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Carbon factors and models for forest carbon estimates for the 2005–2011 National Greenhouse Gas Inventories of the United States

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ABSTRACT

Most nations have ratified the United Nations Framework Convention on Climate Change, and are mandated to report National Greenhouse Gas Inventories, including the land use, land use change and forestry sector when it is significant. Participating countries commonly use data from national forest inventories as a basis for their forest-related emissions estimates. The estimates are required to be consistent, comparable among parties, transparent, and well-documented. To help meet these requirements, we describe the data and methods used to calculate the forest carbon component of the United States' greenhouse gas emissions and sinks which we provided to the US Environmental Protection Agency to be compiled for the submission years 2005–2011. Past forest inventories were not designed to measure or take samples of data directly related to quantifying ecosystem carbon stocks necessary for greenhouse gas reporting. This study provides information used to bridge that gap and enable harmonized reporting. Specifically, we provide the forest inventory plot-data-to-carbon-stock conversion factors and associated uncertainty bounds in use for the reporting years prior to the availability of more directly measured or sampled carbon stocks. The factors are similar to default values supplied by the Intergovernmental Panel on Climate Change and current scientific literature. Overall, this approach indicates that forest ecosystems of the United States sequester approximately 170 Tg of carbon per year, which represents a net annual increase of half a percent of forest carbon stocks.

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1. Introduction

The forest sector in the United States is substantial, with the largest net carbon sink of all land uses (Heath et al., 2011a). Forest carbon estimates are part of the ''Land Use, Land-Use Change, and Forestry'' section within the annual US National Greenhouse Gas Inventory (GHGI), part of the United States' participation in the United Nations Framework Convention on Climate Change (UNFCCC, 2012) compiled by the US Environmental Protection Agency. In addition, a periodic Agriculture and Forestry GHGI focused on providing more information at the sub-national or state-level is produced by the US Department of Agriculture (USDA, 2011). The principal data source for these annualized estimates of forest carbon stock and stock change is the National Forest Inventory (NFI) conducted by the USDA Forest Service's Forest Inventory and Analysis (FIA) Program.

Traditional forest inventories have long been recognized and used to produce credible estimates of forest characteristics and conditions (Scott and Gove, 2002). The NFI inputs to the US forest carbon stock and stock-change estimates are a compilation of FIA forest inventories collected over an interval of more than 30 years. The NFIs include field plot measurements, but also rely on ancillary data such as remote sensing and official census area quantities to estimate forest area or to improve precision. Because the survey was not designed for carbon estimation, the NFI data did not explicitly include carbon pools (Heath, 2012), so carbon factors and models were developed to enable development of consistent and comparable estimates of carbon stock across time based on available inventory data. These estimates quantify carbon in live trees, standing dead trees, understory vegetation, down dead wood, forest floor litter, and soil organic carbon.

Using NFI data for the GHGI in the forest sector is common among nations, but approaches to conduct inventories can vary, which means the inputs to estimating carbon stocks are also subject to change. For purposes of GHGIs, harmonizing either forest inventories or carbon factors ensures consistent carbon estimates under potentially different systems of forest inventory. Harmonized reporting is challenging for several reasons (Dunger et al., 2012; McRoberts et al., 2010), including that many nation's NFIs were originally developed for purposes that did not include carbon monitoring. When various forest carbon estimates are developed using different definitions of carbon pools or dissimilar calculation procedures, harmonization permits the estimates to be made consistent with one another to facilitate direct comparison.

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Harmonization of NFIs alone is not sufficient for comparison of the US forest carbon estimates with those developed by other nations, states, or provinces; the comparison should encompass both the NFIs and carbon conversion process.

The purpose of this study is to make transparent the data-to-carbon-stock conversion factors and uncertainties associated with harmonizing forest GHGI reporting as applied to NFIs (Dunger et al., 2012). The methods described focus on the forest sector national GHGI estimates we provided to US EPA, with publication dates ranging from 2005 to 2011 (i.e., USEPA, 2005 through USEPA, 2011). This presentation significantly expands on the methods outlined in the respective USEPA publications with a focus on information relevant to harmonizing carbon from NFIs. Specifically, we: provide parallel regional and forest type classifications applicable to different inventory formats; identify data gaps in forest inventories where these carbon factors are not applicable and provide the carbon densities we used to fill these gaps; and, finally link specific source forest inventories, carbon factors, and reporting years. Change estimates for US forests for this period are shown in Fig. 1. This interval is distinct because reports compiled prior to 2005 relied primarily on modeling and a different inventory format as the primary data source (Heath, 2012; Heath et al., 2010; Woodbury et al., 2007). Reports compiled after 2011 begin to reflect changes to the NFI initiated in the late 1990s where plot-level data collection began quantifying specific forest ecosystem carbon pools such as forest floor and soil carbon (Woodall et al., 2010). These data have only recently become available for limited nationwide estimates, and are beginning to be incorporated into the national GHGI (USEPA, 2013).

The compilation of the national GHGI estimates of carbon change in forest ecosystems using survey data following Smith et al. (2010) can be described in four broad steps. The first step is to obtain the available NFI data, which consists of FIA data that has been collected and made available in various forms and formats over the years (USDA Forest Service, 2013a); also see USDA Forest Service (2013b) and Woudenberg et al. (2010) for information about the most-recent FIA data as well as Smith et al. (2010) for information on the older FIA data. The second step focuses on the process of augmenting or converting FIA plot data to plot-level quantities of carbon stock. The third step is to expand the plot-level carbon stocks to total carbon on all forestland, such as for an entire state; see Woudenberg et al. (2010) or Bechtold and Patterson (2005) for additional information. The final step involves summarizing these stocks as annualized stock and stock-change at state and national levels according to Smith et al. (2010), starting with the base annualized estimate year of 1990.

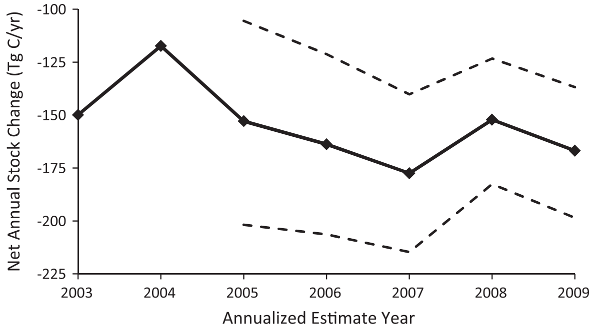

Fig. 1. Net annualized estimates of forest carbon stock change (Tg C per year) for US forest lands. Each point – 2003 (USEPA, 2005) through 2009 (USEPA, 2011) – is the most-current estimate obtained from each of seven successive national greenhouse gas inventories (USEPAs, 2005 through 2011), and change is based on non-soil carbon stocks (i.e., biomass, dead wood, and litter). The dashed lines represent the 95% confidence interval about each estimate; these are provided for the reporting years where the estimates were based on the full set of our carbon conversion factors. Note that by convention, negative change indicates increased carbon stocks in forest ecosystems.

We focus on the second step in the US forest national GHGI, which is augmenting or converting FIA plot or tree data to plot-level quantities of forest carbon stock. The estimates of uncertainty developed for these plot-level conversion factors make it possible to explicitly incorporate this stock change method (Smith et al., 2010) in a Monte Carlo simulation for the uncertainty estimates provided in 2005 (USEPA, 2007) and subsequent reporting years (Fig. 1). Our objectives are to: (1) present the specific carbon conversion factors applied as in Smith et al. (2010) and applicable to USEPA, 2005 through 2011; (2) provide background on their appropriate selection and use, which is a part of the information necessary to harmonize GHGIs; (3) describe the estimates of uncertainty associated with plot level conversion factors; and (4) discuss overall consistency of the factors with the reporting recommendations of the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change, and Forestry (Penman et al., 2003) as well as the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006).

