphere by forest-related emissions. This sign convention is used for consistency with national and international GHG reporting. We present stocks in terms of carbon, but when we present change we use units of $CO_2$ to indicate how atmospheric $CO_2$ is affected by changes in forest carbon.

This study focuses on administrative NFS regions (Fig. 1), rather than strictly ecologically-based areas, because management responses will be implemented by these regions. Regions are a major organizational unit within the Forest Service, and information summarized by region is important for implementation and interpretation. Individual national forest units within these regions are also important for executing carbon management activities. Forest carbon stocks, change and uncertainties are presented by NFS region by three major ownership categories: USFS, other public (all other publicly-owned lands including other federal ownerships, states, and municipalities), and privately-owned land. These groupings were chosen because we wanted a minimum number of broad categories which covered all owners.

### *Forest Inventory and Analysis survey*

The FIA program is the primary source for information about the extent, condition, status and trends of forest resources across all ownerships in the United States (Smith 2002). FIA applies a nationally consistent sampling protocol which began implementation in the late 1990s covering all forestland in the nation following an annualized design (Bechtold and Patterson 2005). An annualized design means a statistically valid subset of plots is measured every year in a state. Several years of data may be required to include all measurements on all forested plots within a state. The complete set of plot data provides for a greater level of precision geographically, but the aggregated data lose temporal specificity. On each permanent inventory plot, field crews collect data on more than 300 variables, including land ownership, forest type, tree species, tree size, tree condition, and other site attributes (e.g., slope, aspect, disturbance, land use) (Smith 2002; Woudenberg et al., *in press*). Plot intensity for measurements is approximately one plot for every 2,400 ha of land (130,000 forested plots nationally). These data are compiled, and are publicly available via the Internet (USDA FS 2010*c*).

The FIA data are collected on all ownerships in the 48 conterminous states, coastal Alaska, and territories. This study does not include forestland in interior Alaska and Hawaii because FIA plot data have either not been collected or are not yet available. Puerto Rico data were not available at the time of this analysis. FIA plot data available before the annualized implementation were surveyed periodically, and may only be available at the plot level rather than the tree level. To calculate change, an approach must include a way to use these older data such that they are comparable to the newer data.

### *Approach*

The current FIA survey was not designed nor was it funded as a carbon inventory. Our approach is based on data taken from FIA surveys (Bechtold and Patterson 2005), but augmented by a set of basic models which are either ecologically process-based or statistical carbon conversion models (USEPA 2010; Heath et al., *in press*). Smith et al. (2010) describes the methods used for estimating the density of carbon component pools, as well as the approach for calculating carbon change. In general, our approach is to calculate carbon stocks derived from the augmented FIA plot data by multiplying area estimates by estimates of carbon density for that area. For example, estimates of carbon per hectare for the permanent inventory plots labeled as NFS ownership are multiplied by the appropriate expansion factors, and then summed over the total area of interest, such as national forest. Privately-owned land occasionally occurs within national forest boundaries; an FIA plot on private lands is labeled as privately-owned and is summed in the private ownership. Change in carbon (also called net sequestration) is calculated as the difference between consecutive stocks (each from a specific inventory), which is then divided by the number of years in the period between the stocks. This approach provides a net annual difference and is known as the stock-change approach.

We used procedures from the computer application of Smith et al. (2010), although we duplicated the code in SAS (SAS Institute 2003) to produce consistent estimates by ownership for NFS regions and for individual national forests. An additional step was included to review the data for consistency in terms of ownership and national forest designation. About 0.1% of the USFS field plots did not include a valid national forest designation, but these were assigned based on state or county codes. Methods and data sources are the same as those in USEPA (2010) with one exception. Data from the Integrated Database (IDB, Waddell and Hiserote 2005) were used for the older forest inventories for California, Oregon, and Washington in place of the corresponding data used for those states as identified in USEPA (2010). Previously, we had focused on using national-level datasets, but we recently recognized that the older data in the IDB were more consistent with the current annualized data for these states, which is a crucial consideration for the inventory-based methods used for change (Smith et al. 2010). Recent GHG reporting (USEPA 2010, and similar previous reports) included notable differences in forestland between past and current inventories for California, although analyses could not attribute the differences to any specific cause. Incorporating data from the IDB into the GHG inventory removed this apparent discontinuity. We applied additional updates to the publicly available IDB on parts of 63 plots in eastern Oregon that were predominantly the juniper forest type because guidelines for classifying these plots had changed over the last 12 years. The modification made the older data more comparable with current inventories in terms of the basis for determining forestland.

We do not include the soil pool when presenting carbon change because changes in the land base can result in transfers of large amounts of soil carbon to other land use which will appear to be losses to or gains from the atmosphere. Thus, we use and report the term nonsoil carbon which includes all pools (live tree and standing dead tree, down dead wood, understory, and forest floor) except soil. We recognize that soil carbon on forestland remaining forestland may be emitting or sequestering GHGs, but this study assumes no change in that pool. We emphasize that both forestland area change and carbon density (carbon per area) change can affect total carbon (Smith and Heath 2010). That is, an increase in forestland area will result in increased carbon sequestration if the average carbon density is not declining. An increase in carbon density will result in increased carbon sequestration even if area of forestland is constant. A decrease in forestland area with an increase in carbon density can result in an increase or decrease in carbon sequestration, depending on the amount of change in each factor.

### *Carbon in harvested wood products*

Carbon removed from forests as harvested wood can also remain stored rather than returning to the atmosphere for a long time, depending on the mix of wood products produced or burned as a substitute for fossil fuels. Carbon in HWP continues to provide carbon benefits, which can be an appreciable part of the overall forest carbon budget (Heath et al., *in press*). The net annual contribution to the total forest carbon budget depends on harvest, allocation to product, life-span, and methods of disposal (Skog 2008). Analyses can also be performed to determine the carbon value chain including accounting for emissions in manufacturing (Heath et al. 2010*a*), but the focus of this study is carbon inventories. For comparison between ownerships, we provide estimates of net annual stock change of carbon in harvested wood disaggregated and associated with forests from the three major ownerships. The estimates were derived by multiplying national estimates of carbon in harvested wood (Skog 2008, USEPA 2010) by proportions of harvested wood associated with ownerships from the base scenario for an empirically-based U.S. forest assessment over the same interval (Haynes et al. 2007, Heath et al. 2010*b*).

### *Uncertainty*

Estimates of uncertainty in total forest carbon stocks and change are based on Monte Carlo simulations (IPCC 2006) of the stock-change methods from Smith et al. (2010), which were modified for estimates corresponding to owner by NFS region and individual national forest unit. The resulting confidence intervals represent the bounds of the central 95% of the distribution produced from numerical simulations. For ease of comparison, we present the bounds as average percentages about the mean. Uncertainty includes inventory-to-carbon conversion factors and sampling error. Uncertainties about plot-level carbon conversion factors are defined as probability densities defining carbon density (megagrams carbon per hectare, Mg C/ha) by pool (Smith and Heath 2001, USEPA 2010) and aggregated to national forest, or other population totals, by iterative sampling.

Sampling error is estimated according to Bechtold and Patterson (2005) by population of interest. Mean carbon and uncertainty estimates were produced for Forest Service forestland on each national forest by state. Totals for forests extending over more than one state are simply the sum of the population estimates of each of the states, because the state estimates were assumed

Table 1. Forest carbon statistics by ownership for the 48 conterminous states and coastal Alaska.

| Ownership | Mean measurement year | Forest C density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (million ha) | Total forest C stock ± 95% CI as percentage of mean (Tg C ± %) |
|---|---|---|---|---|---|
| USFS | 2004.8 | 192 | 56, 514 | 60.4 | 11,604 ± 1.4 |
| Other Public | 2004.9 | 169 | 52, 434 | 43.1 | 7,268 ± 1.5 |
| Private | 2005.0 | 150 | 55, 326 | 173.8 | 26,058 ± 0.6 |
| All | 2005.0 | 162 | 54, 394 | 277.3 | 44,931 ± 0.5 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

to be independent for purposes of combining the simulated uncertainties. The same process was followed for other ownerships or regional totals. These quantities do not account for all uncertainties. For example, the U.S. GHG inventories require a base year of 1990; inventory data prior to about the year 2000 were collected under a periodic inventory system, and in some states may have not included the entire forestland base now being surveyed. Although we have made comparisons and adjustments between these datasets to reduce error (e.g., such as for the state of Oregon with the change to and adjustments to the IDB), there may be other area-based mismatches, as well as additional uncertainties.

