

# Carbon stocks and stock change on federal forest lands of the United States

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**Abstract.** Forest land in the United States offsets more than 11% of total domestic greenhouse gas emissions each year through growth of live woody biomass and accumulation of carbon in trees, dead organic matter, and harvested wood products. Forest lands owned and managed by various agencies of the U.S. government cover 77 million hectares, which is 29% of U.S. forest land and an estimated 33%, or 17.2 Pg C, of forest carbon stocks. Here, we summarize forest inventory-based estimates of forest carbon stocks and indications of carbon stock change on forest lands managed by agencies within the U.S. federal government. Within the conterminous USA, the proportion of forest land that is federally owned is higher in the West representing two-thirds of forest carbon stocks; in the East, federal lands represent 9% of forest carbon. The majority of federal forests and forest carbon are managed by the U.S. Forest Service (13.8 Pg C), but 20% of federal forest carbon stocks, or 3.5 Pg C, are managed by other federal agencies (e.g., National Park Service, Bureau of Land Management). We also briefly review some broad characteristics of the forest inventory that affect forest carbon reported for the USA as included in greenhouse gas inventories such as for United Nations Framework Convention on Climate Change reporting.

**Key words:** biomass; carbon stocks; National Forest Inventory; public land.

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## INTRODUCTION

Forest lands owned by the United States and managed by agencies within the federal government represent almost one-third of total U.S. forest lands (Oswalt et al. 2014). Carbon stored in forests, primarily as wood, is sequestered from atmospheric carbon dioxide, and ongoing growth and carbon storage on those forests are an important offset to greenhouse gas emissions (U.S. EPA 2018). Lands under federal ownership represent a large area of forest ostensibly under a single ownership but managed by separate agencies or departments. The carbon in those forests

is often targeted as the basis for a variety of management, policy, or reporting purposes (Smith and Heath 2004, Smith 2012, Tan et al. 2015, USDA 2016). A principal data source for many U.S. forest carbon assessments is the Forest Inventory and Analysis Data Base (FIADB; USDA Forest Service 2017), which is compiled, maintained, and made publicly available by the Forest Inventory and Analysis Program (FIA) of the United States Department of Agriculture Forest Service (Forest Service hereafter, USDA Forest Service 2018). Here, we summarize federal forest carbon based on this forest inventory data source.

The FIADB provides a comprehensive and longitudinal record of forest lands, is annually updated, and the data are readily available (O'Connell et al. 2017a). Forest inventory-based estimates of carbon stocks are the primary source of forest sector greenhouse gas inventory reporting for the United States as a participant in the United Nations Framework Convention on Climate Change (UNFCCC). The principal records of this ongoing reporting are the annual greenhouse gas inventories compiled by the U.S. Environmental Protection Agency (U.S. EPA; i.e., U.S. EPA 2018 and previous such reports dating back to the late 1990s). The forest inventory data together with sets of carbon conversion factors or models provide estimates of plot-level carbon, which are aggregated as needed for estimation and reporting. These forest carbon estimates are similarly applied to other national reports (USDA 2016) or regional analyses (Heath et al. 2011, Ogle et al. 2015, Hoover and Smith 2017). In turn, summaries such as U.S. EPA (2018) or USDA (2016) are often the sources for subsequent additional analyses. For example, much of the forest carbon analyses in Zhu and Reed (2012, 2014), and Hoover et al. (2014) are based on the U.S. EPA summaries. Smith (2012) also used an EPA report and pointed out the need for a federal lands only version of the same.

A number of other separate approaches to national-scale forest carbon assessments are developed largely independent of the FIA-forest-inventory-to-UNFCCC-reporting pathway, which is the focus of this report. Similarly, the FIA's FIADB is often utilized without reference to that same pathway (i.e., toward reporting via U.S. EPA 2018). The use of remote sensing and simulation modeling are well-established bases for similar scale estimates, which generally also include multiple information sources (sometimes including components of forest inventories), aimed at the same quantity—forest carbon (Dietze et al. 2011, Huntzinger et al. 2012). Additionally, forest carbon estimates are directly available from FIADB tables. For example, in addition to the current tree carbon method of Woodall et al. (2011), tree carbon can be estimated according to individual tree allometries (Jenkins et al. 2003, Chojnacky et al. 2014) or stand models using the FIADB (Hoover and Smith 2017), all of which are in use to quantify forest carbon. Such estimates are

possible without any of the intermediate processing or updates discussed here, which are a part of U.S. EPA (2018). Examples where researchers obtained carbon estimates directly from the FIADB include analyses by Tan et al. (2015), Zhou et al. (2013), and Fahey et al. (2009). The FIADB tables are also the source of forest carbon reported by the U.S. Forest Service in the periodic reports on U.S. forest resources as a part of the Resources Planning Act (RPA) assessment reports on the status and trends of the nation's renewable resources on all forest and rangelands (Oswalt et al. 2014).

This report is not an evaluation of alternate peer-reviewed and published forest carbon assessments such as are cited here, but it is intended to provide useful disaggregate information, generally as tabular summaries, not directly available from either the FIADB (USDA Forest Service 2017) or U.S. EPA (2018), which conform to the inventory-to-UNFCCC-reporting pathway (Domke et al. 2012, Heath 2012, U.S. EPA 2018).

Changes in forests and carbon reported are evident from the series of annual reports over recent years (see current and prior year's information as available and cited in USDA Forest Service 2017 and U.S. EPA 2018). Forest management practices have shifted, in recent years, toward ecosystem- or multiple use-based management priorities and practice (Ellenwood et al. 2012, Dilling and Failey 2013, Keith et al. 2014, Sample et al. 2015). While we make no attempt to identify any effect of changes in management practices, the current inventory largely reflects many such years on federal forest lands. Changes in land use also affect forest carbon, principally through changes in the amount of forest land. While specifically identifying effects of land use change is beyond the scope of this report, the consistent annual forest inventory data collected since the late 1990s (USDA Forest Service 2018) makes it possible to include an informal summary of carbon stock changes over most of forest lands since 2005.

Ongoing updates in the process of obtaining carbon estimates from forest inventory data is an additional source of apparent change in annual reports. Many of the carbon or biomass fields in the FIADB tables that explicitly provide carbon quantities by ecosystem pool, especially in the condition tables, predate most-current estimates (Smith et al. 2013). The Forest Service is continually improving this process of obtaining carbon

estimates from forest inventory (e.g., see Domke et al. 2016, 2017). One result of these updates is that on average over 98% of ecosystem carbon on forest plots is estimated according to different conversion factors or models today (U.S. EPA 2018) relative to similar scope summaries from almost a decade ago (U.S. EPA 2010, Heath et al. 2011). However, all such estimates and changes are documented, and incremental differences, or step changes, in stand level carbon stocks are generally small (Heath 2012, Smith et al. 2013, Domke et al. 2016). Note that the FIA process for inventory-to-carbon conversion is under review with an aim toward continuous improvement and is subject to further change within a few years as new biomass models or better resolution of other carbon stocks within forest ecosystem pools are developed (e.g., dead wood, litter, soils), which means modification of current estimates are likely.

