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Carbon stocks and changes on Pacific Northwest national forests and the role of disturbance, management, and growth

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ABSTRACT

The National Forest System (NFS) of the United States plays an important role in the carbon cycle because these lands make up a large proportion of the forested land in the country and commonly store more wood per unit area than other forest ownerships. In addition to sustaining natural resources, these lands are managed for multiple objectives that do not always align with maximizing carbon (C) sequestration. The objectives of this study were to determine C stocks and flux in measured pools on Pacific Northwest Region NFS lands and the major ecological drivers of C flux. We compiled tree, dead wood, and understory vegetation data from 11,435 systematically-placed inventory plots and estimated growth, mortality, decay, removals, and disturbance events based on two full measurements spanning 1993–2007. The area of NFS-administered lands increased by 0.3% during this period and the area in formally-designated protected status increased by 0.7%. There was 1293 Tg C (±11.2 Tg standard error) in non-soil C stocks at the first measurement, which increased by 45 ± 2.2 Tg (3.4%), with 59% of the increase in the live tree pool and the remainder in the dead tree pools. C stocks followed broad regional patterns in productivity while C flux varied at local scales. Fires affected <1% of the forested area per year and were most prevalent in Wilderness areas. Fires reduced C stocks on burned plots by only 9%, and had a negligible effect on the region as a whole. Most tree harvest on NFS lands in the region consisted of partial harvest and had comparable impacts to fire during this period. C sequestration rates were higher (1.2 ± 0.09 Mg/ha/yr) on the west side of the Cascade Mountains, and primarily stayed in the live tree pool, compared to lower rates (0.5 ± 0.04 Mg/ha/yr) east of the Cascades where most of the increase was seen in the down wood pool. We discuss challenges to estimating forest ecosystem carbon stocks, which requires the application of a large number of equations and parameters for measured and unmeasured components, some with scant empirical support. Improved measurements and biomass models applied to networks of permanent plots would enable improved ground-based estimates of the drivers and components of regional changes in C.

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1. Introduction

Forest ecosystems are important components of the terrestrial carbon cycle because of the ability of many of them to store much larger amounts of carbon (C) than other terrestrial ecosystems (McKinley et al., 2011). These C stocks are dynamic as the area in forest land use changes and forests change with natural disturbance, climatic stressors, forest product harvest, and vegetation growth. Understanding the balance of these processes and the resulting C flux between forests and the atmosphere has been a focus of substantial research, given the implication of rising levels of atmospheric carbon dioxide in recent and future changes in climate (IPCC Core Writing Team, 2007). For example, while it is thought that 1–2 Pg C/yr are being stored in terrestrial ecosystems in the northern hemisphere, the magnitude of fluxes in the various vegetation types are not well understood (Pan et al., 2011; Hayes et al., 2012).

In the USA, national forests play an important role in the carbon cycle, as they cover 78.1 million ha and store more wood per unit area than other forest land ownerships (Smith et al., 2009; Heath et al., 2011). National forests are mandated to be sustainably managed for multiple uses, so need to balance many competing objectives, including watershed protection, providing native plant and animal habitat, and furnishing wood products. Not all of the objectives will maximize C sequestration, and in the case of reducing wildfire severity in dry forest types, maximizing C stocks may be undesirable (Stephens et al., 2013). The implications of different

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land management approaches for mitigating climate change are topics of debate, particularly the impacts of disturbance, long-term storage of harvested wood, decay of dead wood, and vegetation regrowth on C stocks (Mitchell et al., 2009; Malmsheimer et al., 2011; North and Hurteau, 2011; Vose et al., 2012; Hurteau et al., 2013).

The U.S. Forest Service leads efforts to address climate change on all forest lands, including striving to sustain or enhance C sequestration capacity and managing National Forest System (NFS) lands for climate change adaptation (USDA Forest Service, 2011). One strategy being employed consists of an annual Performance Scorecard for each national forest and grassland, which includes requirements for monitoring and for C assessment and stewardship (Coulston et al., 2012). In addition, the 2012 NFS Planning Rule requires national forests to identify and evaluate a baseline assessment of C stocks when revising their land management plans (Code of Federal Regulations, Title 36, sec. 219.6(b)(4)). A wide variety of approaches have been developed to quantify forest ecosystem C stocks and flux that use different accounting frameworks and methods, include different C pools, and apply different metrics of C stocks and flux. Some approaches evaluate a range of scenarios in ecosystem models (e.g., Mitchell et al., 2009). Many approaches use remote sensing models of land cover change tied to climate and ecosystem models to estimate C flux over large regions (Turner et al., 2007; Coops et al., 2009). Forest inventory data are often used to calibrate models of C stocks at a point in time, but the data are also useful to directly estimate regional C flux from repeated field measurements (Smith et al., 2004; Woodbury et al., 2007; Gray et al., 2014). Official estimates of C flux from US forests have relied primarily on the probabilistic sample of the nation's forested lands by the US Forest Service's Forest Inventory and Analysis (FIA) program (U.S. Environmental Protection Agency, 2013).