2. Materials and methods

2.1. Carbon pools

Carbon factors and models were developed to produce the following distinct, non-overlapping, forest ecosystem carbon pools:

- Aboveground and belowground live tree biomass, which includes all live trees 2.5 cm dbh (at 1.37 m above the forest floor) and larger. The aboveground portion includes stem, stump, branches, bark, seeds, and foliage. The belowground portion is coarse living roots greater than 2 mm diameter.
- Understory, all live biomass less than 2.5 cm dbh.
- Standing dead trees, includes entire portion (above- and below-ground) of standing dead trees 2.5 cm dbh and larger.
- Down dead wood, which includes all non-living woody material lying on the ground and having a diameter greater than 7.5 cm at transect intersection. This pool also includes stumps, above- and belowground.
- Forest floor, or litter, which includes the litter, fulvic, and humic layers, and all non-living woody biomass with a diameter less than 7.5 cm at transect intersection, lying on the ground.
- Soil organic carbon (SOC), all organic material, including fine roots, in soil to a depth of 1 m but excluding the coarse roots of the belowground pools.

Each pool is expressed as a carbon density (tonnes per hectare or Mg per hectare) for the forested conditions on FIA inventory plots. These plot-level carbon-from-inventory conversions are then compiled as the forest carbon stock and stock-change estimates reported annually in the US national GHGI.

We first describe the NFI data sources on which the US national GHGIs are built; we then present the methodology for converting forest inventory data to carbon. The approaches for calculating carbon density by pool for inventory plots make reference to tabular summaries and coefficients which are provided in the accompanying supplemental tables. Most of the estimates are classified by region (Fig. 2). For clarity, we describe three terms to distinguish different application of “year” in the text that follows. The initial field-collected survey data, or state-level forest inventories, which are compiled as the NFI and labeled according to state, are classified by “source inventory years.” These data are then processed to provide annualized estimates of forest carbon stock and

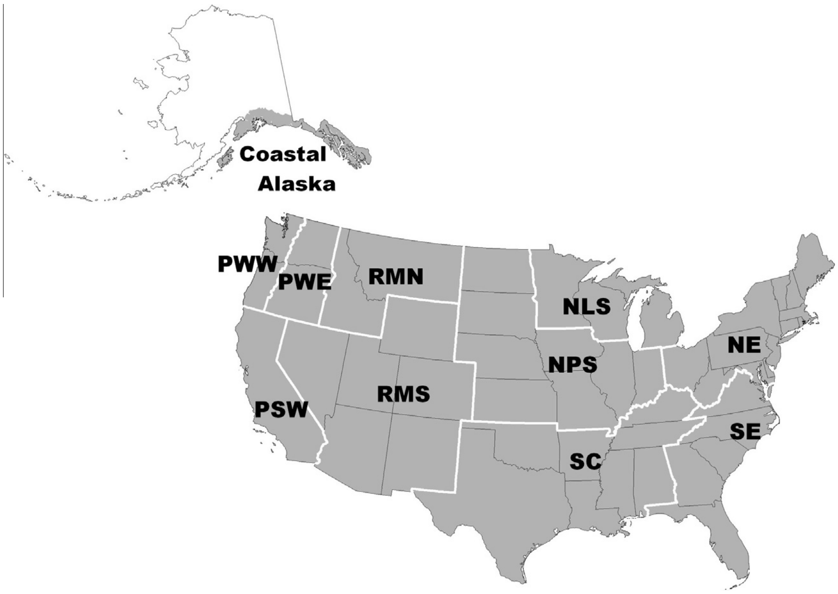

Fig. 2. Definition of regions used to classify carbon factors; combinations of these regions are also used. The regions are defined as: Pacific Southwest (PSW: California), Pacific Northwest, Westside (PWW: western portions of Oregon and Washington), Pacific Northwest, Eastside (PWE: eastern portions of Oregon and Washington), Coastal Alaska (south central and southeastern Alaska), Rocky Mountain, North (RMS: Idaho and Montana), Rocky Mountain, South (RMS: Arizona, Colorado, Nevada, New Mexico, Utah, and Wyoming), Northern Prairie States (NPS: Illinois, Indiana, Iowa, Kansas, Missouri, Nebraska, North Dakota, and South Dakota), Northern Lake States (NLS: Michigan, Minnesota, and Wisconsin), South Central (SC: Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Oklahoma, Tennessee, and Texas), Southeast (SE: Florida, Georgia, North Carolina, South Carolina, and Virginia), and Northeast (NE: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, and West Virginia).

stock-change, which begin with the base year of 1990; the calculated stock and stock-change are classified by ‘‘annualized estimate years.’’ Finally, the annual GHGI reporting in EPA publications (e.g., USEPA, 2005 through 2011) are named by ‘‘reporting years.’’ For example, reporting year 2009 presents annual carbon estimates for 1990–2007.

Each reporting year (USEPA, 2005 through 2011) is primarily based on the latest version of FIA’s Forest Inventory and Analysis Database (FIADB) available at the time of compilation. These data are documented (USDA Forest Service, 2013c) and the most current version of the FIADB is freely available for download (USDA Forest Service, 2013b). The forest inventory surveys within the FIADB are organized as separate surveys by state and by years of data collection (i.e., source inventory years). In general, surveys from the last 10 to 15 years are known as ‘‘annualized inventory’’ where a portion of the survey data are collected each year on a continuous cycle whereas older surveys are known as ‘‘periodic inventory’’ where all state-wide data were collected in 1 or 2 years followed by a 5–15 year interval before a state was resurveyed (USDA Forest Service, 2013c). The versions of the database principally used to create these forest carbon inventories – FIADB 1.7 through FIADB 4.0 – are no longer available through USDA Forest Service (2013c), but the FIA data used to create USEPA, 2010 are available from Smith et al. (2010). Currently available forest inventory data are in the FIADB 5.1 format (USDA Forest Service, 2013b), which provides basically the same survey information with different formats and some additional modifications. The FIADB forest inventory surveys used in USEPA (2005 through 2011) are also included in the current FIADB 5.1 version, and application of these carbon factors will produce essentially the same results as in the respective GHGIs. However, the FIADB is updated over time; tables are added and deleted and computational methods and algorithms may also be modified from version to version. For this reason, data retrieved from a prior version of the FIADB may not yield precisely the same results as data from the current version. Consult the FIA database documentation for a description of changes (USDA Forest Service, 2013c).

Some of FIA’s forest inventory data from the late 1980s and early 1990s is not available in the FIADB format. However, these state surveys are applicable and necessary to develop the forest carbon stock and stock-change annualized estimates for the national GHGIs which must start in 1990. Thus, available FIA inventory datasets in older pre-FIADB formats are incorporated into the estimates. Their use includes special considerations in the formation and application of carbon conversion factors so that both definitions of carbon pools and forestlands are consistent among carbon stock and stock-change estimates based of these different inventory data sources. This is done to develop consistent sequences of carbon stocks for the interval 1990–present within individual states as described in Smith et al. (2010). Databases housing these inventories include the Eastwide (Hansen et al., 1992), Westwide (Woudenberg and Farrenkopf, 1995), Southern FIA unit (see Smith et al., 2010), and PNW integrated database (IDB: Waddell and Hiserote, 2005) formats. In addition, FIA inventory data are periodically summarized in support of the Forest and Rangeland Renewable Resources Planning Act of 1974; these inventory compilations, particularly before tree-level data were widely available, are usually referred to as RPA data (USDA Forest Service, 2013a; Smith et al., 2009; Miles et al., 2004). Some of FIA’s RPA data are used as needed to supplement the above inventory data sources. A basic difference between the RPA database and the other inventory data in use is that the RPA provides only plot-level summaries of the tree information, such as volume per hectare. Having only plot-level information limits precision associated with the conversion to biomass (Smith et al., 2003). For this reason, the live tree carbon conversions are in two forms, one based on individual-tree data and the other based on plot-level data, as appropriate.