## Results and Discussion

### *Forest carbon stocks and uncertainties*

Relevant U.S. carbon statistics include average year of measurement, forestland areas, average carbon stock per hectare (carbon density), and total carbon and uncertainties estimated from the most recent FIA inventory for each ownership (Table 1). The carbon stocks (and their corresponding forestland areas) are based on data from different survey years, but the mean survey year is 2005. That is, 2005 represents the overall average year of data collected by field crews over the large number of permanent inventory plots maintained by FIA. USFS forestland features greater carbon density, on average 28% more per forested hectare, than that of private land. Results further indicate that the range of carbon density is also notably greater: 514 Mg C/ha compared to 326 Mg C/ha on private land at their respective 97.5 percentile values, with the value for other public ownership in the middle (434 Mg C/ha). The values on the low end of this interval (2.5 percentile) are about the same for all ownerships, about 55 Mg C/ha.

Within each region, Forest Service forestland features greater carbon density than other ownerships (Fig. 2) with the exception of other public ownership being greater in the Pacific Northwest region, and other public and USFS carbon densities being similar in the Southern region. In spite of differences in magnitude, the pattern of carbon density arranged by largest to smallest by region within each ownership is quite similar. Carbon densities in the Alaska and Pacific Northwest regions rank highly, with the largest depending on owner, followed by carbon densities of the Eastern and Pacific Southwest regions. The Southwestern and Intermountain regions exhibit the least carbon stock density in all ownerships, respectively. The order varies in the remaining regions of intermediate values, but these regions have similar magnitudes.

These similar patterns across regions indicate the importance of regional effects such as soil, forest type, and underlying climatic drivers, on carbon stocks. Land use history can also affect broad regions. In the Eastern region, for instance, national forests were established on cutover land, whereas in the West, many areas were inaccessible and the forests relatively unused when they were designated as national forests. Thus, although the land use history of both areas is quite different, intra-regional differences are minor. Carbon stocks of the coastal Pacific Northwest and coastal Alaska regions occur in areas of mostly publicly owned land, with tree species large at maturity, low decay and disturbance rates, and a history of limited deforestation and active management so large carbon stock densities are expected. In the Southwest region, the less productive growing conditions with greater likelihood of disturbance will generally feature lower forest carbon stocks on average.

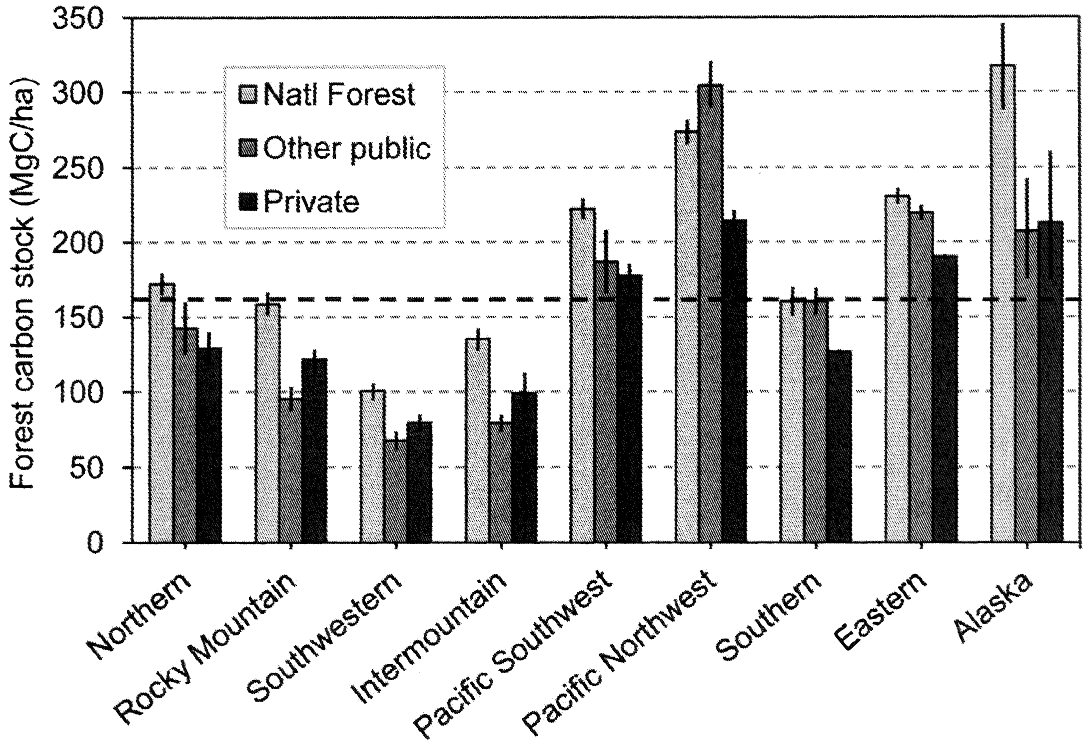


Fig. 2. Mean forest carbon density (Mg C/ha) by ownership by National Forest System region, 2005. Horizontal dashed line represents the overall average carbon stock on U.S. forestland, 162 Mg C/ha. Error bars indicate a 95% confidence interval of uncertainty about the regional average, from carbon conversion factors and sampling error.

In contrast to carbon densities, total forest carbon is 2.2 times greater (26,058 Tg C compared to 11,604 Tg C; Table 1) for privately-owned land, largely because of the almost three-fold difference in forestland area (173.8 Mha (million hectares) private compared to 60.4 Mha USFS; Table 1). At the national level, about 63%, 22%, and 15% of forestland area (Table 1) is in private, USFS, and other public ownership. There are large regional differences in ownership patterns, with notably more area of forestland in private ownership in the Eastern and Southern regions (Fig. 3), and least in Alaska (this is a survey of only coastal Alaska), and in the Intermountain region. If all forestland in Alaska were surveyed, there would be substantially more forestland area in private and other public ownerships.

Within USFS forestland only (Table 2), the Pacific Northwest region has the largest area of forestland (9.1 Mha), followed closely by the Intermountain and Northern region, with Alaska the least (4.4 Mha). The carbon stocks (and their corresponding forestland areas) from different states are likely based on data from different survey years, but the mean survey year of most regions is similar to the mean for all USFS land, 2004.8, which we round up for this discussion to year 2005. That is, 2005 represents the overall average of data collected by field crews over the large number of permanent inventory plots maintained by FIA. The exception to similar year of data collection is the Southwestern region with mean survey year of 2001 (rounded up from 2000.8). Considering the ecological conditions in the Southwest, the difference in results due to the four-year average lag time is likely minor. In terms of uncertainties, the percent uncertainty ranges from ±1% for all USFS forestland up to 6% for USFS forestland in one region only.