The national forests of the Pacific Northwest (PNW) Region attain some of the highest C densities in the U.S. (>300 Mg/ha) and have a higher proportion of forests in old age classes (>100 years) than other ownerships (Campbell et al., 2010; Heath et al., 2011). Given the late-successional character of much of the forests, it is not clear how much additional C they are sequestering. While harvest levels on these forests are substantially lower than they were during the 1960–1980s, it appears that the impacts of wildfires and insect outbreaks are increasing in recent decades (Westerling et al., 2006; Meigs et al., 2011). Most of the wood remains on site when trees are killed by these different agents, but it is not clear how rapidly the newly-dead trees decay, how much the older dead wood is consumed by fire, and how rapidly the ecosystem recovers from emitting to sequestering C.

Forest inventory data have been applied to estimate C flux on national forests, often (by necessity) from a combination of different kinds of measurements over time (e.g., Heath et al., 2011). However, remeasurement inventories now exist for some national forests, which enables a more detailed assessment of components of change for trees (i.e., growth, removals, mortality) and drivers of change of tree, vegetation, and down wood pools (e.g., harvest and natural disturbance events). The objectives of this paper were to compile and assess a remeasurement inventory to: (1) determine C stocks and flux in measured pools on Pacific Northwest NFS lands, (2) determine the major ecological and management drivers of C flux, and (3) discuss the strengths and limitations of inventory-based C assessments in relation to alternative approaches.

2. Methods

2.1. Study area

We assessed C stocks and flux on the 10.1 million ha of federal land administered by the Pacific Northwest (PNW) Region of the National Forest System (NFS), found primarily in the states of Oregon and Washington as well as parts of California and Idaho, USA, between 41.8°N and 49.0°N latitude and 116.3°W and 124.7°W longitude (Fig. 1). NFS lands in this region occur in a great variety of conditions, with annual precipitation ranging from 25 to over 350 cm, mean annual temperature from −1 to 12 °C, and elevations from 0 to 3300 m above sea level (Franklin and Dyrness, 1973). We grouped the nineteen national forests into five zones to reflect regional variation in composition and productivity (Fig. 1, Table 1). On average, vegetation west of the Cascade Mountain crest (western Oregon (WOR) and western Washington (WWA) zones) is more dense and productive than that east of the Cascade crest (Blue Mountains (BLUES), northeastern Washington (NEWA), and central Oregon (CEOR) zones). To assess finer-scale patterns within these zones, we grouped plots by 5th order watersheds (USDA Natural Resources Conservation Service et al., 2013).

We also assessed C stocks and flux by the broad land management groups within NFS lands. Twenty-four percent of NFS lands in the region have been nationally designated and are classified as "reserved" from timber production (i.e., where management for production of timber products is precluded; management for other objectives may be appropriate, including incidental tree cutting). Most of the reserved lands are congressionally-designated Wilderness (82%), with the remainder in National Recreation Areas (9%), National Monuments (3%), Wild and Scenic Rivers (3%), and other land management classifications (3%).

2.2. Field data

The primary data used in this study were collected by the Pacific Northwest Region of the U.S. Forest Service for a strategic inventory of vegetation conditions on all NFS lands in the PNW Region (Max et al., 1996), using a probability-based sample design (Olsen et al., 1999). The sample consisted of a systematic square grid at a 5.47 km spacing across all lands, and a denser grid at a 2.74 km spacing outside of designated Wilderness areas, providing a sample density of one plot per 3000 and 750 ha, respectively. Plots were installed using the Current Vegetation Survey (CVS) design (Max et al., 1996) between 1993–1997 and remeasured between 1997–2007 in four spatially- and temporally-balanced panels. The CVS plot remeasurement period ranged from 1 to 14 years with a mean of 7.1 years. Some plots fell on lands that changed ownership and were only measured once. The same grid of plots was also measured with the nationally-standardized Forest Inventory and Analysis (FIA) design starting in 2001 (USDA Forest Service, 2006); we applied the FIA land classification to the data in this study. The FIA measurement overlaps substantially in time with the second CVS measurement and therefore will allow a seamless assessment of change in the future as remeasurement of the plots using the FIA design began in 2011.