2.1.1. Live trees

The live tree carbon pools include aboveground and belowground (coarse root) carbon mass calculated on a per tree basis. All tree estimates on a plot are combined according to the specific plot design. Initial calculations are for aboveground biomass; the belowground component is determined as a percentage of aboveground. Estimates based on individual-tree data use the Jenkins et al. (2003) set of allometric relationships, which are functions of species group and diameter. The link between the species groups of Jenkins et al. (2003) and the FIADB 4.0 species codes as included in USEPA (2011) is provided in Table S1, which differs slightly from a similar list in Jenkins et al. (2003). Updates to the FIADB in the time between the publication of the species list in Jenkins et al. (2003) and the list provided in Table S1 include some additions or modifications of a very few species codes. These lists of paired values are checked annually and modified as needed to keep current with the FIADB as it evolves. The list specific to FIADB 4.0 and associated with USEPA (2011) is provided (Table S1) because it is the most broadly applicable. An example form of the calculation for the estimate of aboveground biomass for a live tree of a species in the aspen/alder/cottonwood/willow group is:

$$\text{Biomass (kg dry weight)} = \exp(-2.2094 + 2.3867 \times \ln(\text{dbh})),$$

where dbh is in cm, "exp" is the natural exponential function, and "ln" is natural logarithm. Carbon is calculated by multiplying biomass by 0.5 because biomass is approximately 50% of dry weight (Penman et al., 2003). A full set of coefficients can be found in Jenkins et al. (2003; Table 4). Belowground root biomass is estimated as a ratio of roots to total aboveground biomass. The equation for ratio of root biomass of a live hardwood tree, which includes the aspen/alder/cottonwood/willow group, is:

$$\text{Ratio} = \exp(-1.6911 + 0.8160/\text{dbh}).$$

Belowground biomass is calculated by multiplying the ratio by total aboveground biomass. The belowground coefficients can be found in Jenkins et al. (2003; Table 6). The Jenkins et al. (2003) estimates were the basis for all tree-based live tree carbon calculations included in the reports of USEPA (2005 through 2011).

As noted previously, some inventory databases do not provide measurements of individual trees. The RPA data provide growing-stock volume, defined as the volume of merchantable wood per unit area (e.g., cubic meters per hectare). For these source inventory data, this plot-level growing-stock volume of live trees is used to estimate carbon in live tree biomass per unit area as in Table S2, for example. The initial application of this approach for GHGI reporting was the plot-level biomass estimates according to Smith et al. (2003), which were developed to provide estimates comparable to the tree-based biomass obtained through Jenkins et al. (2003). These volume-based estimates were introduced with USEPA (2002) and were the exclusive source of live tree carbon density estimates through USEPA (2004).

These equations were also applied in USEPA (2005), but only to a small proportion of forestland because the individual-tree data of the FIADB became the primary inventory data source for USEPA (2005) and subsequent reporting years. The extent of the transition from volume-based to tree-based estimates for live tree carbon is evident in the USEPA (2011) report where the 1990 annualized estimate relies on volume-based estimates for six percent of forestland. This was reduced to one percent of forestland for the 2000 annualized estimate.

The volume-based estimates of Smith et al. (2003) did provide regional biomass totals identical to the Jenkins et al. (2003) values when applied to the FIADB. However, precision was lower with smaller area estimates for some forest types, and accuracy was sometimes affected in lower density stands. In response to these limitations, a modification of the plot volume-based equations was developed during 2005 and 2006. A preliminary set was applied to the volume-based live tree estimates in USEPA (2006) with coefficients provided in Table S3. The combined above- plus belowground coefficients for estimates in USEPA (2007 through 2011) are provided in Tables S2, with the corresponding aboveground-only coefficients in Table S4. Although the regression model was altered, and the region and forest type classifications were slightly modified, the data selection and reduction methods are as described in Smith et al. (2003). Carbon density is based on the growing-stock volume of the plot, where growing-stock includes live trees of commercial species meeting specified standards (Smith et al., 2009) and at least 12.7 cm (5 in.) dbh, but the resulting biomass is expanded to include all live trees (i.e., including the non-merchantable and smaller trees as well). For an example of the plot volume-based calculation, the total carbon in tree biomass per hectare of aspen-birch in the North is assigned the mean of 8.1 Mg C/ha if growing-stock volume is zero (Table S2). If growing-stock volume is greater than zero, the estimate is derived in two steps. Carbon density of non-growing-stock trees (sapling and cull trees) is 14.3 Mg C/ha (Table S2), and the form of the equation for carbon in growing-stock trees is:

$$\text{Growing-stock trees (Mg C/ha)} = \exp(-0.337 + \ln(\text{volume}) \times 0.933),$$

where the independent variable – growing-stock volume – is in m^3/ha. The dependent variable is an important consideration in the use of these volume based calculations. Carbon density (Mg C/ha) is the direct result in the example above and from Tables S2 and S4. However, calculations based on Smith et al. (2003) or Table S3 result in dry weight density, which is then multiplied by 0.5 for carbon density. For additional information on the appropriate classification or application of these plot-level calculations based on volume, see the footnotes of the respective tables. The decisions between the alternate approaches to determine live tree carbon and the various possible sources of forest inventory are illustrated in Fig. 3.

2.1.2. Understory vegetation

Understory vegetation is a minor component of biomass and is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.5 cm (1 in.) dbh. Carbon estimates in understory vegetation are based on Birdsey (1996) and the age- and volume-based estimates from a preliminary version of FORCARB2 (Heath et al., 2010), which were applied to the FIADB and fit according to forest type classifications from Smith et al. (2003). We assume that 10% of understory carbon mass is belowground; this general root-to-shoot ratio (0.11) is near or below the lower range of whole-forest values provided in Penman et al. (2003) and Eggleston et al. (2006) and was selected based on two general assumptions: ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and a greater proportion of all root mass will be less than 2 mm diameter, which is part of the SOC pool. In this calculation, "ratio" is the ratio of understory carbon density (Mg C/ha) to live tree carbon density (Mg C/ha of above- plus belowground). A full set of coefficients is in Table S5. As an example of the form of the calculation, the understory carbon in aspen-birch forests in the Northeast is:

$$\text{Understory (Mg C/ha)} = (\text{live tree C density}) \times \exp(0.855 - 1.03 \times \ln(\text{live tree C density})).$$

Three post-calculation limits were applied to the initial understory value obtained above. First, the maximum value for the ratio is set by the "Maximum ratio" field (e.g., 2.02 for the aspen-birch example above); this also applies to stands with zero tree carbon, which is otherwise undefined in the above equation. Second, the minimum ratio is set to 0.005 based on discussion in Birdsey (1996). These limits are to reduce effects of extreme values. Third, information was limited for nonstocked and pinyon/juniper stands, so those plots are set to constant ratios, which are defined by field "A" for these records. These understory carbon density calculations were introduced in USEPA (2004) and applied in the subsequent reports of USEPA (2005 through 2011).