This report is based on inventory and carbon estimates underlying annual greenhouse gas reporting as in U.S. EPA (2018), but the data cannot be obtained from that report at the scale or level of detail provided here. In a similar way, these estimates are primarily based on the Forest Service's forest inventory data, but most are attainable only after the intermediate processing steps as outlined and cited here. We bridge the data source and reporting outlet with information not available in either. Specifically, our purpose is to describe FIADB-based carbon consistent with U.S. EPA (2018); that is, we (1) quantify carbon stocks on federally owned and managed forest lands, which includes location geographically or by administrative agency; (2) provide an overview of effects of changes in inventory or classification as well as effects of recent updates in forest-inventory-to-carbon conversions; (3) identify indications of change in forest carbon stocks since 2005; and (4) provide extensive intermediate level tabular summaries as Appendix S1 and Data S1 that are at a more disaggregate level but consistent with the inventory-to-forest carbon stocks provided in the U.S. greenhouse gas inventory (U.S. EPA 2018).

## METHODS

### *Forest inventory*

The forest inventory data (as available in the FIADB) that underlie the carbon estimates are

organized as continuous systematic annualized sampling of permanent plots over all land within individual states so that a portion of the survey data is collected each year on a continuous series of cycles, with remeasurement at 5, 7, or 10 yr depending on the state (Bechtold and Patterson 2005). This current inventory design and sampling process was implemented beginning in 1998 and is known as the FIA annual inventory. Permanent inventory plots are located across the country at a minimum density of one plot for approximately every 2,400 hectares of land. Only plots that have at least one forested condition are measured in the core inventory; that is, domains mapped on each plot as a forest land use and specifying forest type, stand size, ownership, tree density, stand origin, or disturbance history (there may be multiple conditions on a single inventory plot). As such, the current or most-recent data for the entire U.S. land base includes over 135 thousand plots that include forest measurement data. Data were obtained from the publicly available Datamart (USDA Forest Service 2017) on 30 August 2017. Note that within this 2017 version of the FIADB the most recent evaluation (or population estimate) per state is most commonly for 2016, which means field data collection extends back over the previous five or more years. For consistency in presenting results, current estimates are based on these most-recent data per state, and estimates of change are based on interpolation or extrapolation from 2005 through 2017 (discussed in more detail below).

Carbon estimates are currently organized into six separately determined ecosystem pools (live tree biomass, live understory biomass, standing dead wood, downed dead wood, litter, and soil organic carbon) developed to encompass essentially all forest ecosystem organic carbon. These pools are more formally defined in various sources cited here, including U.S. EPA (2018) and USDA (2016). Estimates are based on models applied to inventory data collected on the permanent inventory plots, and generally not the result of direct sampling of carbon. For example, live tree carbon stocks are based on allometric relationships, wood density, and carbon conversion constants applied to individual tree measurements (e.g., height, diameter, crown dimensions, species, or stand structure; Woodall et al. 2011). Note that the carbon estimation process applied

here is identical to U.S. EPA (2018), yet the version of the FIADB used here (30 August 2017) is not identical to the FIADB version applied U.S. EPA (2018). Any differences in derived carbon stocks are expected to be very minor. The U.S. EPA (2018) annex describing the methodology for forest estimates is the best single source for the current carbon estimations (see also Woodall et al. 2011 [live tree biomass]; Domke et al. 2012 [standing dead wood]; Domke et al. 2013 [downed dead wood]; Domke et al. 2016 [litter]; and Domke et al. 2017 [soil carbon]).

The current FIADB includes only a portion of Alaska forests—along the south central and southeastern coast, which constitutes about 12% of the state's estimated forest land. Otherwise, the inventory includes forests of the remaining 49 states as well as Puerto Rico, U.S. Virgin Islands, Guam, Northern Mariana Islands, Palau, and American Samoa. Estimates for area of forest land are available for all of these areas, and estimates of current change in forest land are available for many but not all areas. Both Northern Mariana Islands and Palau have no federal forest land identified within the FIADB, so they are not specifically identified in the tabular summaries of federal forests. Similarly, Rhode Island has no federal forest land, so it is not included in the federal forest summaries.

#### *Forest carbon for greenhouse gas reporting*

Carbon estimates are not yet available for all forest lands identified within the FIADB. Forest carbon is reported here for the 48 conterminous states as well as southeast and south central coastal Alaska; this is similar to U.S. EPA (2018). The balance of the inventory data does not have complete forest ecosystem estimates of carbon that are consistent with those reported here. These other mostly tropical forest inventories are more recent than the long established inventories within the conterminous 48 states. The carbon factors developed for and applied to temperate forests are unlikely to be directly applicable to the tropical forests in these newer inventories.

Initial estimates of carbon are made at each individual forested plot following the methods cited. Subsequent estimates of totals for forest area and carbon stocks as well as the additional ratio estimates of carbon density or annual forest area change follow the evaluations, or

population estimates, provided within the FIADB (Bechtold and Patterson 2005, O'Connell et al. 2017b). Confidence intervals are estimates of sampling error and are provided in tables as the interval from the mean to either of the 95% bounds. They are based on the 67% sampling error (Bechtold and Patterson 2005), which are then multiplied by 1.94 to provide 95% bounds to conform to reporting of confidence bounds in U.S. EPA (2018). Separate processes were followed for calculating error for totals (e.g., Tg C) vs. ratio estimates (e.g., Mg C/ha). Similarly, separate estimates were made for each successive inventory cycle (i.e., same population but different years for data collection). We do not include estimates for modeling error, as in application of the carbon conversion factors.

Two additional modifications to the currently reported forest land in FIADB were applied here before processing carbon or land area estimates; these also applied to U.S. EPA (2018). First, unmanaged lands in Alaska are not reported in order to maintain consistency with current UNFCCC reporting guidelines, which report on managed lands only. All forest lands of the 48 conterminous states are considered managed, but a portion of Alaska has been identified as unmanaged (Ogle et al. 2018, U.S. EPA 2018). The second modification involves woodland forest types that are identified as forest within the FIADB but do not meet the potential minimum tree height for classification and reporting as forest (Oswalt et al. 2014, Coulston et al. 2016, U.S. EPA 2018). These too-short woodlands are specifically identified (Coulston et al. 2016) and removed from U.S. EPA (2018) reporting and similarly removed here. Note that neither of these modifications are as yet explicitly identified within the FIADB.

The focus here is on forest lands under federal ownership. Four federal land management agencies administer over 95% of federally owned lands (Vincent et al. 2017); these are as follows: Forest Service; National Park Service; Bureau of Land Management; and Fish and Wildlife Service. Summaries presented here are according to agencies that are explicitly identified in the FIADB; these are as follows: Forest Service; National Park Service; Bureau of Land Management; Fish and Wildlife Service; Departments of Defense or Energy; and the pooled set of all remaining

federal government entities that include some forest land “Other Federal.” The Forest Service lands include not only the National Forest System but also National Grasslands or Prairies as well as other Forest Service land. Note that only forest land is addressed here; that is, total land area by agency is not included here (or in the database). Summaries including all U.S. forest land are allocated to three broad ownerships; in addition to the federal classification, forests are identified as private (private ownership) or other-public (state, county, or municipal ownership). In addition to allocating forest carbon among federal agencies, the carbon reporting area is divided into four regions (Fig. 1; Pacific Coast, Rocky Mountain, North, and South). The regional divisions also correspond to the four FIA units (USDA Forest Service 2018).