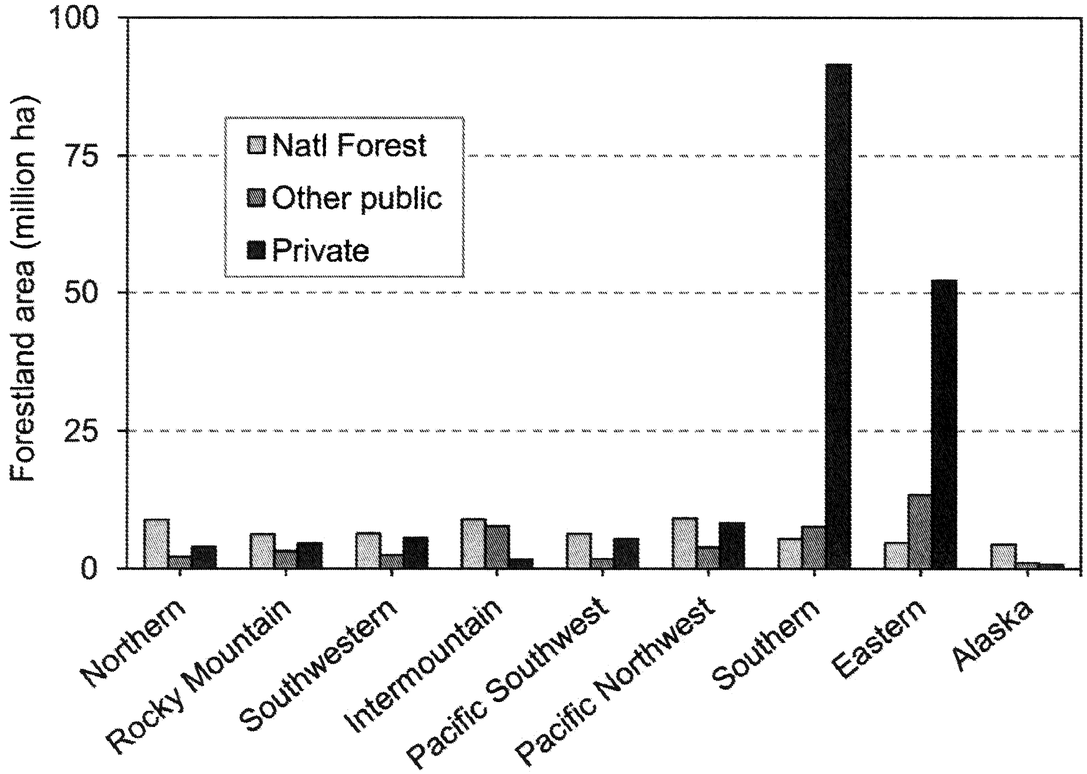


Fig. 3. Forestland area (million hectares) by ownership summed by National Forest System region, 2005. Error bars for a 95% confidence interval of sampling error for forest area are not included because they are too small for the resolution of the figure.

Table 2. Forest carbon and area statistics for USDA Forest Service forestland only by National Forest System region.

| National Forest System region | Mean measurement year | Forest C density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C stock ± 95% CI as percentage of mean (Tg C ± %) |
|---|---|---|---|---|---|
| Northern | 2006.2 | 172.0 | 76, 328 | 8,896 | 1,530 ± 3 |
| Rocky Mountain | 2004.5 | 158.6 | 56, 306 | 6,265 | 993 ± 4 |
| Southwestern | 2000.8 | 100.6 | 49, 254 | 6,371 | 641 ± 4 |
| Intermountain | 2004.9 | 135.3 | 54, 286 | 8,964 | 1,213 ± 4 |
| Pacific Southwest | 2005.0 | 222.4 | 63, 548 | 6,331 | 1,408 ± 2 |
| Pacific Northwest | 2005.2 | 273.3 | 94, 689 | 9,107 | 2,493 ± 2 |
| Southern | 2005.1 | 160.2 | 74, 280 | 5,423 | 869 ± 4 |
| Eastern | 2005.6 | 230.7 | 111, 392 | 4,652 | 1,073 ± 2 |
| Alaska | 2006.2 | 317.1 | 101, 607 | 4,363 | 1,384 ± 6 |
| All USFS | 2004.8 | 192.1 | 56, 514 | 60,372 | 11,604 ± 1 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

Uncertainty estimates should be interpreted carefully. In this case, one percent (116.04 Tg C) of the all USFS carbon stock is still greater in magnitude than 6% (83.04 Tg C) of the Alaska region USFS carbon stock.

Forests in the Alaska region have the greatest

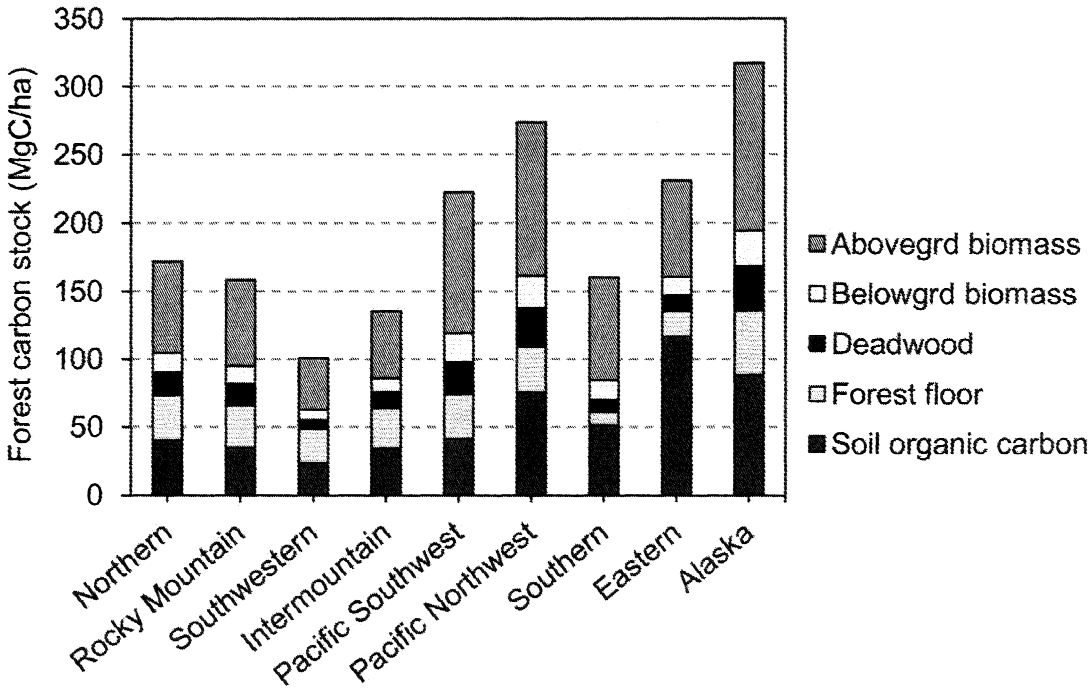


Fig. 4. Mean forest carbon density (Mg C/ha) by component pools for USDA Forest Service forestland only by National Forest Service region, 2005. Biomass includes live trees and understory vegetation.

carbon density for all pools averaging 317.1 Mg C/ha, whereas the Southwest and Intermountain regions have the least carbon densities, at 100.6 Mg C/ha and 135.3 Mg C/ha, respectively (Fig. 4). The greatest percentage of aboveground live biomass carbon is in the Southern region (47%), and lowest (30%) in the Eastern region. The Eastern region has the highest relative soil carbon (51%), followed by the Southern region (30%), with a number of regions in the western United States in the 20–30% range. The relatively high proportion of forest carbon in forest floor in the Southwest region is thought to be due to the use of regional models for dead wood and forest floor pools for hardwood woodland forest types.

Within most regions (Fig. 5), forest carbon stock densities from individual national forests are relatively similar (e.g., Southern), with distinct patterns emerging in others. (See Appendix B for carbon stock statistics including uncertainties for USFS forestland by individual national forest.) For instance, as might be expected, the carbon densities on the west side of the Cascades in Oregon and Washington are large due to the forest types, older forests, and relatively lush growing conditions, but on the eastern side with less favorable growing conditions, carbon densities are relatively smaller. The Pacific Southwest region appears to show the greatest distinctions between forests within a region. The highest carbon densities per national forest are in the Pacific Northwest and Pacific Southwest regions, and the least in the semi-arid areas in the Intermountain and Southwest regions. Some forested plots fall within national grasslands or other USFS administered lands, and these are included (as additional USFS areas in Appendix B.)