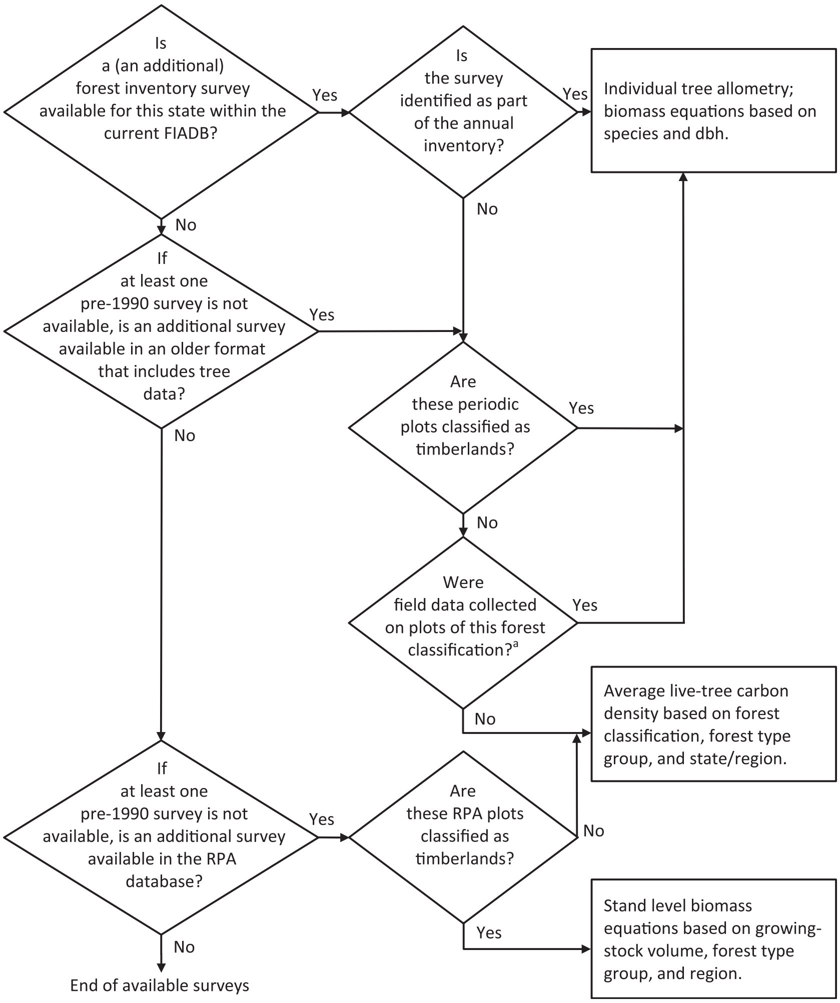

Fig. 3. Process for identifying appropriate factors to determine live tree carbon density on inventory plots. Carbon factors can vary by forest classification (i.e., timberland, reserved, other) for each state by survey combination. This evaluation is made independently for the reserved versus other classifications, and all such plots within each classification are sorted identically.

2.1.3. Standing dead trees

The standing dead tree carbon pool includes aboveground and belowground (coarse root) mass; no separate estimate is provided for aboveground only. Due to differences among inventories (across time and regions) in terms of sampling of standing dead trees, estimates have not been based on the individual-tree procedure as described above for live trees. Only the more recent annual FIA surveys reliably included standing dead trees on all forested conditions for all states (USDA Forest Service, 2013b,c). Instead, estimates are based on plot-level summaries of live tree growing-stock volume. Data from a subset of states that were judged to include a complete representation of standing dead trees were used to develop the estimates. The volume-based estimates of Smith et al. (2003) were applied for the standing dead tree estimates in USEPA (2005) (and the previous reports of USEPA, 2002 through 2004). Modifications to the volume-based estimates, similar to the process for live trees, were applied to the estimates of USEPA (2006 through 2011); these coefficients are provided in Table S6. Two motivations for revising the estimates for standing dead were: (1) the inclusion of an estimate of the 2.5–12.7 cm dbh (1–5 in.) dead trees, and (2) the greater availability of useful standing dead tree data since Smith et al. (2003). An example form of the calculation for standing dead tree dry weight as a function of stand growing-stock volume (m^3/ha) in aspen-birch forests in the Northeast is:

$$\text{Dry weight (Mg/ha)} = 1.0 \times (\text{live tree growing stock volume})^{0.499}.$$

The result is multiplied by 0.5 to convert dry weight to carbon. Note that nonstocked stands are assigned a constant carbon density (the value of Coefficient A, Table S6).

2.1.4. Down dead wood

Down dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. Down dead wood includes stumps and roots of harvested trees. Estimates of the ratio of down dead wood to live tree biomass were developed within model simulations during development of FORCARB2 (Heath et al., 2010); these simulations were initialized from a small set of published values. The carbon pool was modeled as the result of adding or removing carbon through processes such as mortality and decay, using literature-based stocks and fluxes. Ratios developed in the simulation were applied to the respective version of the FIADB and verified by comparison to published values and preliminary down dead wood data from FIA plots (Chojnacky et al., 2004; Chojnacky and Heath, 2002; Heath and Chojnacky, 2001). The set of ratios used for reporting years 2005 through 2011 is provided in Table S7. An example of the process for calculating down dead wood in aspen-birch forests in the Northeast is:

$$\text{Carbon density (Mg C/ha)} = (\text{live tree C density, above-plus belowground}) \times (0.078),$$

which is 7.8% of live tree carbon. Conversion to carbon mass is not necessary if the live tree value is already in terms of carbon. This component of down dead wood carbon density was introduced in USEPA (2004) and applied in the subsequent reports of USEPA (2005 through 2011).

An additional component of down dead wood was added to provide an estimate of logging residue, or slash, starting with USEPA (2010), which continued with USEPA (2011). This component provides a regional mean based on stand age which was applied to all plots. The calculation follows Smith et al. (2006) and assumes first-order decay of an initial carbon density according to stand age (Table S8). An example of the process for calculating logging residue for hardwood forest type groups in the Northeast is:

$$\begin{aligned}\text{Carbon density (Mg C/ha)} &= \text{initial carbon density} \\ &\quad \times \exp(-\text{stand age}/\text{decay coefficient}) \\ &= (13.9) \times \exp(-\text{stand age}/12.11),\end{aligned}$$

which is added to the initial down dead wood calculation from Table S7. Conversion to carbon mass is not necessary because the initial density is already expressed as carbon.

2.1.5. Forest floor carbon

Carbon in the forest floor, which can also be described as litter plus small woody debris, is the pool of organic carbon (including material known as litter, humus, and fine woody debris) above the mineral soil and in this definition includes woody fragments with diameters of up to 7.5 cm. The IPCC guidelines allow for alternate, but clearly documented, bounds between litter and larger down woody material (Penman et al., 2003). Estimates for the USEPA reporting years 2005 through 2011 are based on equations of Smith and Heath (2002, in particular see Table 4 for the complete set of coefficients) applied at the plot level. The equations simulate processes for decay or loss of forest floor following harvest and the net accumulation of new forest floor material following stand growth. For example, the format for calculating total forest floor carbon at a given number of years after a clearcut harvest for aspen-birch forests in the North is:

$$\begin{aligned}\text{Total forest floor C (Mg C/ha)} &= (18.4 \times \text{years})/(53.7 + \text{years}) \\ &\quad + 10.2 \times e^{(-\text{years}/9.2)},\end{aligned}$$

where years refers to stand age. Note that these are direct estimates of carbon density; in other words, the 0.5 conversion is not applied to these estimates. Also note that default (coefficient C) values for the nonstocked forest group were added following the information and methods of Smith and Heath (2002); these post-Smith and Heath (2002) publication estimates are 4.8, 2.7, 7.2, and 17.3 Mg C/ha for North, South, Pacific Northwest, and West, respectively. These forest floor carbon density calculations were introduced in USEPA (2001) and applied in subsequent reports, including USEPA (2005 through 2011).

2.1.6. Soil organic carbon

Soil organic carbon (SOC) estimates are based on the national STATSGO spatial database (USDA, 1991), and the general approach described by Amichev and Galbraith (2004). In their procedure, SOC was calculated for the conterminous United States using the STATSGO database, and data gaps were filled by representative values from similar soils. Each FIA plot was assigned an SOC estimate, and SOC estimates by region and forest type group were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center (USDA Forest Service, 2013d) by overlaying FIA forest inventory plots (mid-2004) on the SOC map, similar to the approach used by Johnson and Kern (2003). The results of this overlay process are provided in Table S9, which includes the additional region by type group classifications subsequently assigned to account for all forests defined in the FIADB and RPA data (the Eastwide, Westwide, Southern, and IDB type groups fit within the FIADB classifications). Note that the means remain constant within region and type and do not reflect stand age, management, or effects of past land use change. These SOC densities were first applied in USEPA (2005), and their use continued through USEPA (2011).

2.2. Non-timberland carbon in some older inventories

The older forest inventories, which are important for defining forest carbon for the early 1990s, did not have sufficient information to predict tree carbon for the nontimberland forests (Smith et al., 2010). Specifically, these were reserved forests (timber harvest not permitted by legal restrictions) and the other nontimber, nonreserved forests (lower productivity, hereafter referred to as "other"). In general, the information available for these non-timber plots included forest type and area (expansion factor) but additional stand or tree information was lacking or only provided for a very few plots. Note that only the forest floor and SOC pools are not directly dependent on an estimate of live tree carbon density. This lack of tree data to serve as inputs to the carbon conversion factors was common to non-timber plots of the Eastwide, Westwide, Southern, and RPA data. This inconsistency of tree data is also true of some of the older reserved or other forest inventories in the FIADB. The state and source inventory years of older FIADB surveys which were evaluated to have insufficient tree information to predict carbon are listed in Table S10. These were identified by examining the number and distribution of trees on reserved and other plots, and comparing among states and source inventory years. All reserved and other forestlands specified in Table S10 as well as the older inventory formats derived their carbon densities from assigned mean.