The CVS plot design consisted of a cluster of five points within a 1-ha circle, with four points spaced 40.8 m in cardinal directions from the central point (Appendix Fig. A.1). At each point, crews measured live and standing dead trees of different sizes (2.5–7.6, 12.7–33.0, and >33 cm diameter at breast height (DBH; 1.37 m from the ground)) in nested circular subplots of 0.004, 0.020, and 0.076 ha, respectively. Seedlings >15 cm tall and <2.5 cm DBH were counted by species on the smallest subplot size. Trees >76 cm DBH east of the Cascades or >122 cm DBH west of the Cascades were measured on the full 1-ha circle. Crews sampled down wood with the line-intercept method and estimated cover of shrub and forb vegetation on a 15.6 m transect at each point. The vegetation cover protocol changed between measurements: transect distances covered by vegetation were estimated in five segments per transect at time 2 instead of a single percent cover estimate for the whole

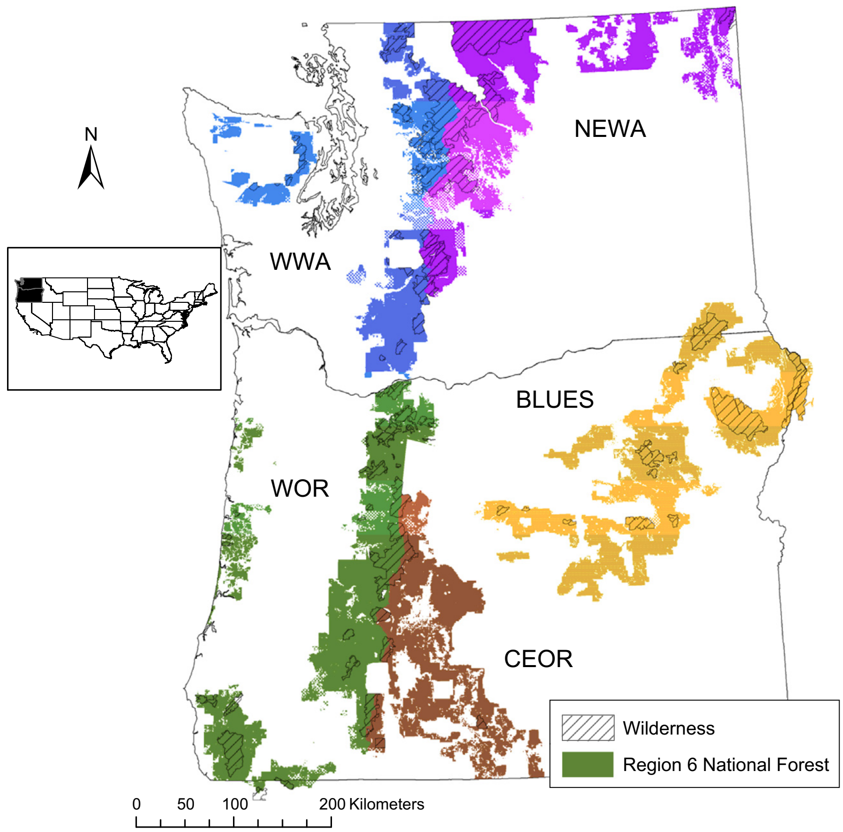

Fig. 1. Study area, depicting Pacific Northwest Region national forests grouped into 5 zones (WWA = western Washington, NEWA = northeastern Washington, WOR = western Oregon, CEOR = central Oregon, and BLUES = Blue Mountains) and designated Wilderness areas.

Table 1
National forests in the Pacific Northwest (PNW) Region, their assignment to different zones (Fig. 1), the land and water area administered, and the inventory-estimated area of forest land and standard error (area in 10^3 ha).