National forest units are not randomly located across the landscape (Fig. 5). For example, the forests are bunched together in much of the West, in mountainous terrain where forests are more likely to occur or where land had not yet been settled upon before establishment of the national forests. In the Southern region, only 5% of the forestland is in USFS ownership, with 88% in private ownership varying from highly productive forestland intensively managed for timber

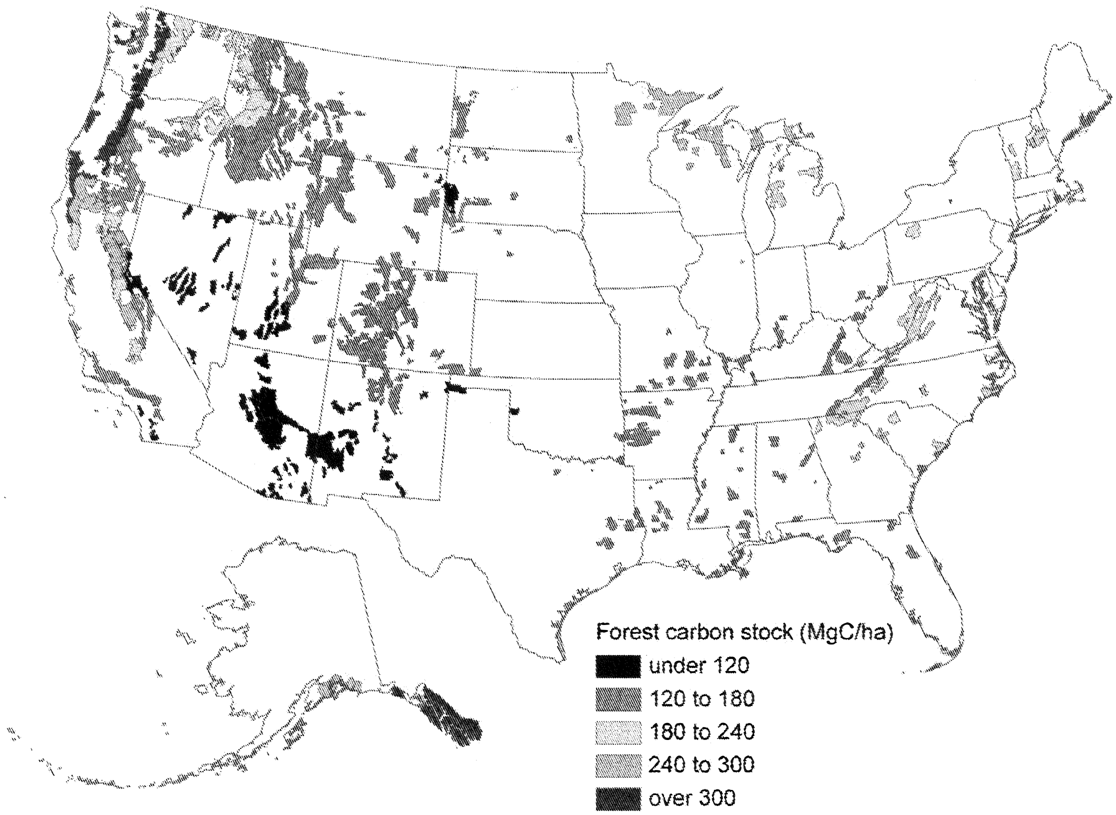


Fig. 5. Mean forest carbon density (Mg C/ha) by individual USDA Forest Service unit, 2005. Shaded areas indicate national forest or grassland administrative boundaries, and color indicates carbon stock density (Mg C/ha) category on the Forest Service owned forestland within those areas. Data are not available for Hawaii; data for Puerto Rico were not available at the time of this analysis.

production, to areas of woodlands in west Texas managed predominantly for grazing. Given this diversity of forest ecosystems, climate, productivity, ownership patterns and local preferences, effective, preferred management activities to increase carbon benefits will likely need to differ regionally if not by individual forest.

### *Net $CO_2$ change and carbon in harvested wood products*

Over the period 2000–2008, private and USFS forests sequester about 30% of total average annual nonsoil net $CO_2$, with other public forestland accounting for 38% (Table 3). Most of the statistically significant net sequestration on NFS land is occurring in the Pacific Northwest and Southern regions, with net sequestration on other public and privately owned forestland higher in the Eastern and Southern regions (Fig. 6). Error bars of 95% confidence indicate relative large uncertainties with estimates for a number of the regions not significantly different from zero. Change is not calculated for forestland units smaller than regions because the carbon changes on smaller areas will likely not be significantly different from zero.

The increase on other public forestland is due in large part to the estimated increase in forestland (0.45 million ha/yr) over this period. Additional data exploration (results not shown) did not identify specific regions of the United States or unusual circumstances for this increase. USFS forest area also increased although the rate of increase was almost one-quarter of that of

Table 3. Average net forest ecosystem and products carbon stock change by ownership over the period 2000–2008.

| Ownership | Nonsoil forest ecosystem net carbon stock change (Tg $CO_2$/yr) | Uncertainty of net stock change (95% CI as percentage of mean, %) | Carbon in harvested wood products net change (Tg $CO_2$/yr) | Mean annual change in forest area (1000 ha/yr) |
|---|---|---|---|---|
| USFS | −147.3 | ±40 | −2.9 | 107.1 |
| Other Public | −184.6 | ±28 | −6.1 | 449.0 |
| Private | −149.2 | ±41 | −92.1 | −77.2 |
| All | −481.1 | ±22 | −101.1 | 478.9 |

*Notes:* Negative net carbon change indicates less $CO_2$ in the atmosphere and more in the forest. Negative area change indicates decreasing forest area. Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