#### *Recent change in carbon stocks*

Annualized stock and stock change estimates follow the approach applied for estimates of forest carbon change in USDA (2016), which is based on Smith et al. (2010). In this presentation, we incorporate only the FIA annual inventories and sum population totals from successive

inventory cycles. Net annual stock change is based on interpolation over the intervals between inventory cycles and extrapolation to net annual change representing 2016, as needed. Change in 2016 represents the most recent estimates based on stock estimates extrapolated through 2017. This provides a ready approximation of carbon change under an assumption of relatively low change in land use, which is a likely characteristic of public lands. For this reason (assumption of relatively low land use change on federal forest lands), we also include an informal evaluation of change in forest land based on the area change evaluations within the FIADB (O’Connell et al. 2017b). The subset of the FIADB in use here includes data collected since 2001 in order to characterize forests between 2005 and the present. The year 2005 is selected because a large number of states have complete annual inventory datasets available from that time forward.

Within the 49 states included in carbon reporting and the constraint of annual-inventory only, there are a few states or portions of states that cannot be resolved into at least two separate population sequences from available inventory data. These are primarily in the West. Coastal Alaska,



Fig. 1. Regional classifications used for the forest carbon summaries in this analysis. Area of forest inventory used for carbon estimates includes all of conterminous United States as well as southern coastal Alaska (gray shaded areas).

New Mexico, and the western portion of Texas each have a small number of remeasured forest plots, but they represent about 10% of forested conditions. Wyoming and the western part of Oklahoma do not yet include remeasured plots. These five areas (states and partial states) are included in summaries as zero net annual change (i.e., the effective value from no information). The remaining western states (see Fig. 1) are all partly remeasured, and between 20% and 70% of forested conditions on federal forest lands are represented by remeasured annual inventory plots. These states were included in the stock change calculations despite the limitations of the data. Note that Oklahoma and Texas are divided into eastern and western portions for the stock change calculations in order to determine change in the east for both states. See Smith et al. (2010) and O'Connell et al. (2017a, b) for details on subdividing states for stock change and the delineation of Coastal Alaska and the eastern and western portions of Oklahoma and Texas.

Potential effects of land use change on our stock change calculations can be obtained from area change information in the forest inventory. The estimates for forest land converted to non-forest or non-forest converted to forest land are based on the FIADB area change evaluations, which are then expressed as change per year. These change estimates are summarized by region; Rocky Mountain and a portion of South are excluded because of limited change information. We include the eastern parts of Oklahoma and Texas in this analysis; note that complete remeasurement of the annual inventory for the West will be available in several years.

#### *Updated carbon conversions*

The approach to estimating forest carbon stocks based on FIA data has remained consistent for well over ten years as documented in U.S. EPA 2018 and previous annual reports. However, updates in carbon conversions for the various ecosystem pools have changed estimates and have the potential for future modifications, even where the carbon pool being described is ostensibly unchanged (Heath 2012, Smith et al. 2013, Domke et al. 2016). In addition to this potential for change in forest carbon inventories, two additional factors can contribute to year-to-year change in reports. The first is simply change

in forests (i.e., growth, mortality, disturbance), which are reflected in the successive annual FIA updates. The second is inclusion or exclusion of certain lands; unmanaged Alaska forests and the too-short woodlands were not a consideration in reporting several years ago. Similarly, inclusion of Hawaii, interior Alaska, and others is expected in future reports (U.S. EPA 2018).

In order to provide some perspective on changes in carbon reporting arising from updates in the conversion process, we informally summarize additional representative sets of carbon estimates (in addition to current as described here) that reflect updates over several years (approximately an 8-yr interval). A second set of carbon conversion factors applied to a specific inventory at a somewhat similar scope (as this report) is the summary of Forest Service forest lands of Heath et al. (2011), which also corresponds to forest carbon as reported in U.S. EPA (2010). The third set of estimates is from fields currently populated in the tree and forest condition tables of the FIADB, which represents a mix of both current and older carbon conversions. In this set, tree carbon estimates correspond to current methods (U.S. EPA 2018), whereas the remaining forest ecosystem pools either predate or correspond with those of U.S. EPA (2010) and Heath et al. (2011). Exact methodological details for each pool at each time are well documented (U.S. EPA 2010, 2018, Heath et al. 2011, Smith et al. 2013, O'Connell et al. 2017a) and not important to this presentation, which looks at brief summaries of overall effect.

## RESULTS AND DISCUSSION

### *Area of forest land*

Total federally owned forest land in the United States encompasses 78 million ha, which is 29% of reported forest land obtained from the FIADB (Tables 1, 2). In addition to most land over the 50 states, this total also includes Puerto Rico, the U.S. Virgin Islands, American Samoa, and Guam. Additional U.S. territories within the FIADB do not include federal forests. The forest areas specified are defined here according to methods defined for national greenhouse gas inventory reporting as by U.S. EPA (2018) and differ slightly from totals as reported by Oswalt et al. (2014). The principal discrepancy is Alaska and

Table 1. Area of forest land on regions described in Fig. 1, based on estimates developed from current Forest Inventory and Analysis Data Base evaluations.

| Agency or ownership              | Pacific Coast,<br>1000 ha ( $\pm$ CI) | Rocky Mountain,<br>1000 ha ( $\pm$ CI) | North,<br>1000 ha ( $\pm$ CI) | South,<br>1000 ha ( $\pm$ CI) |
|----------------------------------|---------------------------------------|--|-------------------------------|-------------------------------|
| Forest Service                   | 19,426 (220)                          | 29,016 (340)                           | 5301 (51)                     | 5281 (52)                     |
| National Park Service            | 1135 (72)                             | 1464 (115)                             | 329 (48)                      | 806 (61)                      |
| Bureau of Land Management        | 2068 (95)                             | 7970 (236)                             | 21 (13)                       | 6 (9)                         |
| Fish and Wildlife Service        | 409 (35)                              | 144 (36)                               | 258 (43)                      | 822 (81)                      |
| Departments of Defense or Energy | 78 (27)                               | 259 (48)                               | 458 (58)                      | 1740 (123)                    |
| Other Federal                    | 77 (26)                               | 26 (16)                                | 106 (30)                      | 162 (37)                      |
| All federal forest land          | 23,194 (256)                          | 38,878 (434)                           | 6472 (106)                    | 8818 (172)                    |
| All forest land                  | 39,636 (292)                          | 54,291 (378)                           | 73,840 (270)                  | 102,698 (425)                 |

Note: CI, confidence intervals.

Table 2. Area of forest land based on regions that do not also include carbon estimates as well as totals for entire United States, which includes values from Table 1.

| Agency or ownership                 | Caribbean<br>Islands,<br>1000 ha<br>( $\pm$ CI) | Pacific<br>Islands,<br>1000 ha<br>( $\pm$ CI) | U.S. total,<br>1000 ha<br>( $\pm$ CI) |
|-------------------------------------|---|---|---------------------------------------|
| Forest Service                      | 9 (9)   |   | 59,032 (411)                          |
| National Park Service               | 4 (1)   | 26 (12)                                       | 3764 (157)                            |
| Bureau of Land<br>Management        |   |   | 10,064 (255)                          |
| Fish and Wildlife<br>Service        | 9 (5)   | 14 (7)  | 1657 (105)                            |
| Departments of<br>Defense or Energy |   | 35 (16)                                       | 2570 (147)                            |
| Other Federal                       |   |   | 372 (57)                              |
| All federal forest land             | 22 (11)   | 75 (21)                                       | 77,459 (543)                          |
| All forest land                     | 512 (32)  | 705 (42)                                      | 271,682 (696)                         |

Notes: Hawaii forest lands are combined with the Pacific Islands because there is currently insufficient information to estimate Hawaii forest carbon consistent with the other 49 states. Blank cells indicate no forest land within that classification. CI, confidence intervals.

in particular the interior, primarily boreal, forest lands of Alaska, which are estimated for Oswald et al. (2014) but are not included in the FIADB. Within the conterminous United States, the proportion of forest that is federally owned is highest in the West representing 55.0% and 71.4% in Pacific Coast (excluding interior Alaska) and Rocky Mountain, respectively. In the East, federal lands are 8.7% of forest in the North and 8.6% in the South.