Zone	National forest	Administered area		Forest land area	
		NF code	Total	Total	SE
BLUES	Malheur	MAL	697	645	9
BLUES	Ochoco	OCH	293	249	7
BLUES	Umatilla	UMA	564	491	8
BLUES	Wallowa-Whitman	WAW	979	725	13
CEOR	Deschutes	DES	652	609	7
CEOR	Fremont	FRE	478	425	13
CEOR	Winema	WIN	430	420	13
NEWA	Colville	COL	451	442	6
NEWA	Okanogan	OKA	684	610	11
NEWA	Wenatchee	WEN	925	742	17
WOR	Mt. Hood	MTH	433	427	2
WOR	Rogue River	ROR	252	249	13
WOR	Siskiyou	SIS	449	442	13
WOR	Siuslaw	SIU	249	241	5
WOR	Umpqua	UMP	398	393	2
WOR	Willamette	WIL	681	637	7
WWA	Gifford Pinchot	GIP	559	513	6
WWA	Mt. Baker-Snoqualmie	MBS	726	617	14
WWA	Olympic	OLY	249	237	8
Total area			10,150	9115	31

transect at time 1. Crews classified the vegetation community at each point into plant association types (Hall, 1998). On a subsample of trees, they measured heights and took increment cores to estimate recent growth and tree age. See Max (1996) and USDA Forest Service (2002) for additional details on plot design and measurements. The FIA plot design that was subsequently installed was centered on the same grid point with a different configuration of points within the same 1-ha circle (Fig. A.1).

2.3. Data classification and compilation

There were 11,435 grid points ("plots") that fell within NFS lands at either the first or second measurement. We used the FIA definitions to classify each of the five CVS points as either forest land, nonforest land, or water. Forest land is defined as land areas ⩾0.4 ha that support, or previously supported, ⩾10% canopy cover of trees and were not primarily managed for a nonforest land use.

Water is designated for bodies of water ⩾0.4 ha in size or linear features ⩾9.1 m in width, and includes glaciers. The remainder is considered nonforest land. For plots which were classified during the FIA protocol measurement as 100% forest, nonforest land, or water, we assigned that classification to all the CVS points in the plot. On plots with multiple FIA classes, we used the CVS plant association code to classify points. CVS data were not collected in sufficient detail to distinguish effects of land-use change from other changes. Land-use change on NFS land primarily consists of roads being built or de-commissioned, river erosion or deposition, and invasion or loss of trees in rangeland and meadows. The impact of these changes on C stores is expected to have been minor. The combination of FIA codes and plant association codes were used to determine if uninstalled CVS points were potentially forested or nonforest (to enable adjustment to the total area of forestland in the post-stratification statistical estimation phase; see below). A total of 472 plots could not be used to estimate change in C due to being inaccessible forested locations, default on a measurement contract, lost plots, changes in Wilderness status, or remeasurement in the same calendar year as the installation. Of the remaining 10,963 plots, 10,244 had at least one fully-remeasured forested point (97.8% consisted of 3 or more remeasured points), 433 had at least one fully-remeasured nonforest point, 183 were unmeasured nonforest, 60 fell in large bodies of water, and 43 had changed ownership between measurements. Partially-forested plots do not affect estimates because the estimation equations are based on the area sampled in a stratum (i.e., the total number of points in this case), not the plot-level values (Scott et al., 2005).

We grouped points of the same land class and measurement status on a plot into "condition classes" and assigned values for stand age, site productivity, and forest type based on the FIA compilation of the FIA sample of the same plot (e.g., Campbell et al., 2010) where available, or from an FIA compilation of the first CVS plot measurement (Waddell and Hiserote, 2005). We classified forested conditions by productivity and reserved status into reserved, low-productivity, and high-productivity, with the productivity classes dependent on whether the forest was estimated to produce less or more than 1.4 m^3/ha/yr of wood at culmination of mean annual increment (Hanson et al., 2002). We identified the nature and year of disturbances on each plot from estimates of recent logging and disturbance events recorded by crews during the FIA sample, augmented for older events by overlaying plot locations on spatial data layers of harvest and fire events maintained by the PNW NFS (e.g., Eidenshink et al., 2007). Any plot with trees cut on it was included in the cut category. The FIA threshold for recording disturbance was something that caused mortality or damage to 25% of the trees, ground surface, or understory vegetation, while the criteria for the spatial layers was unknown. Fire events included the entire spectrum of intensities, from controlled ground fires to severe crown fires. We cross-checked disturbance codes, tree mortality measured on plots, and crew's written descriptions of stand condition to resolve discrepancies.