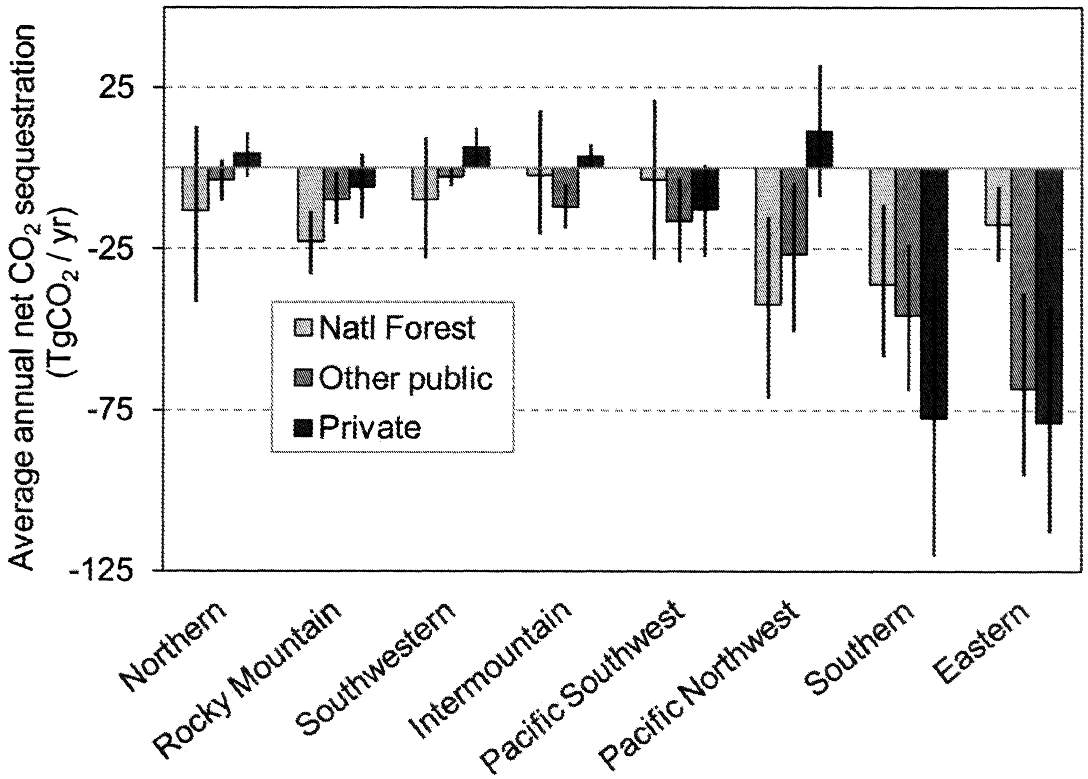


Fig. 6. Average annual net sequestration (Tg $CO_2$/yr) in forests by ownership and National Forest System region over the period 2000–2008. Note that negative values indicate more $CO_2$ is being sequestered by forests than is being emitted to the atmosphere. Error bars indicate a 95% confidence interval of uncertainty about the regional average, from carbon conversion factors and sampling error. (Data values listed in Appendix C.)

other public land. Some of this increase may be due to definitional changes in the FIA survey over this period, or an artifact of the change from the periodic to the annualized survey emphasizing the need to have reconciled FIA datasets available for analysis of trends.

Net nonsoil change over 2000–2008 of −481 Tg $CO_2$/yr (Table 3) is about 8% lower than the corresponding USEPA (2010) 9-year average of −522 Tg $CO_2$/yr. A minor part of this difference is the effect of disaggregating the stock-change calculations beyond the structure defined in Smith et al. (2010) to include the three ownerships. However, most of the difference from the results of the USEPA (2010) report is the effect of using data from the IDB (Waddell and Hiserote 2005) for the Pacific Coast states.

Beyond the forest boundary, additional carbon continues to be stored in HWP, with notable amounts attributed to harvest on privately owned land (Table 3; total carbon sequestered in forests and stored in HWP on average is estimated by summing columns 1 and 3). Products from harvests on private land continue to store an additional 62% of the net carbon sequestration on private forestland, whereas the increase is 3% at most on publicly owned land. Including the continued storage in HWP results in private forestland (and their harvested wood products) contributing to 41% of total forest sector carbon sequestration, with USFS at 26% and other public dropping to 33%. Although carbon in HWP from USFS land is minor, considering this pool is important in the context of landscape-scale management because ceasing harvests in one large area often results in increasing harvests elsewhere, if demand for products remains the same.

Other fates of forest carbon can also be substantial. We do not present change estimates from carbon benefits from harvested carbon that was burned for energy as a substitute for fossil fuel which can be notable for some ownerships. That is, trees harvested for this purpose have been subtracted from the amount in the forest, but we have not recognized that this loss may have positive benefits of substituting for fossil fuel emissions. Emissions of $CO_2$ from forest wildfires and prescribed burning on average rival those from emissions from wood burned for energy, but we currently do not have these emissions partitioned by ownership, or by land cover (e.g., forestland or rangeland).

### *Uncertainty*

The relative uncertainties for total forest carbon stocks are much larger for the individual national forests (usually in the range 8–25%) as compared to the regional uncertainties (2–6%), especially those with a smaller area of forestland or small total carbon. The larger uncertainties are mainly due to the smaller sample size on smaller areas, but may also be due to uncertainty of data sources. For ease of comparisons, we report tabular summaries of uncertainties (Table 2; Appendix B tables) as though the bounds are symmetric, which would be unlikely. However, asymmetry is small, less than 2% off of the mean for the largest percentages (Table 2) and asymmetry averages under 0.5% off of the mean for individual national forests in the Appendix B tables.

By comparison, the percent uncertainty about estimates of net sequestration are relatively large. One aspect of this uncertainty is the sensitivity of small change between relatively large stocks. For example, an additional annual increment of stock equivalent to only 0.1% of current nonsoil carbon stock in the Pacific Southwest region (data not shown) would produce a response of a 33% increase in calculated stock-change (Fig. 6). A contributing factor to the large percentage difference in this example is that the change is relatively close to zero, which further emphasizes the importance of consistent forest and carbon stock representation between successive inventories when examining inventory trends.

### *Discussion of methodology and possible improvements*

Forest carbon estimates based on augmented FIA data have long been considered the standard for landscape level and larger forestland (e.g., Pacala et al. 2001, Smith et al. 2006, USEPA GHG inventories, Climate Action Reserve 2010). Advantages of using FIA data are: it has a national-level statistically sound design, the data are publicly available (with some exceptions related to precise location and specific owner), the data are collected in partnership with state forestry agencies and all major forest components which relate to carbon are measured or sampled. However, the survey was not designed specifically for carbon estimation, so additional work is needed to ensure an efficient framework for carbon stocks and GHG changes. Further, sample precision was designated for state-level reporting, thus, using these data to represent smaller areas such as individual national forests results in higher uncertainties. Consequently, even moderate increases in carbon benefits from management activities may not differ statistically from zero.

A number of near-term improvements could be made to the existing framework for use in future U.S. GHG inventories to reduce uncertainties and align estimates more closely with measured data. These include: using recent measurements from a subset of the plots of non-live tree pools such as standing dead trees, down dead wood, as well as samples of forest floor carbon and soil organic carbon; using a more recent tree biomass equation approach based on regional net volume estimates (Heath et al. 2008) for trees that was recently adopted in FIA's national publicly available database (USDA 2010*c*; Woudenberg et al., *in press*); accounting for results from FIA field data recently available for the national forest in Puerto Rico; and delivering the information produced by the computer application CCT (Smith et al. 2010) used in the U.S. GHG inventories via an online tool. The resulting well-documented online site could then automatically produce forest carbon stock and change estimates for areas chosen by users. One challenge in these improvements is that the carbon changes for the U.S. GHG inventories are required to begin with 1990 carbon change, and older surveys generally do not include non-tree measurements. It is crucial that carbon estimates for these older surveys be derived to be consistent with newer data. Furthermore, some of the older data are only available at the plot-level, so biomass carbon estimates for the older surveys are also needed that are comparable with the newer tree-level data.

In the longer-term, as FIA plots continue to be remeasured, change estimates for most national forests in the future should become available at a precision that allows for change to be detected with increased precision. Remeasured plots will allow for gross growth sequestration to be calculated, which is information that will revolutionalize the use of FIA field plots in analysis. However, these data will still be limited temporally with remeasurements occurring 5 or 10 years apart, such that growth cannot be attributable to a specific year. Coupling these growth measures with the use of geospatially-specific datasets (which are under development) will be especially powerful for explicitly accounting for disturbances. One annual dataset under development by the Monitoring Long-Term Burn Severity project (Eidenshenk et al. 2007) will allow forest wildfire emissions to be calculated explicitly by cover type and ownership. Another relevant dataset is the National Land Cover Dataset (MRLC 2010), available for the years 1991 and 2002, with work ongoing for the year 2006. One important lesson learned from this analysis is that, no matter what sources are used, data should be carefully screened for impacts of changing definitions. Using the dataset tailored for the three Pacific Coast states changed national net sequestration by 8%, a notable amount.

Although this study focused on forestland, management activities on all lands are capable of emitting or sequestering GHGs, including non-$CO_2$ gases. For instance, wetlands or peatlands in particular can feature much higher carbon densities than forests. Monitoring all land covers and uses with activities that cause significant GHG emissions or sequestration should be considered. We have not discussed livestock emissions, but USFS land (and land under other ownerships) can include grazing. Significant livestock activity should be considered for base GHG emissions. Finally, because land management can produce multiple environmental benefits on the same land area, the process for making any inventory and monitoring improvements for carbon should also consider other important benefits.