Most of federal forest land is administered by the Forest Service as national forests, experimental forests, or other areas. Bureau of Land Management forests are the next most common in the

West, while Departments of Defense or Department of Energy forests are second most common in the East (Table 1). Forest composition on federal lands, as indicated by forest type group, generally reflects that of non-federal lands by region; however, softwood forest types generally are in slightly greater proportion of federal forests relative to other forestlands (e.g., see Appendix S1: Tables S1 and S2). Federal forests in the West are 84% softwood type groups, while non-federal forests are 72% softwood type groups; in the east, the proportions of softwood types are 29% on federal and 25% on non-federal forest. Mean stand age is greater on federally owned forests than on other ownerships in both the West and the East (data not shown). Various summary classifications are provided for federal forest in the Appendix S1 tables and Data S1. For additional information on the composition or structure of federally owned forest lands, see USDA (2016) and Oswald et al. (2014).

#### Forest carbon for greenhouse gas reporting

Forest areas and carbon stocks as reported here conform to greenhouse gas reporting guidelines, as presented in Chapter 6 "Land use, land use change, and forestry" of U.S. EPA (2018). The two modifications to the forest-carbon-from-inventory calculations (unmanaged lands in Alaska and too-short woodlands) applied to the FIADB are consistent with U.S. EPA (2018), but their effects on reporting totals have not been described. Federal forest lands in the coastal Alaska portion of the FIADB identified as unmanaged (Ogle et al. 2018) are 5.7% by area and are excluded from reporting. In other words, current managed federal forest land in coastal

Alaska is reported as 4.65 million ha (see Data S1: sd1\_stateByAgency), but raw forest area from the FIADB is 4.94 million ha (i.e., 0.28 million ha as the deducted unmanaged forest land). Total forest carbon stocks identified as unmanaged are 5.4% of the initially calculated total, which amount to 86.2 Tg C deducted. Within the conterminous United States, those woodlands identified as not meeting minimum potential tree height for classification as forest (Oswalt et al. 2014, Coulston et al. 2016, U.S. EPA 2018) amounted to 3.99 million ha deducted from federal forests; this is 4.9% of all federal forest area and 30.7% of federal forests identified as woodland type groups (pinyon/juniper or woodland hardwoods). Ninety-seven percent of these too-short woodland hectares are in the Rocky Mountain region. Total forest carbon stocks on these lands, which are deducted from initial FIADB calculations, are 452.4 Tg C deducted; this is 2.6% of all federal forest carbon stock and 25.8% of that on federal forests identified as woodland type groups. The same deduction of some woodlands as discussed here is also applied in the RPA forest land and forest carbon reported by Oswalt et al. (2014), which accounts for all woodlands, not federal-only. However, associated quantities of carbon will differ somewhat because RPA forest carbon pools are directly from the FIADB.

### Current carbon stocks

Aboveground live tree carbon is the most-often quantified pool of forest carbon, the most

affected by management and utilization, and thus is a major component of carbon management. Carbon density—tonnes per hectare—in aboveground live trees on federal forest land is greater on average than the mean over major ownerships within each region (Table 3) except for the North, where there is little difference among the ownership groups. Carbon density in aboveground live trees is greatest for the Pacific Coast and lowest for Rocky Mountain. The average density in the South is greater than that of the North. Regionally, federal forest average carbon per ha is slightly less than the average for the other-public ownership for the Pacific Coast and Northern regions. Federal forest has greater density relative to other-public in the Rocky Mountain and Southern regions, which is also where the Forest Service forests have the highest density among federal agencies. National Park Service forests have the highest forest carbon density in the Pacific Coast and Northern regions. The overall lowest carbon density among federal agencies is on Bureau of Land Management lands (Table 3).

Broad region by ownership summaries of level of forest stocking (Fig. 2) or tree carbon density (Table 3) shows no particular trend or indicator that federal forest lands are under-utilized relative to other ownerships. We include a brief informal analysis of federal lands relative to other forest ownerships to identify pertinent similarities or differences in non-stocked forest land, which has been identified as an indicator of under-utilized carbon storage (Sample 2016).

Table 3. Mean aboveground carbon density in live tree biomass based on ratio estimates for forest land developed from current Forest Inventory and Analysis Data Base evaluations.

| Agency or ownership              | Pacific Coast, Mg C/ha ( $\pm$ CI) | Rocky Mountain, Mg C/ha ( $\pm$ CI) | North, Mg C/ha ( $\pm$ CI) | South, Mg C/ha ( $\pm$ CI) | U.S. total, Mg C/ha ( $\pm$ CI) |
|----------------------------------|------------------------------------|-------------------------------------|----------------------------|----------------------------|---------------------------------|
| Forest Service                   | 92.3 (1.6)                         | 37.9 (0.6)                          | 56.4 (0.8)                 | 73.1 (1.1)                 | 60.6 (0.6)                      |
| National Park Service            | 147.4 (10.4)                       | 31.3 (2.9)                          | 62.8 (5.9)                 | 63.1 (4.0)                 | 76.2 (3.7)                      |
| Bureau of Land Management        | 85.8 (5.4)                         | 16.0 (0.6)                          | 24.9 (12.0)                | 7.1 (3.7)                  | 30.4 (1.2)                      |
| Fish and Wildlife Service        | 28.9 (5.0)                         | 8.5 (2.4)                           | 53.6 (7.2)                 | 55.5 (5.2)                 | 44.4 (3.3)                      |
| Departments of Defense or Energy | 72.6 (29.2)                        | 11.9 (6.6)                          | 58.5 (5.2)                 | 55.7 (3.0)                 | 52.2 (2.7)                      |
| Other Federal                    | 78.6 (32.9)                        | 14.1 (12.0)                         | 52.4 (11.1)                | 60.1 (9.4)                 | 58.5 (9.0)                      |
| All federal forest land          | 93.2 (1.6)                         | 32.9 (0.5)                          | 56.6 (0.9)                 | 66.8 (1.1)                 | 56.8 (0.6)                      |
| Other-public forest land         | 102.5 (6.1)                        | 25.2 (1.8)                          | 57.2 (0.8)                 | 54.8 (1.9)                 | 58.3 (1.0)                      |
| Privately owned forest land      | 63.5 (1.5)                         | 21.5 (0.6)                          | 57.9 (0.4)                 | 44.5 (0.3)                 | 48.6 (0.3)                      |
| All forest land                  | 83.5 (1.1)                         | 29.8 (0.4)                          | 57.7 (0.3)                 | 46.9 (0.3)                 | 51.8 (0.2)                      |

Note: Additional ownerships are included for comparison of relative average carbon stocks on federal forest lands. CI, confidence intervals.