We used a combination of CVS status codes, estimated growth rates, and disturbance information to identify changes in individual tree status. We estimated plot-specific diameter growth rates for live trees that were new at the second measurement (i.e., were either missed or grew into the plot) by fitting a simple mixed model of annual squared diameter growth (ASDG) on diameter for remeasured trees ($\ln(\text{ASDG}) = b0 + b1 * \ln(\text{DBH})$), with plot as the random subject, and correcting estimates for back-transformation bias (Sprugel, 1983). The number of years between measurements on a plot was multiplied by the growth rate and subtracted from the time 2 DBH to estimate time 1 DBH and determine whether a tree had grown into the plot or had been missed at time 1. We used disturbance information and crew's written descriptions to resolve any ambiguity in distinguishing cut trees from measurement error; we removed the latter from further consideration. We estimated diameters of trees at the approximate time they died or were cut between measurements using ASDG and the harvest or disturbance date where applicable, or the mid-point between measurements. We reduced ASDG by half for natural mortality trees based on analysis of new standing dead trees that indicated slower growth rates for trees that died. Tree heights were estimated from each plot's subsample of trees with measured heights by fitting a non-linear mixed model of height (HT) for trees with unbroken tops on DBH using the Richards model form (e.g., Barrett, 2006): $\text{HT} = 4.5 + \beta_1 * (1 - \exp(-\beta_2 * \text{DBH}))^{\beta 3}$. For trees with heights measured once, we used the difference in heights predicted from measured DBHs to estimate height growth and calculate the missing height. Of the 1,007,561 tree records used in the analysis, 68% were measured alive at both times, 9% were alive at time 1 and died, 10% were new live trees at time 2, and 13% were standing dead trees at one or both measurements.

Estimates of above- and below-ground live tree and standing dead tree woody C followed FIA procedures (Woodall et al., 2011), based on regional equations of merchantable bole volume, national equations of stump and bark volume, species-specific wood- and bark-density parameters, and ratios of top and branch biomass to merchantable bole biomass. Bole volumes were calculated from DBH and HT, and accounted for the missing volume of broken-topped trees. We estimated tree foliage and coarse-root biomass using the ratios to total biomass in Jenkins et al. (2003) and the total biomass adjustment in Woodall et al. (2011) and added these to the above-ground wood estimates to calculate total tree biomass. We calculated biomass of tree seedlings assuming their mean size would be the middle of the range of seedling sizes, or ½ the DBH and HT, and therefore 1/8th the biomass, of 2.5 cm DBH trees of the same species. Above- and below-ground biomass estimates for standing dead trees were reduced to account for decay using hardwood- and softwood-specific decay class constants for proportional wood density, as well as proportional bark and branch loss with decay, from Harmon et al. (2011). We multiplied biomass by 0.5 to estimate C mass. A standard "trees per hectare" expansion factor derived from the appropriate fixed-area plot size was used to convert individual live tree and standing dead tree C to an area basis (Mg per ha).

We calculated C in down dead wood >7.6 cm diameter using line-intercept diameter and transect length to calculate volume (van Wagner, 1968), the species-specific wood density constants used for live trees, and hardwood- and softwood-specific density-reduction constants by decay class for down dead wood (Harmon et al., 2011). The CVS data were collected using a 3-decay class system at time 1 and the 5-decay class system used by FIA at time 2. Based on examination of piece measurements on undisturbed plots remeasured within 2–3 years, we converted time 1 decay classes to the closest values in the 5-class system (1–1, 2–3, and 3–4). Piece counts by size class of wood 0.64–7.6 cm diameter were converted to volumes using the equations, wood density constants by forest type group, and default inclination adjustment from Woodall and Monleon (2008), and the weighted national mean quadratic mean diameter by size class constants from Woodall and Monleon (2010). We based biomass of understory vegetation on separate estimates of shrub and forb cover (vegetation heights were only recorded at time 1, so were not used), by applying selected species-specific equations. Results from selected equations fell within the range of values of the height and cover equations in Olson and Martin (1981) and Gonzalez et al. (2013) and using the median time 1 heights of 0.3 and 0.6 m for forbs and shrubs, respectively. We used unpublished equation numbers 810 and 168 (developed for graminoids and *Salix jepsonii* C.K. Schneid., respectively) documented in Means et al. (1994). These equations calculate biomass in Mg/ha as 0.0192 and 0.1024 times percent cover for forbs and shrubs, respectively. Soil and forest floor were not measured for this inventory so estimates of C in those pools are not available.