The assigned carbon densities for data gaps in some of the older non-timber plots were calculated from more-recent reserved and other forest inventories and based on the carbon conversion factors described above and summarized by region and forest type group (Smith et al., 2003). Specific classifications and applications of these defaults were subject to change from one reporting year to the next, depending on modification to carbon factors or increases in available data. Most of the changes (Tables S11, S12, S13, and S14) associated with reporting year were related to modifications in the volume-based tree biomass estimates. Region by forest type group summaries (Table S12) for live trees (total tree and aboveground only), understory, standing dead trees, down dead wood, and forest floor were applied to USEPA (2005). Values for SOC were based on region and forest type group. Following the modifications of the volume-based tree biomass calculations, the assigned reserved and other values were revised for USEPA (2006) (Table S13) and USEPA (2007, 2008) (Table S14), with different classifications for each table. Note that these tables (Tables S13 and S14) provide only the values for tree carbon density; all other carbon pools were calculated according to their respective carbon factors and these assigned tree values, as needed. Also note that the state by region classification (Table S14) produces separate means for eastern versus western Oregon and Washington. For USEPA (2009), the reserved and other assigned values were again updated (Table S11); this was related to preliminary analysis in preparation to include the tree-level data for standing dead trees, but this step was ultimately postponed due to unresolved issues of data consistency. Note that these means include values for coastal Alaska. These same Table S11 values were also applied to USEPA (2010, 2011), with a change for two carbon pools. Mean carbon densities were determined for forest floor and the newly defined logging residue component of down dead wood (Table S15) and applied to the 2010 and 2011 reports.

2.3. Uncertainty bounds for plot-level densities

Some uncertainty is associated with each carbon conversion. Quantifying this depends on the information available, which varies among factors and is quite limited for most of these estimates (Smith and Heath, 2001). Probability density functions (PDFs) were defined for each plot-level carbon conversion to develop the uncertainty estimates for current net flux of forest ecosystem carbon such as is provided in Chapter 7 of USEPA (2011). These plot-level PDFs were randomly sampled as the first step in a Monte Carlo simulation of total net annualized carbon stock change for US forests, which is consistent with the IPCC-recommended Tier 2 methodology (Penman et al., 2003).

Marginal PDFs were associated with each of the carbon conversion factors. These were assigned per tree where individual tree data were used for live tree carbon. However, all other carbon factor PDFs were defined at the condition level, that is, they were assigned to either the density (Mg C/ha) or total carbon (Tg C) associated with each forested condition. These per carbon factor PDFs represent model uncertainty, or in other words, uncertainty about the inventory-to-carbon conversion, per plot. Sampling error is also determined for each carbon pool (Bechtold and Patterson, 2005) at the state or sub-state level (Smith et al., 2010). Monte Carlo sampling was used to pool the condition level and sampling error estimates before calculating net annualized stock-change. See uncertainty and stock-change calculation discussions in Smith et al. (2010) and the forest carbon methodology sections of USEPA (2011) for additional information on the stock change process.

Live tree carbon based on individual-tree diameters (Jenkins et al., 2003) is assigned normal PDFs, which are defined according to variability information in Table 5 of Jenkins et al. (2003). This produced standard deviations for the PDFs that ranged from 15% to 27%, for the true fir and woodland groups, respectively. The variance per tree is expanded to total carbon by squaring the trees-per-area and volume-expansion factors. The resulting stand, or condition, level variability in carbon density was usually under five percent. Note that the tenth and ninetieth percentiles (Table 5 of Jenkins et al., 2003) used to define the per tree variability suggest a slight skew to the right for the PDF, which we did not include in our per tree definition of uncertainty. However, we expect the totals to tend toward normal as tally trees are summed for a plot and plots are summed for the population totals. Uncertainty about the volume-based estimates for live or standing dead tree carbon density were based on the respective regression equations (e.g., as illustrated by figures in Smith et al., 2003). See Table 10 of Smith et al. (2006) for relative precision of the stand-level estimates.

Distributions for the remaining, non-tree, carbon pools are triangular or uniform. Both the form of the PDFs and the relatively wide bounds reflect the lower level of information available about these estimates. Down dead wood, understory, and forest floor are assigned triangular distributions with the mean at the value calculated for each plot; the minimum is set to 10% of this value and the mode is coincident with the minimum – that is, a right triangle with skew to the right. The use of these PDFs skewed to the right reflects the assumption that a small proportion of plots will have relatively high carbon densities. Joint Monte Carlo sampling of PDFs is specified for two pairs of samples: understory PDF sampling is slightly negatively correlated with live tree PDF sampling, and down dead wood sampling is slightly positively correlated with live tree sampling. This also reflects the structure of the estimates, which are dependent on live tree carbon. Soil organic carbon is considered highly uncertain, but PDF bounds approaching ±100% are unlikely so SOC is defined as a uniform PDF at ±50% of the mean. Uncertainty about the assigned carbon densities for the older reserved and other forests (Tables S11, S12, S13, S14, and S15) were based on the summaries obtained from the more-recent plots used to determine the averages, but the PDFs applied to these values were set as uniform distributions bounded by the minimum and maximum identified from the more recent data.

2.4. Carbon factor and inventory changes over 2005 through 2011

Most of the carbon factors remained unchanged over the seven reporting years of inventories. Specifically, these pools were the live tree (tree data), understory, forest floor, and soil organic carbon pool. The exceptions were the plot volume-based estimates for live and standing dead tree biomass and the modification of down dead wood for 2010. However, the inventory database accrued new data and changed over the interval from FIADB 1.7 in the 2005 report to FIADB 4.0, which was applied to 2011. Database changes can include fields, allowable values, or algorithms to populate fields such as forest type group. Each database version was reviewed to address changes to fields important for classifying and applying carbon factors. For example, the list of forest type groups in FIADB 1.0 (USDA Forest Service, 2013c) in 2003 when the down dead wood estimates were developed has changed slightly over time with the versions of the FIADB. The list of forest type groups in Table S7 reflects those changes; we include the list corresponding to USEPA (2011) because these are the most applicable classifications.

An important contribution to the overall change in forest carbon as reported for 2005 through 2011 was the steady accumulation of newer whole-state annual FIA inventories provided within the FIADB. For example, the 2005 report included 23 surveys over 23 states that were identified as statewide annual FIA inventories, while 182 such totals over 47 states were available for the 2011 report.

3. Results and discussion

The carbon conversion factors arose from the development of two forest carbon simulation modeling systems, FORCARB2 (Heath et al., 2010), and the inventory-based stock-change approach most recently described in Smith et al. (2010). Some of the factors have been in use for many reporting years. As noted above, the earliest GHGI report application of some of these factors was in USEPA (2001) and many are still essential to forest carbon estimates in current inventories. This detailed information makes it possible to develop comparable summaries – both estimate and uncertainty – that are consistent with the national GHGI reporting values for forests, but at other levels of aggregation of the plot data such as for individual counties or for National Forest lands by region (Heath et al., 2011b). These sub-national applications follow the same methods in terms of inventory use, carbon conversion, and uncertainty estimates from plot-level summaries to total stock change comparable to scaled versions of Fig. 1. The overall effect of the carbon conversion factors can be summarized as regional averages for ecosystem carbon pools by forest type groups and region across the United States (Table 1).

In order to illustrate general consistency of forest carbon estimates of the US national GHGI with the IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006), we provide information on some components of constructing estimates for biomass carbon stock for comparison. In particular, we compare with tabular Tier 2 and Tier 1 regional values for the ratio

Table 1
Regional mean carbon density (Mg C/ha) by carbon pool and forest area (1000 ha) according to region and forest type group, based on the most recent inventory survey available for each state within FIADB 4.0 as applied for USEPA (2011).