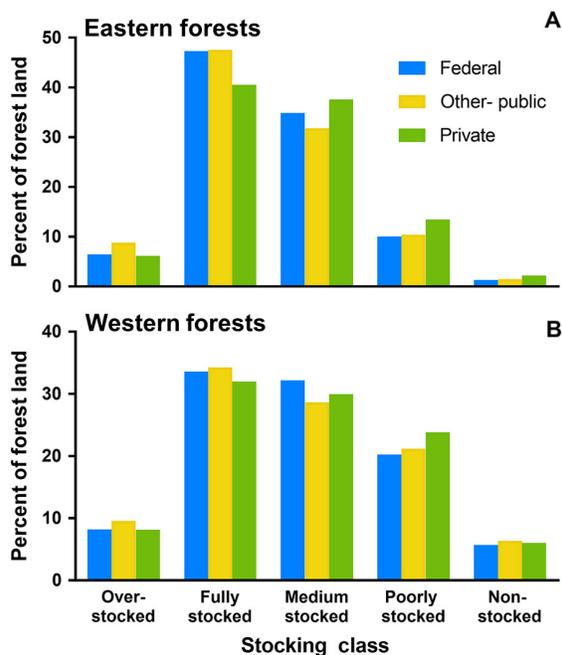


Fig. 2. Percentage of forest land within each of the three broad ownership classifications (federally owned, other public ownerships, or privately owned) as each are allocated to five stocking classifications (i.e., the stocking class) in the Forest Inventory and Analysis Data Base (FIADB) for eastern (A: North and South) and western (B: Pacific Coast and Rocky Mountain) forests.

Forests classified as non-stocked (Fig. 2, which is class 5 in the FIADB forest condition table) include very few or none of trees meeting certain minimum size requirements according to standard growth algorithms (O'Connell et al. 2017a). However, non-stocked can be a transient condition, which suggests that one-time (or snapshot) summaries are less informative; for example, stands regenerating after harvest or disturbance can be temporarily classified as non-stocked. An example analysis of this possibly transient condition is possible in the eastern United States where most inventory plots are remeasured. The percentage of forest land in the current inventory that is non-stocked, by ownership is 1.3%, 1.5%, and 2.2% for federal, other-public, and private ownerships, respectively (Fig. 2). However, this percentage of forest land in the current inventory that remained non-stock over two consecutive surveys (based on remeasured plots) is 0.6%, 0.5%, and 0.3% for federal, other-public, and

private ownerships, respectively. While this does possibly suggest that the percentages of forest remaining non-stocked in the East may be proportionally greater under federal ownership, the total areas are small. At this relatively broad-scale summary, there is no general indication that federal forests are overtly understocked with respect to carbon sequestration.

Total ecosystem carbon stocks on federal forests in the West are greater than either the other-public or private ownerships (Table 4). This is reversed in the East where federally owned forest carbon stocks total less than either private or other-public when summed for the entire East. These trends in Table 4 reflect forest area of Table 1. Forest Service carbon stocks are greatest among the federal agencies, while Bureau of Land Management forests are the second largest pool in the West, while the Department of Defense or Department of Energy forests represents the second largest pool in the East.

A characteristic of public lands in general and federal forest lands in particular is that some are set aside as reserved. The reserved designation broadly limits or eliminates harvesting and affects management options on such lands (Olander et al. 2012, O'Connell et al. 2017a). While the reserved status is not directly an indicator of carbon stocks or sequestration potential, management scenarios leading to older stands are generally linked to greater carbon stocks. In this regard, we repeated the summaries of Tables 1–4 with federal forests separated into reserved and non-reserved forest land for federal ownership (see Appendix S1: Tables S3–S5). Overall, there is no clear and consistent increase or decrease in carbon stocks on forest lands designated as reserved. Twenty-three percent of federal U.S. forest lands are identified as reserved. Within federal agencies, both the National Park Service and the Fish and Wildlife Service forest lands are entirely reserved; of the remaining agencies, the Forest Service forests have the greatest proportion of reserved, with the proportion greater in the West relative to the East. Overall, federal forests within the four regions identified by Fig. 1 have 25% of total forest ecosystem carbon stocks on reserved land.

Forest Service forest land accounts for 76% of all federal forest land. For this reason, we include summaries of current forest area and carbon stocks on Forest Service forest land (Table 5;

Table 4. Total forest ecosystem carbon stocks based on estimates developed from current Forest Inventory and Analysis Data Base evaluations.

| Agency or ownership              | Pacific Coast,<br>Tg C ( $\pm$ CI) | Rocky Mountain,<br>Tg C ( $\pm$ CI) | North,<br>Tg C ( $\pm$ CI) | South,<br>Tg C ( $\pm$ CI) | U.S. total,<br>Tg C ( $\pm$ CI) |
|----------------------------------|------------------------------------|-------------------------------------|----------------------------|----------------------------|---------------------------------|
| Forest Service                   | 5755 (54)                          | 5872 (52)                           | 1087 (9)                   | 1048 (10)                  | 13,761 (76)                     |
| National Park Service            | 426 (19)                           | 278 (16)                            | 75 (8)                     | 167 (9)                    | 945 (27)                        |
| Bureau of Land Management        | 541 (18)                           | 1116 (27)                           | 3 (1)                      | 1 (1)                      | 1662 (33)                       |
| Fish and Wildlife Service        | 111 (7)                            | 16 (3)                              | 53 (6)                     | 154 (11)                   | 333 (15)                        |
| Departments of Defense or Energy | 20 (5)                             | 30 (5)                              | 91 (8)                     | 297 (15)                   | 448 (19)                        |
| Other Federal                    | 20 (5)                             | 4 (2)                               | 21 (4)                     | 28 (4)                     | 72 (8)                          |
| All federal forest land          | 6873 (61)                          | 7316 (61)                           | 1329 (16)                  | 1694 (23)                  | 17,212 (91)                     |
| Other-public forest land         | 823 (27)                           | 423 (19)                            | 2,892 (32)                 | 861 (26)                   | 4,999 (53)                      |
| Privately owned forest land      | 3276 (37)                          | 1977 (35)                           | 11,211 (47)                | 13,952 (59)                | 30,416 (91)                     |
| All forest land                  | 10,971 (76)                        | 9716 (73)                           | 15,432 (59)                | 16,507 (69)                | 52,627 (139)                    |

*Note:* Additional ownerships are included for comparison with carbon stocks on federal forest lands. CI, confidence intervals.

Table 5. Forest Service managed forest area and carbon summaries according to the nine National Forest System regions based on estimates developed from current Forest Inventory and Analysis Data Base evaluations.

| National Forest System region          | Forest land area,<br>1000 ha ( $\pm$ CI) | Aboveground live tree carbon density,<br>Mg C/ha ( $\pm$ CI) | Total ecosystem carbon stock,<br>Tg C ( $\pm$ CI) |
|--|--|--|---|
| Northern (Region 1)                    | 8999 (172)                               | 52.3 (1.4)   | 2114 (31)   |
| Rocky Mountain (Region 2)              | 6249 (172)                               | 39.4 (1.2)   | 1299 (26)   |
| Southwestern (Region 3)                | 5801 (152)                               | 25.4 (1.0)   | 880 (18)  |
| Intermountain (Region 4)               | 8570 (200)                               | 29.8 (1.0)   | 1683 (30)   |
| Pacific Southwest (Region 5)           | 6009 (104)                               | 83.0 (2.6)   | 1595 (24)   |
| Pacific Northwest (Region 6)           | 9062 (58)                                | 99.9 (1.8)   | 2744 (22)   |
| Southern (Region 8)                    | 5330 (52)                                | 73.2 (1.1)   | 1059 (10)   |
| Eastern (Region 9)                     | 4779 (46)                                | 59.2 (0.8)   | 1001 (8)  |
| Alaska (Region 10)                     | 4225 (190)                               | 90.7 (5.3)   | 1385 (43)   |
| All National Forest System forest land | 59,024 (421)                             | 60.6 (0.6)   | 13,761 (77)                                       |

*Notes:* Summaries include all Forest Service forest within each of the region's boundaries, and values correspond to summaries provided in Tables 1–4. The Region 8 summary here does not include Puerto Rico because there is currently insufficient information to develop forest carbon estimates consistent with the other forest land of the table. CI, confidence intervals.