2.4. Statistical analyses

Statistical calculation of survey estimates differs from standard approaches commonly applied to designed studies (e.g., ANOVA). We calculated means and variances for all values using double-sampling for stratification based on sampled condition classes and their measurements (Cochran, 1977; Scott et al., 2005). The study area was divided into strata designed to capture the variation in vegetation attributes and sampling intensity in order to improve the precision of plot-based estimates and adjust for non-sampled forestland. Estimation units were defined by the area in each national forest in Wilderness and non-Wilderness designations to account for the different plot densities in different categories, as maintained in Automated Lands Project spatial databases. The area of parcels that changed ownership between 1993 and 2007 was calculated as annual acquisition and disposal rates; these were multiplied by the median plot remeasurement period (7 years) and the resulting area divided among the plots measured on acquired and disposed lands.

Land cover classes from satellite imagery (Homer et al., 2004) were buffered into edge and internal classes and grouped to differentiate forest from nonforest (Dunham et al., 2002). Predicted plant community zones for the region (Henderson, 2009) were used to further stratify the area. Plot locations were intersected with spatial layers and the numbers of pixels and plots were counted by strata and estimation unit. The ratios of the number of pixels in each stratum to the known area of sampled NFS lands in each estimation unit were used to calculate population means and variances (e.g., MacLean, 1972). Ratio estimates (e.g., Mg per ha) and their variances were calculated using the ratio of means estimator (Scott et al., 2005). We compared attributes of interest (e.g. C in mortality vs. removals) by calculating their difference at the plot level and estimating the mean difference and variance with the same double-sampling for stratification used for population estimates. The statistical significance of estimated means (e.g., carbon flux rates and differences between attributes) being different from zero was assessed from means and variances with the Type I error for the Z-statistic (Zar, 1984). Means were considered significantly different from zero if the probability of a Type I error was less than 0.05. Error estimates reported in results and text are the standard error of the mean. For simplicity of reporting, the 1993–1997 and 1997–2007 sample periods are labeled as 1995 and 2002, respectively. Our analyses investigate the primary variables associated with forest C density and flux, namely region, watershed, management history, and disturbance.

3. Results

We estimate there were 1293 teragrams (Tg) of C in the below- and above-ground woody and live foliage pools on Pacific Northwest NFS lands in 1995, which increased by 45 ± 2.2 Tg by 2002 (Z = 19.6, P < 0.0001; Table 2). The NFS total land area increased by only 0.3% during this time, resulting in an estimated net increase of 1.3 Tg C. All C pools except for understory vegetation increased during this period, with 59% of the increase attributed to the live tree pool and the remainder to the standing dead tree and down dead wood pools. Although we estimated C in understory vegetation to have declined by 2.3 ± 0.1 Tg during this period (Z = 26.5, P < 0.0001), a trend that was consistent across all land classes, we suspect this was due to the change in measurement methods rather than a real decline. As expected, most of the aboveground C in the study area was on forested lands, with nonforest lands covering 9% of the area but contributing just 0.3% to the total C stored. Unlike other pools and land types, the increase of live tree C on reserved forestland was due to an increase in newly-designated reserved area; the decline of 3.1 ± 2.2 Tg on existing reserved lands was not significantly different from zero (Z = 1.38, P = 0.083).

Although most of the increase in C occurred on unreserved forestland, C density was greater on reserved forest lands (by 34 ± 4.2 Mg/ha, Z = 8.2, P < 0.0001), mainly due to the live tree and standing dead tree pools (Table 3). Down dead wood and understory vegetation C density were similar between unreserved and reserved forestland. C density on nonforest lands was greater on unreserved lands than on reserved lands. On reserved lands, 66% of the nonforest area was classified as non-vegetated (e.g., rock, talus, and cinders), while on unreserved lands only 19% was non-vegetated.

Total C density on forested lands and the relative contribution of the different pools varied substantially among individual national forests across the region (Fig. 2). The Siuslaw National Forest (SIU) had the highest estimated C density of 269 ± 9.5 Mg/ha, while the Malheur National Forest (MAL) had the lowest estimated C density of 63 ± 1.4 Mg/ha. Total C density was 2.5 times greater in the westside zones (WOR and WWA) than in the east-side zones (BLUES, CEOR, and NEWA; Table 4). The mean total C density across all forested lands was 146.3 ± 1.2 Mg/ha. The proportion of total C density contributed by live trees was greater in west-side zones than in east-side zones (difference = 6.3 ± 0.5%, Z = 13.2, P < 0.0001), while the contribution of standing dead trees, down dead wood, and understory vegetation was greater in east-side zones than west-side zones (difference = 1.7 ± 0.3%, 4.2 ± 0.3%, 0.4 ± 0.1%; Z = 5.2, 13.2, and 3.3; respectively, P < 0.0001 for all). For all NFS forestland, the mean live-tree C density was 114 ± 1.0 Mg/ha (88.4 ± 0.8 Mg/ha aboveground C), which was 78% of the total C.