## Conclusions

Forestland under USFS ownership features the largest average carbon density among ownerships, approximately 192 Mg C/ha in the year 2005, which is about 28% greater than that of private forestland. All carbon component pools are included: live and dead standing trees, down wood, forest floor and soil. In terms of total carbon stocks, however, private forests contain more carbon: 58%, 26% and 16% of the total forest carbon is in private, USFS, and other public ownership, reflecting the fact at the national level the majority ownership of area of U.S. forestland is private, about 63% compared to 22% and 15% for USFS and other public.

However, over the period 2000–2008, USFS and private lands have similar total net carbon sequestration in forests (not including soil carbon effects), sequestering about −148 Tg $CO_2$/yr each, with 40% uncertainty. If carbon in HWP is also accounted for, private lands contribute to an additional −92 Tg $CO_2$/yr sequestered compared to an additional −3 Tg $CO_2$/yr from USFS lands. Other public ownerships indicate a larger total net sequestration of −185 Tg $CO_2$/yr, heavily influenced by an estimated notable increase in forest area over the period. We could not pinpoint any specific reason or particular region for this estimated forest area increase, so we look to future studies for more information about this unexpected increase.

In spite of differences between ownerships, the pattern of carbon density arranged by largest to smallest by region within each ownership is quite similar. This shows the importance of regional effects such as soil and forest type, and underlying climatic drivers. However, the pattern of total average annual sequestration by ownership by region differs because totals are influenced greatly by amount of forest area. The largest net sequestration rates are in the Eastern and Southern regions for private and other public ownerships, whereas the largest net rates in the Pacific Northwest followed by the Southern and then Rocky Mountain region for USFS ownership. Due to the large uncertainties in change calculations, change for most of the other regions is not statistically different from zero.

The greatest gains in mitigation effects minimize net carbon dioxide emissions to the atmosphere. Because forest carbon has carbon benefit effects beyond forestland boundaries, managing simply to maximize forestland carbon density is not necessarily the same as minimizing forest emissions to the atmosphere (or maximizing net sequestration) during the time frame of interest. That is, a strategy focusing on only increasing forestland carbon density on a limited area over time may produce limited carbon benefits compared to a more comprehensive strategy.

These carbon densities and forest areas by NFS region and individual national forest (Appendix B) could be used as preliminary base estimates for planning adaptation and mitigation activities. To consider the effects of specific silvicultural regimes, a tool such as the Forest Vegetation Simulator (Crookston and Dixon 2005) could be used to project plots into the future; carbon in forests and harvested wood products is an output (Hoover and Rebain 2008). A variety of management activities will be needed to increase carbon benefits in USFS lands across the matrix of ecological, physical, and social conditions, especially when management needs for adaptation are a primary concern. However, demands and management choices on other ownerships should be a consideration in enhancing carbon benefits. A national-level forest futuring analysis that includes carbon outputs such as Heath and Birdsey (1993) and USEPA (2005), as well as climate change effects (Joyce et al. 1995), and global trade (Ince et al. 2007) would help ensure the major effects of large-scale processes are included.

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## Appendix A

Table A1. Forest ecosystem carbon pool definitions (Smith et al. 2006).

| Pool | Definition |
|---|---|
| Live trees | Live trees with diameter at breast height (d.b.h., 1.37 m) of at least 2.5 cm, including carbon mass of coarse roots (greater than 0.2 to 0.5 cm, published distinctions between fine and coarse roots are not always clear), stems, branches, and foliage. |
| Standing dead trees | Standing dead trees with d.b.h. of at least 2.5 cm, including carbon mass of coarse roots, stems, and branches. |
| Understory vegetation | Live vegetation that includes the roots, stems, branches, and foliage of seedlings (trees less than 2.5 cm d.b.h.), shrubs, and bushes. |
| Down dead wood | Woody material that includes logging residue and other coarse dead wood on the ground and larger than 7.5 cm in diameter, and stumps and coarse roots of stumps. |
| Forest floor | Organic material on the floor of the forest that includes fine woody debris up to 7.5 cm in diameter, tree litter, humus, and fine roots in the organic forest floor layer above mineral soil. |
| Soil organic carbon | Belowground carbon without coarse roots but including fine roots and all other organic carbon not included in other pools, to a depth of 1 meter. |

## Appendix B

Table B1. USFS Northern Region (R1) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Beaverhead-Deerlodge | 2006.1 | 170.8 | 77, 304 | 1,146 | 196 ± 8 | 68.1 |
| Bitterroot | 2006.3 | 155.5 | 71, 280 | 605 | 94 ± 13 | 54.0 |
| Clearwater | 2006.7 | 196.8 | 88, 385 | 721 | 142 ± 16 | 80.2 |
| Custer | 2006.0 | 121.1 | 67, 268 | 286 | 35 ± 23 | 33.8 |
| Flathead | 2006.2 | 167.6 | 84, 308 | 849 | 142 ± 12 | 59.0 |
| Gallatin | 2006.0 | 167.3 | 70, 266 | 659 | 110 ± 12 | 60.9 |
| Helena | 2006.1 | 165.4 | 75, 317 | 373 | 62 ± 19 | 66.0 |
| Idaho Panhandle | 2006.4 | 188.1 | 85, 366 | 927 | 174 ± 11 | 73.8 |
| Kootenai | 2006.1 | 177.5 | 76, 311 | 921 | 163 ± 10 | 68.7 |
| Lewis and Clark | 2006.2 | 158.3 | 70, 311 | 686 | 109 ± 13 | 56.8 |
| Lolo | 2006.1 | 158.9 | 73, 280 | 850 | 135 ± 12 | 56.6 |
| Nez Perce | 2006.6 | 195.8 | 85, 411 | 838 | 164 ± 14 | 80.5 |
| Additional USFS† | 2006.3 | 122.0 | 76, 171 | 36 | 4 ± 45 | 21.5 |
| Regional total | 2006.2 | 172.0 | 76, 328 | 8,896 | 1530 ± 3 | 65.2 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

† Includes the Little Missouri National Grassland and administrative areas identified as "Other NFS Areas."

Table B2. USFS Rocky Mountain Region (R2) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Arapaho-Roosevelt | 2005.4 | 150.8 | 60, 271 | 491 | 74 ± 14 | 62.0 |
| Bighorn | 2000.6 | 151.3 | 55, 318 | 298 | 45 ± 15 | 61.1 |
| Black Hills | 2005.5 | 118.3 | 68, 183 | 478 | 57 ± 6 | 37.3 |
| Grand Mesa-Uncompahgre-Gunnison | 2005.6 | 164.1 | 60, 327 | 901 | 148 ± 11 | 63.9 |
| Medicine Bow-Routt | 2003.7 | 157.8 | 55, 306 | 859 | 136 ± 10 | 61.3 |
| Nebraska† | 2006.7 | 121.2 | 68, 171 | 17 | 2 ± 37 | 33.0 |
| Pike and San Isabel | 2005.6 | 146.7 | 53, 278 | 738 | 108 ± 12 | 54.7 |
| Rio Grande | 2005.6 | 170.3 | 57, 292 | 558 | 95 ± 12 | 65.4 |
| San Juan | 2005.6 | 179.9 | 65, 358 | 664 | 119 ± 13 | 74.3 |
| Shoshone | 1999.4 | 156.6 | 53, 307 | 600 | 94 ± 12 | 60.7 |
| White River | 2005.7 | 174.8 | 70, 287 | 662 | 116 ± 12 | 68.3 |
| Regional total | 2004.5 | 158.6 | 56, 306 | 6,265 | 993 ± 4 | 61.5 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

† Consists of the Buffalo Gap, Fort Pierre and Oglala National Grasslands, and the Nebraska and Samuel R. McKelvie National Forests.