Appendix S1: Tables S6 and S7), which correspond to the information previously summarized by federal ownership but are allocated according to the National Forest System regions. As expected, most of the forest land is in the West, the highest aboveground live tree carbon densities are along the Pacific Coast, and the largest stock of carbon is in the Pacific Northwest. Tabular summaries for reserved and non-reserved forest land are provided in Appendix S1: Table S8. Nineteen percent of forest lands and 20% of total forest ecosystem carbon stocks are on reserved land. As with all federal lands, reserved status does not necessarily correspond to greater average carbon stocks. In general, NFS regions along the Pacific Coast (regions 5, 6, and 10) have

greater proportions in reserved, and southern and eastern (regions 3, 8, and 9) have lower proportions of carbon in reserved forest.

The current estimate of total ecosystem carbon on Forest Service forests is 13,761 Tg carbon. This is 19% greater than the 11,604 Tg carbon identified by Heath et al. (2011), which was also based on carbon factors applied to the FIADB plot-level records on the same overall area of the United States. Total forest area as reported here is 2% lower relative to the earlier report. These differences are from FIADB-based summaries developed eight years apart, and differences can be attributed to both the more complete annual forest inventories in the West and the intervening modifications to the inventory-to-carbon

calculations. Changes in the carbon conversion factors over the interval are the greater source of the carbon differences. Carbon conversion factors have been modified or entirely changed since the earlier report (U.S. EPA 2010, Heath et al. 2011) for all of the forest ecosystem pools except understory, which typically represents <2% of forest carbon. As an illustration of the conversion factor effect, total forest carbon on Forest Service forest land if calculated according to the methods of Heath et al. (2011) and applied to the current FIADB is 11,446 Tg carbon—slightly over 1% lower than the previous report. That is, the analysis of Heath et al. (2011) repeated with current carbon conversion factors would be 1% different according to changes in forest inventories alone. This 1% decrease in carbon stock may be associated with the 2% decrease in forest area, but both differences represent very small annual changes and are not informative at this level of detail. However, the bulk of the apparent difference is identified by changing the carbon conversions in use, which underscores the role of the carbon factors in the apparent change.

#### Recent change in carbon stocks

Successive FIADB-based population totals within each state are used to develop annualized estimates of forest area, carbon stocks, and net stock change based on interpolation (Smith et al. 2010). These repeated forest inventories indicate that federally owned forest land area has increased since 2005 for five out of six regions—Rocky Mountain, North, South, Caribbean Islands, and Pacific Islands. The single region showing a slight decrease in federally owned forest land is Pacific Coast. These annualized forest area and carbon data are available by state and year within Data S1: sd2\_annualized and sd3\_annualizedAreaOnly.

Annualized net carbon stock and annual net change summaries according to the six agency groups over the area of the 49 continental states (Fig. 3) show an increase in total forest carbon stocks since 2005, with the exception of the catch-all Other Federal category. Area of forest land by agency generally followed the same pattern. That is, within the six agency group by four region classes, an increase in carbon stocks over the 12-yr interval was associated with an increase in forest area. The two exceptions were Forest Service and

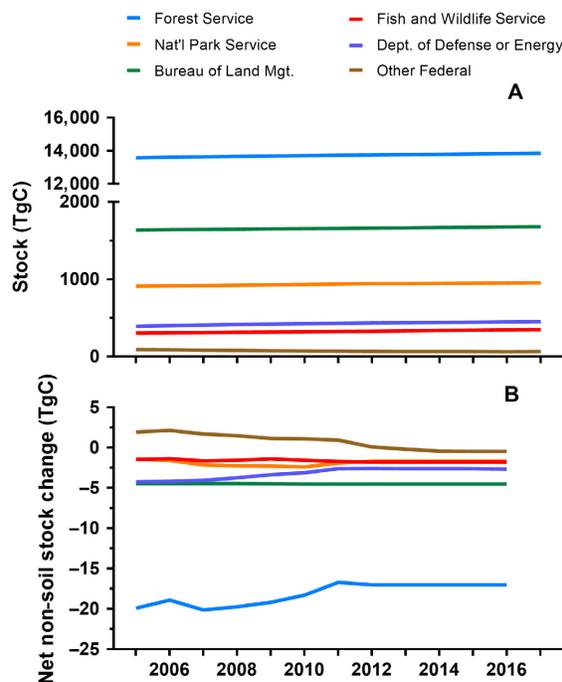


Fig. 3. Annualized total forest carbon stocks (A) and net annual non-soil stock change (B) on federal forest land within conterminous United States and southern coastal Alaska (see Fig. 1) classified according to federal agency. Note that estimates follow the sign convention where negative net change indicates forest gain in carbon stocks.

Bureau of Land Management forests in the Pacific Coast where decreases in forest area over the interval were accompanied by net increases in carbon stocks (see Data S1: sd2\_annualized and sd3\_annualizedAreaOnly for this information). Note that estimates of net annual change follow the sign convention (U.S. EPA 2018) where negative net ecosystem change indicates forest gain in carbon stocks (and thus removed from atmosphere).

Stock change estimates indicate that total forest ecosystem carbon stocks tended to increase in the Pacific Coast, Rocky Mountain, North, and South regions (Appendix S1: Fig. S1, Data S1: sd2\_annualized). Note that similar total carbon stock estimates are not yet available for the Caribbean and Pacific Islands, and a few states are limited to only a single forest inventory over the interval and do not contribute to the general regional trend (e.g., Hawaii, New Mexico, and others listed above in “Methods”). The most-

current annualized estimates for net annual carbon stock change (annualized net change for 2016 from Appendix S1: Fig. S1) by the four regions are provided with the 95% confidence interval in Table 6. The error bounds we provide for this approach to stock change (Smith et al. 2010) are based on sampling error and an assumption of independence between successive inventory cycles, except where successive population totals for a state include overlapping plot data (i.e., panels in use by both of the pair of population totals). In that case, we assume correlation between the two stocks is proportional to the amount of redundant data involved. These assumptions likely inflate the size of the confidence interval because two successive inventories are not entirely independent but assigning zero change and zero error where these data are available likely underestimates error. In addition, the bounds do not reflect uncertainty in the carbon conversion factors, or models, applied to produce carbon stocks from forest inventory.

Tan et al. (2015) evaluated the potential for future carbon storage in terrestrial ecosystems on federal lands of conterminous United States. They projected continued sequestration but a slightly decreasing role of federal lands in the overall U.S. carbon budget. They also highlight the role of federal forest lands in determining carbon totals, which underscores the need for both a resource summary such as this as well as additional details addressing the possible decreasing role in carbon storage. The broad summaries here do not provide information necessary to evaluate effects of forest aging or management on sequestration.