While the zones (Fig. 1) reflect broad differences in climate and productivity, C density and flux varied at finer scales (Fig. 3). Variation in C density followed regional geographic patterns, while flux varied substantially among watersheds within zones. C density and flux are not only affected by fine-scale variation in productivity from topographic and climatic gradients, they are also affected by disturbance and management events, and growth rates in recovering and undisturbed vegetation. For example, low sequestration rates can be caused by inherently low site productivity, or by biomass approaching maximum density on productive sites.

Fire or cutting events affected 12% of forestland area over the period studied, for a rate of 1.7% of forestland area per year (Appendix Table A.1). Natural disturbances affected more of Wilderness forestland than the other forestland classes (42% vs. 28%, respectively) particularly for fire (12% vs. 5%, respectively). Cutting rates were 0.9% of unreserved forestland per year, and included a range of treatments from pre-commercial thinning to light- and heavy-thinning commercial harvest. Fire was important on nonforest lands, particularly for non-Wilderness reserved areas (affecting 16% of the area), which includes many low-elevation grass- and shrub-land community types (e.g., Hells Canyon National Recreation Area).

The C pools were affected differently by the types of disturbance that occurred between the two inventory measurements. On average, C density across all pools increased by 1.2 ± 0.05 Mg/ha/yr in undisturbed forests, primarily due to increases in the live tree pool but with some increases in down dead wood as well (Fig. 4). In forestlands experiencing cutting, C density across all pools declined by 1.3 ± 0.2 Mg/ha/yr, primarily due to losses in the live tree and standing dead tree pools. The lack of change in

Table 2
Estimated area, carbon stocks, and standard errors by vegetation category and land status, and changes between 1995 and 2002, on National Forest lands in the Pacific Northwest.

	Unreserved land				Reserved land				Water		Total	
	Forest	SE	Nonforest	SE	Forest	SE	Nonforest	SE	Value	SE	Value	SE
Area (10^3 ha)												
1995	7252.8	23.2	440.4	15.5	1840.3	30.0	507.1	27.0	82.3	8.1	10122.8	11.3
From NFS	−16.3	1.7	−2.4	1.6							−18.7	0.7
To NFS	38.0	4.4	7.8	4.3							45.9	0.3
To reserve	−71.0	4.2	−3.0	1.0	71.0	4.2	3.0	1.0				
2002	7203.5	23.6	442.8	16.0	1911.2	30.0	510.1	27.0	82.3	8.1	10150.0	11.3
Live tree C (10^{12} g)												
1995	763.3	6.9	1.90	0.24	244.2	7.5	1.04	0.31	0.1	0.1	1010.5	9.7
From NFS	−1.5	0.4	0.00	0.00							−1.5	0.4
To NFS	2.1	0.5	0.00	0.00							2.1	0.5
To reserve[a]	−14.2	1.0	0.00	0.00	15.8	1.0	0.00	0.00			1.6	0.2
Internal chg	29.4	1.5	0.05	0.04	−3.1	2.2	0.06	0.11	0.0	0.0	26.5	2.7
2002	779.1	6.9	1.95	0.25	257.0	7.7	1.10	0.38	0.1	0.1	1039.2	9.8
Standing dead tree C (10^{12} g)												
1995	80.7	1.1	0.22	0.04	32.2	1.3	0.13	0.03	0.0	0.0	113.3	1.7
From NFS	−0.2	0.0	0.00	0.00							−0.2	0.0
To NFS	0.2	0.1	0.00	0.00							0.2	0.1
To reserve[a]	−1.6	0.1	0.00	0.00	1.5	0.1	0.00	0.00			−0.1	0.2
Internal chg	4.8	0.8	0.00	0.03	5.5	1.6	0.00	0.02			10.3	1.8
2002	83.9	1.3	0.22	0.04	39.3	1.9	0.13	0.03	0.0	0.0	123.6	2.3
Down dead wood C (10^{12} g)												
1995	125.5	1.5	0.03	0.02	28.1	1.2	0.00	0.00	0.0	0.0	153.7	1.8
From NFS	−0.2	0.0	0.00	0.00							−0.2	0.0
To NFS	0.7	0.2	0.00	0.00							0.7	0.2
To reserve[a]	−1.9	0.2	0.00	0.00	1.2	0.2	0.00	0.00			−0.6	0.2
Internal chg	4.5	1.1	0.01	0.01	3.6	0.8	0.00	0.00	0.0	0.0	8.1	1.3
2002	128.6	1.5	0.04	0.03	32.9	1.3	0.00	0.00	0.0	0.0	161.6	1.9
Understory vegetation C (10^{12} g)												
1995	11.59	0.09	0.45	0.02	3.43	0.11	0.51	0.04	0.00	0.00	16.0	0.1
From NFS	0.00	0.00	0.00	0.00							0.0	0.0
To NFS	0.05	0.01	0.01	0.01							0.1	0.0
To reserve[a]	−0.13	0.01	−0.02	0.01	0.07	0.01	0.01	0.01			−0.1	0.0
Internal chg	−1.51	0.06	−0.04	0.01	−0.70	0.06	−0.05	0.02	0.00	0.00	−2.3	0.1
2002	10.00	0.08	0.40	0.02	2.81	0.09	0.45	0.04	0.00	0.00	13.7	0.1
All forest C (10^{12} g)												
1995	981.0	7.9	2.58	0.28	308.0	8.8	1.68	0.33	0.1	0.1	1293.4	11.2
From NFS	−1.8	0.4	0.00	0.00							−1.8	0.4
To NFS	3.1	0.6	0.01	0.01							3.1	0.6
To reserve[a]	−17.8	1.2	0.01	0.00	18.6	1.2	−0.01	0.00			0.8	0.3
Internal chg	37.2	1.6	0.02	0.04	5.3	1.5	0.02	0.12	0.0	0.0	42.5	2.2
2002	1001.7	8.0	2.61	0.30	332.0	8.9	1.69	0.40	0.1	0.1	1338.0	11.3