Region[a] Forest type group	AG[b] live tree	BG[c] live tree	Under-story	Standing dead	Down dead	Forest floor	SOC	Forest area
	Mg C/ha							1000 ha
Northeast								
White/Red/Jack Pine	90.2	18.8	1.6	5.3	6.5	13.7	78	1584
Spruce/Fir	51.4	11.1	1.4	6.2	7.1	30.7	98	2970
Oak/Pine	74.6	15.0	2.6	3.8	6.0	27.4	67	1234
Oak/Hickory	80.8	15.4	1.8	4.1	7.1	8.1	53	13,007
Elm/Ash/Cottonwood	57.7	11.1	1.8	4.0	5.9	6.9	112	1450
Maple/Beech/Birch	76.4	14.8	1.7	6.4	6.9	27.1	70	13,673
Aspen/Birch	46.2	9.3	2.1	3.8	5.6	8.6	87	1704
Minor Types and Nonstocked	46.3	9.3	2.1	3.2	7.0	10.9	74	1855
All	72.9	14.2	1.8	5.1	6.8	17.8	69	37,478
Northern Lake States								
White/Red/Jack Pine	52.3	11.1	2.0	3.4	5.6	12.3	121	1821
Spruce/Fir	38.9	8.4	1.8	4.0	4.6	33.1	262	3213
Oak/Hickory	68.8	13.1	1.8	4.0	6.7	7.9	97	3815
Elm/Ash/Cottonwood	50.7	9.8	1.9	5.0	4.1	7.5	180	2118
Maple/Beech/Birch	72.8	14.1	1.4	4.6	6.9	27.3	134	4301
Aspen/Birch	39.1	7.7	2.0	4.4	5.1	8.3	146	5272
Minor Types and Nonstocked	32.7	6.6	2.0	3.1	5.7	18.0	123	1113
All	52.9	10.5	1.8	4.2	5.6	16.4	152	21,654
Northern Prairie States								
Ponderosa Pine	38.8	8.3	1.6	3.4	3.7	14.3	49	576
Oak/Pine	49.0	9.8	3.3	3.0	4.6	25.5	40	551
Oak/Hickory	68.2	13.0	1.8	3.8	5.9	7.7	49	9570
Elm/Ash/Cottonwood	73.0	13.8	1.9	5.2	6.6	6.8	83	1874
Minor Types and Nonstocked	40.1	8.0	1.8	3.0	5.3	17.9	60	1231
All	64.3	12.3	1.8	3.9	5.8	9.5	55	13,803
South Central								
Loblolly/Shortleaf Pine	42.5	9.0	3.6	1.3	5.7	9.6	42	13,256
Pinyon/Juniper	13.1	2.8	3.6	0.0	1.9	12.2	38	3894
Oak/Pine	45.1	9.0	3.4	2.0	4.6	9.3	42	5115
Oak/Hickory	55.5	10.6	3.3	2.1	4.7	6.4	39	24,619
Oak/Gum/Cypress	74.8	14.3	1.6	3.3	5.9	6.5	53	5131
Elm/Ash/Cottonwood	50.4	9.6	1.7	3.0	4.2	5.9	50	3441
Woodland Hardwoods	6.2	1.2	4.6	0.0	0.9	5.0	65	8977
Minor Types and Nonstocked	29.1	5.9	3.5	1.5	4.3	7.1	54	4271
All	42.9	8.5	3.3	1.6	4.3	7.4	45	68,704
Southeast								
Longleaf/Slash Pine	31.4	6.7	3.7	0.8	5.5	9.7	110	4139
Loblolly/Shortleaf Pine	45.5	9.6	3.5	1.7	6.8	9.6	73	9137
Oak/Pine	49.6	9.9	3.4	2.0	4.7	9.3	61	4054
Oak/Hickory	70.4	13.5	3.1	3.3	5.7	6.4	45	12,014
Oak/Gum/Cypress	72.8	14.2	1.6	3.7	6.1	6.5	158	4551
Elm/Ash/Cottonwood	56.4	10.8	1.6	4.5	5.2	5.6	96	760
Minor Types and Nonstocked	43.0	8.4	3.1	2.6	6.4	5.8	107	1389
All	56.2	11.2	3.1	2.5	5.9	7.9	79	36,044
Pacific Northwest, Westside								
Douglas-fir	143.2	30.3	3.4	14.3	24.7	32.0	95	5956
Fir/Spruce/Mt. Hemlock	147.6	31.4	2.8	22.6	19.0	38.3	62	1187
Hemlock/Sitka Spruce	172.2	36.5	2.8	24.3	25.7	37.8	116	1566
Alder/Maple	82.0	16.3	3.1	12.4	11.8	7.6	115	1189
Minor Types and Nonstocked	65.8	13.3	3.5	6.6	11.4	13.5	86	1216
All	132.7	28.0	3.3	15.6	21.4	28.8	96	11,114
Pacific Northwest, Eastside								
Douglas-fir	74.2	15.9	3.6	9.0	10.5	36.3	95	2089
Ponderosa Pine	46.4	9.9	2.7	4.0	7.2	22.5	51	2742
Fir/Spruce/Mt. Hemlock	93.1	19.9	2.5	14.8	13.0	37.9	62	1781
Lodgepole Pine	38.9	8.4	2.6	5.3	6.7	21.1	52	1041
Western Larch	60.2	12.9	3.6	10.1	9.1	35.7	45	204
Other Western Softwoods	12.4	2.7	3.7	1.8	2.7	36.2	79	1252
Minor Types and Nonstocked	32.4	6.7	4.0	9.2	6.9	25.1	82	999
All	54.3	11.6	3.1	7.5	8.3	30.1	68	10,109
Pacific Southwest								
Pinyon/Juniper	20.2	4.3	4.4	0.3	2.0	21.1	26	742
Douglas-fir	160.1	33.5	3.0	16.2	21.1	35.7	40	442
Ponderosa Pine	61.2	13.0	2.8	4.5	10.4	22.4	41	899
Fir/Spruce/Mt. Hemlock	156.1	33.2	2.1	23.2	21.9	38.3	52	824
Redwood	217.2	45.6	2.7	16.7	31.4	60.5	54	299
Other Western Softwoods	28.2	6.0	6.1	2.4	5.1	37.5	50	806
California Mixed Conifer	126.2	26.6	1.8	15.9	16.9	37.9	50	3159

Table 1 (*continued*)

Region[a] Forest type group	AG[b] live tree	BG[c] live tree	Under-story	Standing dead	Down dead	Forest floor	SOC	Forest area
	Mg C/ha							1000 ha
Western Oak	63.3	12.3	4.2	4.3	3.6	29.7	28	3791
Tanoak/Laurel	128.4	25.6	4.0	13.2	6.9	28.0	28	830
Minor Types and Nonstocked	54.5	11.3	3.6	7.1	10.5	25.2	37	1540
All	89.0	18.4	3.4	9.4	10.5	31.9	39	13,333
Interior West, North								
Douglas-fir	70.6	15.1	2.4	8.5	6.0	37.0	39	5587
Ponderosa Pine	37.7	8.1	2.6	3.3	4.9	22.9	34	1865
Fir/Spruce/Mt. Hemlock	65.5	14.1	2.4	13.3	8.8	37.4	44	4471
Lodgepole Pine	48.3	10.5	2.2	6.3	4.6	23.1	37	2761
Western Larch	57.7	12.4	2.6	9.8	5.6	36.3	34	492
Other Western Softwoods	42.7	9.2	2.4	3.2	3.7	39.3	31	649
Aspen/Birch	27.8	5.6	4.5	5.2	7.3	26.8	57	533
Minor Types and Nonstocked	25.0	5.3	3.7	9.7	7.2	22.5	43	2655
All	54.1	11.6	2.6	8.7	6.5	31.4	40	19,012
Interior West, South								
Pinyon/Juniper	20.4	4.4	2.8	0.1	0.8	21.1	20	18,738
Douglas-fir	73.6	15.7	1.2	9.9	6.9	38.1	31	1797
Ponderosa Pine	45.9	9.8	1.6	3.5	4.7	23.6	24	3570
Fir/Spruce/Mt. Hemlock	78.1	16.7	1.6	15.3	7.6	38.8	31	4262
Lodgepole Pine	50.4	10.9	1.9	6.5	6.4	24.0	27	2024
Aspen/Birch	53.1	10.5	4.2	7.7	5.5	28.5	59	2555
Woodland Hardwoods	14.8	3.1	4.7	1.0	3.5	28.2	26	4135
Minor Types and Nonstocked	15.3	3.2	3.8	4.0	3.9	22.6	25	3088
All	33.8	7.2	2.8	3.7	3.3	25.4	26	40,168
United States (lower 48 states)	56.5	11.4	2.8	4.5	6.2	17.0	61	271,419
Coastal Alaska								
Spruce/Fir	20.9	4.6	3.7	2.1	3.5	33.8	62	367
Fir/Spruce/Mt. Hemlock	93.3	20.0	3.0	16.4	10.4	43.2	62	2233
Hemlock/Sitka Spruce	139.7	29.8	2.9	20.2	17.3	50.5	116	2754
Aspen/Birch	38.4	7.6	4.1	6.1	3.0	10.6	42	310
Minor Types and Nonstocked	36.6	7.4	3.8	5.5	5.2	19.5	76	469
All	102.7	21.9	3.1	15.9	12.3	42.5	87	6132
United States (entire reporting area)	57.5	11.6	2.8	4.8	6.3	17.6	62	277,552