Table 6. Region-wide estimates of most-recent annualized net stock change of forest ecosystem carbon, based on estimate for 2016.

| Region         | Annualized net stock change, Tg C/yr ( $\pm$ CI) |
|----------------|--|
| Pacific Coast  | -11.9 (10.1)                                     |
| Rocky Mountain | -8.0 (18.4)                                      |
| North          | -11.9 (9.2)                                      |
| South          | -3.2 (11.8)                                      |

*Notes:* Estimates follow the sign convention where negative net change indicates forest gain in carbon stocks and they are based on the annualized stock change approach of Smith et al. (2010) and are not directly from the Forest Inventory and Analysis Data Base or U.S. EPA (2018). CI, confidence intervals.

Forest Service forest lands within each of the nine regions of the National Forest System are also evaluated for annualized stock and net stock change (Table 7; Appendix S1: Fig. S2, and Data S1: sd4\_annualizedNFS). Forest carbon stocks increase overall and in most regions. Region 10 (Alaska) is set as zero net stock change (i.e., no change) due to insufficient remeasurement to date, as discussed in the Methods. Region 3 (Southwestern) had a small net loss of carbon in biomass (Table 7) despite variability in forest area over the interval. The net loss of carbon after 2010 in Region 8 (Southern) is associated with a decrease in forest area and soil organic carbon stocks. Despite the decrease in area, carbon in biomass increased throughout most of the interval. These observed trends are based on net differences between successive inventory cycles and serve as possible indicators of change but do not provide any mechanistic information on details or causes.

The annualized stock and change estimates are based on evaluating total stocks for each inventory cycle within each state. Resolving the FIADB-based populations to a sequence of carbon stock totals and interpolating between successive whole-state (or sub-population of interest such as a federal agency) stocks provides the annualized estimates of total forest carbon over

Table 7. Region-wide estimates of most-recent annualized net stock change of forest ecosystem carbon according to National Forest System, based on estimate for 2016.

| National Forest System region | Annualized net stock change, Tg C/yr ( $\pm$ CI) |
|-------------------------------|--|
| Northern (Region 1)           | -3.6 (7.7)                                       |
| Rocky Mountain (Region 2)     | 0.3 (7.0)  |
| Southwestern (Region 3)       | 2.5 (3.4)  |
| Intermountain (Region 4)      | -1.0 (9.1)                                       |
| Pacific Southwest (Region 5)  | -2.7 (5.6)                                       |
| Pacific Northwest (Region 6)  | -6.8 (5.1)                                       |
| Southern (Region 8)           | 3.1 (9.1)  |
| Eastern (Region 9)            | -7.9 (4.7)                                       |

*Notes:* Summaries include all Forest Service forest within each of the region's boundaries. The Region 8 summary here does not include Puerto Rico (as explained in text), and Region 10 is excluded due to insufficient change data. Estimates follow the sign convention where negative net change indicates forest gain in carbon stocks, and they are based on the annualized stock change approach of Smith et al. (2010) and are not directly from the Forest Inventory and Analysis Data Base or U.S. EPA (2018). CI, confidence intervals.

the intervening years as well as net annual change between successive annualized stocks. However, this approach to accounting can produce misleading or inaccurate results where the system defined for analysis includes only forest land at each period even where land use change occurs, as opposed to also accounting for carbon exchange with adjacent non-forest land uses as well. With only net population differences, carbon emitted to the atmosphere (e.g., via mortality or fire) is not distinguished from carbon apparently lost from forests due to system boundaries and transferred among land uses (i.e., not exchanged with the atmosphere). For example, change from forest to non-forest land use usually includes some transient increase in emissions, possibly associated with some tree removal, but this effect is variable, depends on the new land use, and large portions of the carbon stock are typically retained in the terrestrial system under the new land use.

These stock change methods were developed for net change over large areas, and estimates do not reflect the kind of change information available from plot-level remeasurement (Smith et al. 2010). However, the annualized stock change accounting artifact (or, edge effect) is assumed to have a small contribution to total stock change when land use change is relatively low (Smith and Heath 2010, Smith et al. 2010). Land use change on federal forest lands is generally low relative to other ownerships. A brief informal summary based on the area change evaluations in FIADB (O'Connell et al. 2017b) provides the proportion of current forest area associated with conversion of land as either forest-to-non-forest or non-forest-to-forest, based on remeasured plots (Table 8). These are summarized for the Pacific Coast (but not Alaska), North, and South

(but not Central & West Oklahoma or Texas, see O'Connell et al. (2017b) for these sub-state regions) and indicate that current percentage of forest land annually changing on federal forest lands is generally lower than forests under other ownerships. Effects depend on specific forests and actual carbon exchanged or emitted on transfer to other land uses.

#### Updated carbon conversions

The comparison of Forest Service stocks obtained for this report with those of Heath et al. (2011) points out the role of carbon conversion factors in contributing to differences in large area assessments such as these. This effect of carbon factors also extends to ongoing reporting such as U.S. EPA (2018) in comparison with previous reporting as U.S. EPA (2010), which are reporting on the same resource yet subject to continuous improvements (Smith et al. 2013, Domke et al. 2016). In a similar way, researchers have access to analogous estimates of these same carbon pools via fields of the tree and condition tables within the FIADB. These carbon values can differ from the currently in-use values and reflect past updates, but they are also directly applicable to large area assessments. For example, Tan et al. (2015) produced estimates that were primarily based on the FIADB; forest area and non-soil carbon estimates were consistent with carbon from the tree and condition tables of the database. Ongoing changes through adaptation of alternate approaches, improvements, or other revisions of existing methods can add to the array of potential reported values.

Assessing the sources of change and relative influence of inputs on forest carbon totals is beyond the scope of this study, and the changes are documented elsewhere (Heath 2012, Smith et al. 2013, Domke et al. 2016). However, as an illustration of such change we calculate carbon on federal forest lands according to three alternate but related approaches (or, inventory-to-carbon conversion factors). These approaches correspond to (1) the current carbon pool estimates used in this study and U.S. EPA (2018); (2) the carbon pool estimates used in Heath et al. (2011) and cited as following U.S. EPA (2010); and (3) estimates as obtained from the current FIADB condition and tree tables (USDA Forest Service 2017). That is, each of these three

Table 8. Estimated annual percentage of forest land associated with land use change.

| Region  | Federal | Other-public | Private |
|---|---------|--------------|---------|
| Pacific Coast (but not Alaska)                        | 0.6     | 0.6          | 0.8     |
| North   | 0.4     | 0.6          | 1.0     |
| South (but not central and western Oklahoma or Texas) | 0.3     | 0.8          | 1.0     |

*Note:* Based on land identified as changing from forest to non-forest or non-forest to forest from the Forest Inventory and Analysis Data Base change evaluations.

approaches is applied to the FIADB records of 30 August 2017. The choice of Heath et al. (2011) for comparison is because it provides a well-defined forest carbon assessment where differences over time are clearly defined. The inclusions of the FIADB tables as a source are because they are publicly available and readily used to develop estimates (Tan et al. 2015). The mean distribution of plot-level carbon densities is shown in Fig. 4. The major revision in estimating tree biomass