Table B3. USFS Southwestern Region (R3) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Apache-Sitgreaves | 2005.1 | 105.3 | 50, 235 | 677 | 71 ± 14 | 39.8 |
| Carson | 1998.8 | 132.0 | 53, 285 | 522 | 69 ± 14 | 50.2 |
| Cibola | 1997.5 | 86.5 | 49, 177 | 568 | 49 ± 12 | 28.0 |
| Coconino | 2004.7 | 97.0 | 49, 196 | 613 | 59 ± 14 | 35.0 |
| Coronado | 2004.6 | 83.0 | 49, 209 | 515 | 43 ± 16 | 17.8 |
| Gila | 1994.4 | 95.4 | 49, 242 | 1,180 | 113 ± 8 | 34.3 |
| Kaibab | 2004.9 | 100.6 | 51, 216 | 526 | 53 ± 15 | 38.0 |
| Lincoln | 1997.8 | 97.1 | 47, 267 | 391 | 38 ± 15 | 33.6 |
| Prescott | 2005.1 | 70.4 | 47, 167 | 259 | 18 ± 23 | 17.9 |
| Santa Fe | 1998.6 | 146.1 | 51, 315 | 593 | 87 ± 12 | 62.4 |
| Tonto | 2004.8 | 78.5 | 49, 172 | 527 | 41 ± 15 | 20.0 |
| Regional total | 2000.8 | 100.6 | 49, 254 | 6,371 | 641 ± 4 | 35.4 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

Table B4. USFS Intermountain Region (R4) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Ashley | 2004.5 | 138.0 | 53, 251 | 389 | 54 ± 15 | 49.1 |
| Boise | 2006.5 | 151.9 | 67, 295 | 686 | 104 ± 15 | 53.1 |
| Bridger-Teton | 1999.3 | 158.0 | 53, 309 | 969 | 153 ± 9 | 60.0 |
| Caribou-Targhee | 2006.1 | 148.0 | 72, 305 | 839 | 124 ± 12 | 48.0 |
| Dixie | 2004.5 | 111.3 | 52, 257 | 584 | 65 ± 13 | 38.3 |
| Fishlake | 2004.5 | 108.3 | 52, 271 | 448 | 48 ± 14 | 33.3 |
| Humboldt-Toiyabe | 2005.1 | 92.2 | 53, 225 | 1,458 | 135 ± 16 | 30.7 |
| Manti-La Sal | 2004.6 | 120.3 | 53, 280 | 441 | 53 ± 16 | 42.2 |
| Payette | 2006.6 | 147.9 | 71, 313 | 747 | 110 ± 15 | 49.0 |
| Salmon-Challis | 2006.6 | 151.1 | 81, 282 | 1,250 | 189 ± 10 | 50.7 |
| Sawtooth | 2006.4 | 176.3 | 78, 367 | 451 | 79 ± 19 | 67.3 |
| Uinta | 2004.4 | 134.7 | 57, 278 | 283 | 38 ± 18 | 44.8 |
| Wasatch-Cache | 2004.4 | 142.5 | 60, 263 | 417 | 59 ± 14 | 50.0 |
| Additional USFS† | 2005.9 | 64.9 | 65, 65 | 2 | 0 ± 126 | 17.1 |
| Regional total | 2004.9 | 135.3 | 54, 286 | 8,964 | 1213 ± 4 | 46.7 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

† Forested area of the Desert Range Experiment Station.

Table B5. USFS Pacific Southwest Region (R5) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Angeles | 2005.1 | 135.6 | 57, 319 | 87 | 12 ± 37 | 47.2 |
| Cleveland | 2006.8 | 95.0 | 65, 162 | 7 | 1 ± 83 | 20.3 |
| Eldorado | 2004.9 | 281.9 | 91, 526 | 232 | 65 ± 20 | 135.4 |
| Inyo | 2005.1 | 138.9 | 55, 353 | 456 | 63 ± 15 | 52.6 |
| Klamath | 2004.8 | 264.2 | 66, 558 | 638 | 169 ± 12 | 126.2 |
| Lake Tahoe Basin | 2005.3 | 200.5 | 90, 847 | 75 | 15 ± 49 | 86.0 |
| Lassen | 2005.0 | 213.9 | 71, 499 | 420 | 90 ± 15 | 91.2 |
| Los Padres | 2005.1 | 125.8 | 54, 330 | 304 | 38 ± 20 | 47.6 |
| Mendocino | 2005.1 | 221.6 | 68, 529 | 307 | 68 ± 19 | 104.6 |
| Modoc | 2004.7 | 142.9 | 73, 391 | 517 | 74 ± 15 | 38.8 |
| Plumas | 2004.8 | 252.2 | 82, 563 | 454 | 114 ± 13 | 116.5 |
| San Bernadino | 2005.0 | 156.2 | 62, 314 | 110 | 17 ± 32 | 60.1 |
| Sequoia | 2005.1 | 203.6 | 63, 593 | 393 | 80 ± 17 | 88.6 |
| Shasta-Trinity | 2005.1 | 256.2 | 75, 551 | 838 | 215 ± 10 | 122.0 |
| Sierra | 2004.9 | 244.3 | 72, 581 | 455 | 111 ± 14 | 115.5 |
| Six Rivers | 2004.9 | 308.8 | 80, 806 | 391 | 121 ± 13 | 166.2 |
| Stanislaus | 2004.9 | 235.3 | 62, 560 | 320 | 75 ± 18 | 106.5 |
| Tahoe | 2005.0 | 242.1 | 82, 548 | 327 | 79 ± 17 | 111.1 |
| Regional total | 2005.0 | 222.4 | 63, 548 | 6,331 | 1408 ± 2 | 100.5 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

Table B6. USFS Pacific Northwest Region (R6) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plots (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Colville | 2005.5 | 221.1 | 107, 389 | 418 | 92 ± 11 | 71.7 |
| Deschutes | 2005.0 | 167.4 | 86, 389 | 578 | 97 ± 14 | 55.4 |
| Fremont | 2004.7 | 170.7 | 89, 394 | 417 | 71 ± 17 | 56.3 |
| Gifford Pinchot | 2005.4 | 393.1 | 121, 763 | 501 | 197 ± 11 | 181.1 |
| Malheur | 2004.9 | 172.9 | 85, 295 | 532 | 92 ± 13 | 53.9 |
| Mt. Baker-Snoqualmie | 2005.3 | 387.0 | 124, 743 | 608 | 236 ± 12 | 176.4 |
| Mt. Hood | 2005.0 | 380.2 | 112, 779 | 420 | 160 ± 12 | 170.7 |
| Ochoco | 2005.3 | 158.7 | 86, 296 | 316 | 50 ± 20 | 44.8 |
| Okanogan | 2005.5 | 209.0 | 101, 435 | 636 | 133 ± 15 | 64.9 |
| Olympic | 2005.6 | 397.6 | 165, 752 | 244 | 97 ± 14 | 172.8 |
| Rogue River | 2004.9 | 328.3 | 98, 651 | 260 | 86 ± 20 | 150.8 |
| Siskiyou | 2005.2 | 346.9 | 114, 828 | 400 | 138 ± 16 | 146.3 |
| Siuslaw | 2005.2 | 395.2 | 153, 888 | 256 | 101 ± 21 | 178.7 |
| Umatilla | 2005.3 | 195.0 | 86, 366 | 512 | 100 ± 17 | 63.6 |
| Umpqua | 2005.0 | 418.6 | 141, 911 | 381 | 160 ± 16 | 198.2 |
| Wallowa-Whitman | 2005.0 | 187.6 | 85, 381 | 717 | 134 ± 12 | 57.4 |
| Wenatchee | 2005.8 | 241.4 | 97, 518 | 820 | 199 ± 13 | 87.5 |
| Willamette | 2005.0 | 420.9 | 133, 944 | 622 | 262 ± 10 | 195.6 |
| Winema | 2005.1 | 183.6 | 86, 459 | 434 | 80 ± 16 | 66.3 |
| Additional USFS† | 2005.2 | 176.6 | 118, 382 | 34 | 6 ± 59 | 37.2 |
| Regional total | 2005.2 | 273.3 | 94, 689 | 9,107 | 2493 ± 2 | 109.6 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

† Includes the Columbia River Gorge National Scenic Area and the Crooked River National Grassland.