[a] Regions follow Fig. 2: Northeast (NE); Northern Lake States (NLS); Northern Prairie States (NPS); South Central (SC); Southeast (SE); Pacific Northwest, Westside (PWW), Pacific Northwest, Eastside (PWE); Pacific Southwest (PSW); Interior West, North (RMN); Interior West, South (RMS); and Coastal Alaska.

[b] Aboveground.

[c] Belowground.

of biomass to merchantable volume (Table 2) and mean biomass density (Table 3). While the US forest biomass estimates are considered Tier 3, the purpose is to illustrate overall agreement. We also briefly discuss relative allocation of biomass to aboveground versus belowground (i.e., root-to-shoot) and the assumption of 50% for carbon content of biomass.

3.1. Comparison of biomass expansion factors

Biomass expansion factors (BEFs) are a common approach to convert forest inventory data to carbon stocks. Generally, they are statistical models of the ratio of biomass-to-volume that can then be applied to estimate dry mass or carbon mass from merchantable volume. They can be applicable to individual inventory plots but are often used with aggregated volume data (Guo et al., 2010; Brown and Schroeder, 1999; Somogyi et al., 2007). A range of BEFs for temperate forests is provided in Table 4.5 in Eggleston et al. (2006). Note that these factors are provided to estimate total aboveground biomass, which includes all live tree and understory components. That is, the expansion is to account for all biomass, not just the trees contributing to stand volume. While BEFs are not a part of our carbon factors, the IPCC default values provide a basis for an informal comparison of factors. We developed two sets of corresponding stand level volume-to-biomass summaries according to these classifications; these are not BEFs, but rather summaries for comparison. An example set of such results is shown in Table 2, which can be used to compare the IPCC values with the tree-based (Jenkins et al., 2003) and volume-based (Table S4) summary values for northern United States (as defined for Table S4). Similar calculations for other regions of the United States produced qualitatively similar results (data not shown).

The informal comparison of these ratios is provided to illustrate the general level of agreement among approaches developed for two different types of NFI tree data. Table 2 provides a mean followed by a range of values in parentheses; the range obtained from FIA data includes 95% of the plots, which eliminates the extremes. The tree-and volume-based ratios were similar to the IPCC defaults but in most cases slightly higher. This is expected in light of the definitions for volume in US forest inventories (USDA Forest Service, 2013c) relative to many other national forest inventories (McRoberts et al., 2010). The IPCC BEF ratios, which represent a composite from several sources, broadly correspond to the FIADB-to-carbon conversions, with the exception of the lowest growing-stock levels (<20 m^3/ha), which were all notably different. This is probably due to the pools defined for biomass and volume. The summaries calculated from the FIADB include trees to 2.5 cm for biomass, but volume is limited to trees 12.7 cm dbh and larger. The effect of such a difference in potential pool size is more apparent in the lower volume stands. In contrast, many other BEFs are based on a single minimum diameter for biomass and volume, which is also several cm below the minimum diameter for volume in the FIADB (McRoberts et al., 2010; Fang and Wang, 2001; Lehtonen et al., 2004); these

Table 2
Examples of biomass-to-merchantable-volume summaries derived from our carbon conversion factors and scaled for comparison with biomass expansion factors of IPCC standard tables (Eggleston et al., 2006). Examples are based on northern forests.

Forest type[a] and source of estimates	Aboveground biomass to merchantable volume (Mg dw/m^3) Stand volume (m^3/ha)				
	<20	21–40	41–100	100–200	>200
Hardwoods					
IPCC Table 4.5[b]	3.0 (0.8–4.5)[f]	1.7 (0.8–2.6)	1.4 (0.7–1.9)	1.1 (0.6–1.4)	0.8 (0.6–1.1)
North – tree[c,e]	8.2 (1.3–42)[g]	2.4 (1.1–5.5)	1.6 (1.0–3.0)	1.2 (0.9–1.9)	1.0 (0.7–1.5)
North – v2b[d,e]	8.7 (2.4–42)[g]	2.1 (1.7–2.6)	1.5 (1.2–1.9)	1.2 (1.0–1.4)	1.1 (0.9–1.2)
Pines					
IPCC Table 4.5	1.8 (0.6–2.4)	1.0 (0.7–1.5)	0.8 (0.6–1.0)	0.7 (0.4–1.0)	0.7 (0.4–1.0)
North – tree	7.0 (1.1–49)	1.8 (0.9–5.8)	1.2 (0.8–2.3)	1.0 (0.7–1.5)	0.8 (0.6–1.2)
North – v2b	6.3 (1.8–35)	1.6 (1.4–2.0)	1.2 (1.1–1.4)	1.0 (0.9–1.0)	0.8 (0.8–0.9)
Other Conifers					
IPCC Table 4.5	3.0 (0.7–4.0)	1.4 (0.5–2.5)	1.0 (0.5–1.4)	0.8 (0.4–1.2)	0.7 (0.4–0.9)
North – tree	7.0 (1.3–35)	2.1 (0.9–4.6)	1.4 (0.8–2.4)	1.0 (0.7–1.5)	0.9 (0.7–1.2)
North – v2b	8.7 (2.4–42)	1.9 (1.6–2.4)	1.3 (1.1–1.7)	1.0 (0.9–1.2)	0.9 (0.8–1.0)

[a] Examples from FIADB are based on northern forests (NE, NLS, and NPS, from Fig. 2) with forest types sorted as hardwood, pine, or other conifer types.

[b] From 2006 IPCC guidelines Table 4.5 (Eggleston et al., 2006).

[c] Based on individual tree estimates (Jenkins et al., 2003) applied to the FIADB.

[d] Based on volume-based estimates (Table S4) applied to the FIADB.

[e] Based on FIADB 4.0 as applied for USEPA (2011). Estimates are for expanded dry weight per unit volume (Mg dw/m^3, not carbon mass) and include an aboveground component of understory (see text and Table S5).

[f] Values are mean (range).

[g] Values are mean (95% of plots (i.e., 2.5–97.5 percentile)).

Table 3
Comparison of aboveground biomass, that is dry weight density (Mg dw/ha) in forests for selected ecoregions with biomass displayed by approach. Estimates are for dry weight and include an aboveground component of understory (see text and Table S5).