(Woodall et al. 2011) that was implemented after U.S. EPA 2010 is not readily apparent at this level of summary (Fig. 4, top row). However, the recent move toward directly basing litter and soil organic carbon estimates on FIA plot data (Domke et al. 2016, 2017) is more apparent (Fig. 4, middle and bottom rows). As an example of the net effect on totals, total carbon stock on Forest Service forest land over the 48 conterminous states plus coastal Alaska is 13,761, 11,446,

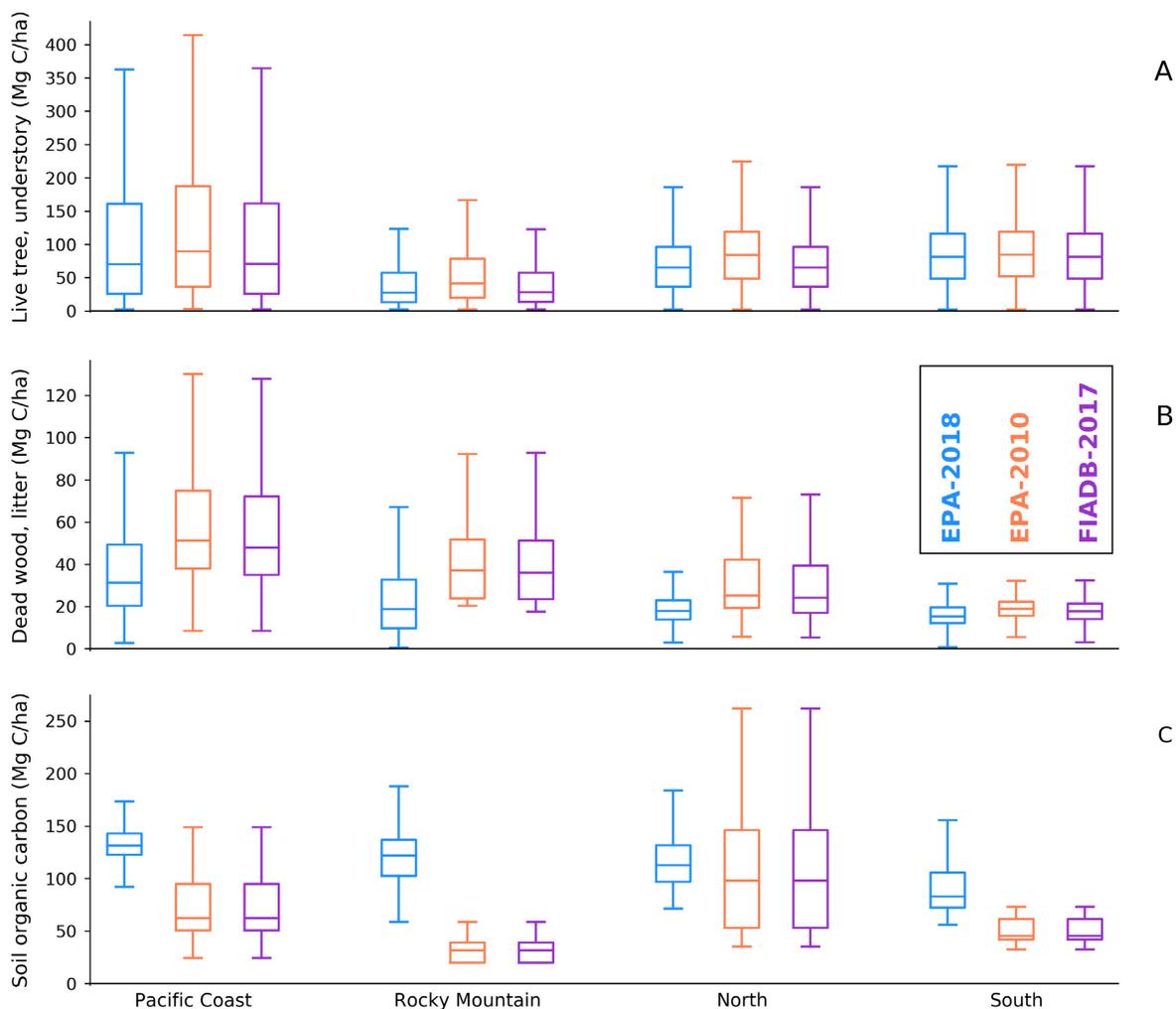


Fig. 4. Effect of three sets of inventory-to-carbon conversion factors applied over region and carbon pools grouped as live (A), dead (B), and soil (C). The three conversion sets are labeled EPA-2018 (blue) the current carbon pool estimates used in this manuscript and EPA (2018); EPA-2010 (orange) the carbon pool estimates used in Heath et al. (2011) and EPA (2010); and Forest Inventory and Analysis Data Base (FIADB)-2017 (purple) estimates as obtained from the 30 August 2017 condition and tree tables of the FIADB. The box and whisker graphics as used here provide the 1st, 25th, 50th, 75th, and 99th percentiles of plot-level carbon densities.

or 10,500 Tg carbon for the current FIADB if calculated according to methods of this study, Heath et al. (2011), or the current FIADB (USDA Forest Service 2017), respectively. The 20% increase in the current calculated value relative to Heath et al. (2011) is the net result of average decreases in specific carbon densities for biomass, dead wood, and litter and increases in soil organic carbon estimates (Fig. 4).

## CONCLUSION

The current state of federal land increasingly reflects years of management where priorities shifted to include multiple resources, including ecosystem services and multiple uses of forest land (Duan et al. 2016). Carbon stocks on federal forest lands represent one part of the overall forest resource, and specific carbon densities (per unit area estimates) are higher than the overall average for U.S. forest lands. Forest area and carbon stocks are relatively stable on federal lands, with indications of only small changes over the past several years. Results also suggest little effect of land use change in eastern forests where such an analysis is feasible.

We also briefly reviewed some broad characteristics of the forest inventory that affect U.S. forest carbon as included in greenhouse gas inventories such as for UNFCCC reporting. Specifically, on federal lands: A substantial area of interior Alaska forest land is not currently included in the inventory (19.2 million ha) although first-order estimates will be included in the 2019 report; a relatively minor 97,000 ha of tropical forest land is in inventory but not yet a part of reported carbon stocks; 86 Tg C of currently inventoried Alaska forest is deducted from reporting because it is identified as unmanaged land; 452 Tg C of woodlands is reassigned from forest land to shrubland; and 23% of federal forest is identified as reserved, which affects management options.

An analysis at the scale of the results presented here as well as in the Appendix S1 and Data S1 can usefully identify broad trends such as forest carbon ownership by state or region. Plot-level data of the FIA inventories have many application at multiple scales, but the state by ownership population estimates that make up the core of this manuscript provide limited spatial or

temporal resolution. Similarly, attribution of likely causes of trends observed here—such as effects of management practices, forest aging, or specific disturbances—is beyond the scope of this manuscript.

Apparent changes in reported carbon stocks relative to some past reports largely reflect updates in carbon conversion factors. That is, carbon conversion factors have been revised and are increasingly defined by data collected with forest inventory, rather than based on modeling. The land base of forest inventory has expanded in recent years so that the only remaining substantial gap in the extensive array of FIA permanent inventory plots is in interior Alaska. However, consistent inventory-to-carbon conversion factors for both boreal and tropical forests are not in place, so this report was limited to temperate forests. Probably the most substantial advance in reporting is the use of continuously improving spatial resolution in land use change information. The large extent of federal forest lands and the relative stability of the resource suggests that these lands will continue as a substantial reserve of sequestered terrestrial carbon.

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