Table B7. USFS Southern Region (R8) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Chattahoochee-Oconee | 2005.9 | 180.8 | 92, 261 | 343 | 62 ± 15 | 87.3 |
| Cherokee | 2005.8 | 174.3 | 79, 288 | 259 | 45 ± 17 | 94.0 |
| Daniel Boone | 2003.7 | 162.1 | 84, 272 | 278 | 45 ± 16 | 85.9 |
| El Yunque | ‡ | ‡ | ‡ | ‡ | ‡ | ‡ |
| Francis Marion-Sumter | 2005.4 | 181.2 | 97, 329 | 219 | 40 ± 20 | 64.1 |
| George Washington | 2005.9 | 182.0 | 90, 284 | 442 | 80 ± 13 | 90.9 |
| Jefferson | 2005.9 | 179.7 | 78, 292 | 321 | 58 ± 16 | 92.2 |
| Kisatchie | 2003.5 | 150.8 | 64, 278 | 279 | 42 ± 18 | 68.9 |
| NFS in Alabama | 2005.6 | 138.0 | 69, 231 | 305 | 42 ± 17 | 60.8 |
| NFS in Florida | 2004.9 | 163.1 | 79, 315 | 452 | 74 ± 15 | 34.5 |
| NFS in Mississippi | 2006.6 | 146.5 | 67, 242 | 537 | 79 ± 13 | 66.4 |
| NFS in North Carolina | 2005.3 | 187.6 | 77, 348 | 480 | 90 ± 14 | 95.1 |
| NFS in Texas | 2005.8 | 154.2 | 89, 231 | 279 | 43 ± 17 | 72.8 |
| Ouachita | 2003.1 | 132.1 | 66, 195 | 675 | 89 ± 9 | 58.1 |
| Ozark and St. Francis | 2004.8 | 144.9 | 77, 219 | 460 | 67 ± 13 | 71.1 |
| Additional USFS† | 2005.1 | 142.6 | 48, 255 | 95 | 14 ± 44 | 67.6 |
| Regional total | 2005.1 | 160.2 | 74, 280 | 5,423 | 869 ± 4 | 72.9 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

† Includes administrative areas identified as "Other NFS Areas."

‡ Data for Puerto Rico were not available at time of this analysis.

Table B8. USFS Eastern Region (R9) forest carbon statistics for USFS forestland by individual national forest.

| National forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Allegheny | 2004.3 | 215.2 | 99, 318 | 210 | 45 ± 8 | 90.5 |
| Chequamagon-Nicolet | 2006.1 | 262.9 | 157, 413 | 579 | 152 ± 4 | 60.2 |
| Chippewa | 2006.2 | 251.2 | 156, 396 | 227 | 57 ± 9 | 52.6 |
| Green Mountain | 2005.6 | 221.8 | 146, 316 | 166 | 37 ± 9 | 88.0 |
| Hiawatha | 2004.8 | 276.8 | 143, 443 | 340 | 94 ± 5 | 63.2 |
| Hoosier | 2006.4 | 178.0 | 82, 270 | 78 | 14 ± 11 | 88.4 |
| Huron-Manistee | 2004.9 | 224.1 | 125, 386 | 364 | 82 ± 5 | 61.4 |
| Mark Twain | 2006.2 | 151.4 | 79, 218 | 612 | 93 ± 4 | 70.2 |
| Monongahela | 2006.2 | 229.3 | 144, 345 | 368 | 84 ± 12 | 106.9 |
| Ottawa | 2004.8 | 284.6 | 172, 446 | 366 | 104 ± 5 | 76.2 |
| Shawnee | 2005.9 | 171.2 | 87, 250 | 117 | 20 ± 11 | 86.1 |
| Superior | 2006.3 | 251.3 | 145, 391 | 798 | 201 ± 5 | 39.5 |
| Wayne | 2004.6 | 175.4 | 86, 295 | 92 | 16 ± 10 | 75.1 |
| White Mountain | 2004.8 | 223.4 | 132, 308 | 326 | 73 ± 7 | 85.3 |
| Additional USFS† | 2005.7 | 183.8 | 118, 219 | 11 | 2 ± 85 | 65.5 |
| Regional total | 2005.6 | 230.7 | 111, 392 | 4,652 | 1073 ± 2 | 68.4 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

† Includes the Midewin Tallgrass Prairie and administrative areas identified as "Other NFS Areas."

Table B9. USFS Alaska (R10) forest carbon statistics for USFS forestland by individual national forest.

| National Forest | Average measurement year | Forest carbon density (Mg C/ha) | 2.5, 97.5 percentiles of plot C density (Mg C/ha) | Forest area (1000 ha) | Total forest C ± 95% CI as percentage of mean (Tg ± %) | Aboveground live tree C density (Mg C/ha) |
|---|---|---|---|---|---|---|
| Chugach | 2006.3 | 260.1 | 98, 571 | 442 | 115 ± 31 | 94.2 |
| Tongass | 2006.2 | 323.5 | 105, 610 | 3,921 | 1269 ± 6 | 123.0 |
| Regional total | 2006.2 | 317.1 | 101, 607 | 4,363 | 1384 ± 6 | 120.0 |

*Note:* Estimates calculated using FIA data and methods consistent with U.S. greenhouse gas inventory estimates (Smith et al. 2010).

## Appendix C

Table C1. Data for text Fig. 6. Average annual net $CO_2$ sequestration in forests (Tg $CO_2$/yr; not including changes in soil) by ownership and National Forest System region for the period 2000–2008.

| NFS region | National Forest | | | Other public | | | Private | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.5 | Mean | 97.5 | 2.5 | Mean | 97.5 | 2.5 | Mean | 97.5 |
| Northern | −41.5 | −13.3 | 12.9 | −10.2 | −3.8 | 2.4 | −2.7 | 4.3 | 11.1 |
| Rocky Mountain | −32.8 | −22.8 | −13.4 | −17.3 | −9.7 | −1.2 | −15.6 | −5.7 | 4.5 |
| Southwestern | −27.8 | −9.7 | 9.6 | −5.5 | −2.6 | 0.4 | −0.2 | 6.2 | 12.4 |
| Intermountain | −20.3 | −2.2 | 17.9 | −18.7 | −12.0 | −5.1 | −0.2 | 3.5 | 7.5 |
| Pacific Southwest | −28.1 | −3.5 | 21.4 | −29.1 | −16.3 | −3.2 | −27.1 | −12.8 | 1.1 |
| Pacific Northwest | −71.0 | −42.3 | −14.9 | −50.5 | −26.7 | −4.3 | −8.7 | 11.5 | 32.3 |
| Southern | −58.2 | −35.9 | −11.2 | −68.8 | −45.5 | −23.3 | −120.2 | −77.4 | −32.3 |
| Eastern | −28.7 | −17.4 | −5.6 | −95.3 | −68.1 | −38.4 | −113.0 | −78.7 | −43.3 |

*Notes:* The 2.5 and 97.5 columns are the respective percentile value for a 95% confidence interval of uncertainty about the regional mean stock-change estimates from carbon conversion factors and sampling error. Negative values indicate more $CO_2$ is sequestered by forests than is being emitted to the atmosphere.