Global Ecological Zone[a]	Ecoregion province[b]	General location within 48-states[c]	Tree-based[d]	Volume-based[e]	IPCC Table 4.7[f]
			Mg dw/ha		
Subtropical humid	231, 232, 234	Southern part of Eastern US	107 (7–299)[g]	109 (14–290)[g]	220 (210–280)[h]
Temperate oceanic	242	Pacific Northwest, westside	211 (8–660)	212 (13–625)	660 (80–1200)
Temperate continental, ⩽20 yrs	211, 212, 221, 222, 223	Northern part of Eastern US	35 (4–125)	40 (5–114)	60 (10–130)
Temperate continental, >20 yrs			140 (23–309)	140 (35–303)	130 (50–200)
Temperate mountain, ⩽20 yrs	M242, M261	Pacific Coast	42 (8–167)	42 (9–151)	50 (20–110)
Temperate mountain, >20 yrs			243 (18–743)	238 (26–691)	130 (40–280)
Temperate mountain, ⩽20 yrs	M331, M332, M333	Rocky Mountains, not southern NM	26 (8–76)	30 (9–86)	50 (20–110)
Temperate mountain, >20 yrs			135 (24–328)	134 (32–324)	130 (40–280)
Temperate mountain, ⩽20 yrs	M211, M221	Appalachian Mountains	49 (4–152)	50 (14–136)	50 (20–110)
Temperate mountain, >20 yrs			167 (44–335)	163 (47–332)	130 (40–280)

[a] Global ecological zone from 2006 IPCC guidelines Table 4.7 (FAO, 2001).

[b] Ecoregion province (McNab et al., 2007) selected according to global ecological zone and identified from the ecosubcd field as defined in Woudenberg et al. (2010).

[c] FIADB plots selected for the tree- and volume-based summaries based on location within the global ecological zone and ecoregion province.

[d] From individual-tree estimates (Jenkins et al., 2003) applied to the FIADB 4.0 as applied for USEPA (2011).

[e] From volume-based estimates (Table S4) applied to the FIADB 4.0 as applied for USEPA (2011).

[f] From 2006 IPCC guidelines Table 4.7 (Eggleston et al., 2006).

[g] Mean (95% of plots (i.e., 2.5–97.5 percentile)).

[h] Mean(range).

BEFs have the same pool for biomass and volume and would be less likely to have the higher ratios for lower volume stands.

The stand-level summaries we developed for Table 2 were restricted to FIADB plots where merchantable volume was greater than zero because the ratio is undefined without volume. This highlights a limitation of stand-level BEFs for what can be sometimes 5–10% of plots, depending on the forest and location. Note that this was not a problem for our individual-tree or volume-based biomass estimates, which are not BEFs and do provide estimates for zero-volume. Choice of scale is an approach to circumventing this BEF limitation where volume is based on merchantable volume. This was the approach of Brown and Schroeder (1999) where BEFs were applied for county-level estimates rather than by inventory plot (Smith et al., 2003).

Another set of summary plot level carbon densities were developed from the FIADB based on the tree- and volume-based estimates (Table 3), for comparison with the IPCC tabular forest biomass values provided in Table 4.7 of Eggleston et al. (2006). Subsets of the plot level summaries were paired with the Table 4.7 classes according to ecological zones defined by FAO (2001), ecological provinces of McNab et al. (2007), and stand age class. In this comparison, results of the tree versus volume estimates appeared to be very similar (i.e., Jenkins et al., 2003 versus Table S4). Similarly, the FIADB versus IPCC numbers are largely comparable for the temperate continental and mountain forests. However, the IPCC Table 4.7 default values were clearly greater than the corresponding FIADB-based values for the temperate oceanic and subtropical humid ecological zones. We emphasize that Tables 2 and

3 are not considered a comparison with IPCC methods simply because the carbon factors presented here are consistent with IPCC good practice methodology (Penman et al., 2003); they provide an overview of quantities from alternate approaches. Again, the comparison provided in Table 3 is to illustrate typical carbon values and which would have been used for the US if the FIA's NFI were not available.

3.2. Comparison of root-to-shoot ratios

The average root-to-shoot ratios from these carbon factors applied to the FIADB tend to be at the lower end of the range provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston et al., 2006; Mokany et al., 2006). Specifically, Table 4.4 in Chapter 4 of Eggleston et al. (2006) provides average ratios from 0.2 to over 0.4 to represent belowground biomass to aboveground biomass. This same ratio obtained from Table 1 is in the range 0.19–0.22 (i.e., 84–82% of total biomass as aboveground). Ultimately, our estimates of belowground are based on the coarse-root component model in Jenkins et al. (2003), which does not vary much with size in moderate to large diameter trees. A number of publications have identified carbon fractions slightly different than 0.5; for example, see fractions and references in Table 4.3 of Eggleston et al. (2006). However, the application of these carbon factors is based on the assumption that 50% of biomass is carbon, as in Penman et al. (2003). Any deviation from 50% carbon would likely have a minimal effect on current stock change calculations if forest composition was not significantly changing over time (e.g., hardwood to softwood).

3.3. Harmonization and use of carbon factors

Carbon factors can be viewed as functions relating NFIs to carbon stocks but specific domains and ranges can vary even among ostensibly similar functions. This is illustrated by the BEFs where both definitions of volume as input and resulting biomass can vary from one BEF to another. Comparisons of carbon factors alone are not sufficient to establish a consistent analysis of one GHGI report relative to others because total carbon is dependent on the potentially independent layers of a nation's forest inventory system and the carbon factors applied to that inventory data. So, just as harmonizing NFIs is important for consistency in international reporting and planning (McRoberts et al., 2010), so also is harmonizing GHGI reporting on forests (Dunger et al., 2012). We provide carbon factor information useful for an effort to harmonize reported US forest carbon with any reference (standard) or other national reports, but we do not include any specific bridging methods. The carbon factor information we provide includes the domain (from among the forest inventory database fields) and the range of the estimated carbon pool.

Harmonizing for carbon is not necessarily the same path – or bridge – as for forest inventories. For example, growing-stock is a common reference definition employed for standardizing forest inventory reporting, and the United States' relatively high thresholds for volume would require a bridging method that adjusts values to meet reference definitions that commonly include smaller (i.e., less than 7.5 cm dbh) trees and a greater proportion of each tree (Vidal et al., 2008; McRoberts et al., 2010). However, US tree carbon is based on tree-level conversion of all trees (identified as those greater than 2.5 cm dbh), which potentially simplifies harmonization by reducing any discontinuity associated with trees 2.5–12.7 cm. While the estimate for less-than-2.5 cm trees is perhaps less rigorous (i.e., defined as a part of the understory estimate) than the tree level estimates (i.e., per tree biomass equations), the effort to develop a bridge (to cover 0–2.5 cm) would necessarily be balanced against a relatively small increase in precision (due to the small size of the zero-to-one-inch set). This example underscores the fact that for now, forest inventory and forest carbon inventory are not identical sets and harmonizing one does not necessarily imply harmonizing the other.

Although we have focused on the use of the carbon conversion factors for UNFCCC and periodic GHGI reporting of the USDA (2011), these factors are also used for other significant reporting efforts. They are the basis for forest carbon in the most recent report of the United States for the Global Forest Resources Assessment of the United Nations Food and Agriculture Organization (FAO, 2010), and of the United States' contribution to the reports of the Montréal Process Working Group on the Conservation and Sustainable Management of Temperate and Boreal Forests (USDA Forest Service, 2011). This widespread use underscores the value of understanding and comparing the factors as a useful step toward overall confidence in the estimates and the precision (Petersson et al., 2012; Guo et al., 2010).

The use of these carbon factors is expected to change in upcoming reporting years as US GHGI reporting changes (Domke et al., 2012) and begins incorporating the new carbon-oriented data collection on specialized FIA plots (USEPA, 2013; Woodall et al., 2010). This sampling is beginning to provide data applicable to estimating down dead wood and is expected soon also to affect the forest floor and SOC estimates for carbon reporting (USEPA, 2013). Integrating the current, directly sampled values into the change estimates for the post-1990 interval will require some modeling, which will further affect the transition. The estimates provided for down dead wood carbon in USEPA (2013) are an example of the transition; the estimates are made according to Tables S7 and S8 and then modified, or bounded, according to available down woody material population estimates (USEPA, 2013; Woodall et al., 2010). In the interim, until all parts – new data and models – are in place these factors will continue in use. The phase-out is likely to be gradual as in the example with down dead wood where the latest estimate is a hybrid, with older factors still in use.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.06.061.

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