[a] Net C change on lands that became reserved is included in the reserved lands value.

Table 3
Estimated mean carbon stock densities and standard errors (Mg/ha) by vegetation category and land status on National Forest lands in the Pacific Northwest in 2002.

Carbon pool	Unreserved land				Reserved land				Water		Total	
	Forest	SE	Nonforest	SE	Forest	SE	Nonforest	SE	Value	SE	Value	SE
Live tree	108.2	0.8	4.4	0.3	134.4	13.0	2.2	0.5	1.1	1.0	102.4	1.0
Standing dead tree	11.7	0.0	0.5	0.0	20.6	0.9	0.3	0.0	0.0	0.0	12.2	0.2
Down dead wood	17.9	0.2	0.1	0.1	17.2	0.6	0.0	0.0	0.0	0.0	15.9	0.2
Understory vegetation	1.4	0.0	0.9	0.0	1.5	0.0	0.9	0.1	0.0	0.0	1.3	0.0
Total	139.1	1.1	5.9	0.4	173.7	16.7	3.3	0.6	1.1	1.0	131.8	1.1

down wood in cut areas appears to be due to piling and burning of unmerchantable material in many units, in some cases removing material that was present at time 1 (based on written crew descriptions). The overall C density change in forests experiencing fire was similar to those that were cut, but declines in the live tree pool were higher, with much of that C being transferred to the standing dead tree pool and a substantial decline in the down dead wood pool. The total decline was higher on forests affected by both cutting and fire than by fire alone (1.7 ± 0.6 Mg/ha/yr, $Z = 2.71$, $P = 0.003$), with comparable declines in live trees, less increase in standing dead trees, and no net change in down dead wood (0.043 ± 0.13 Mg/ha/yr on cut and fire, $Z = 0.34$, $P = 0.368$). Nevertheless, the mean reduction in onsite C stocks between measurements was 9.1 ± 1.4% for burned stands and 22 ± 4.0% for burned and cut stands. C density increased on forestland affected by insects and disease (i.e., causing damage or mortality), but less than for undisturbed stands, and the contribution of down dead wood to sequestration in those stands was greater and live trees less so (Fig. 4). The estimated net total increase of 0.4 ± 0.3 Mg/ha/yr on forestland impacted by weather events was not significant ($Z = 1.16$, $P = 0.123$). For all forestland in the study population, the estimated net annual flux for live trees, standing dead trees,

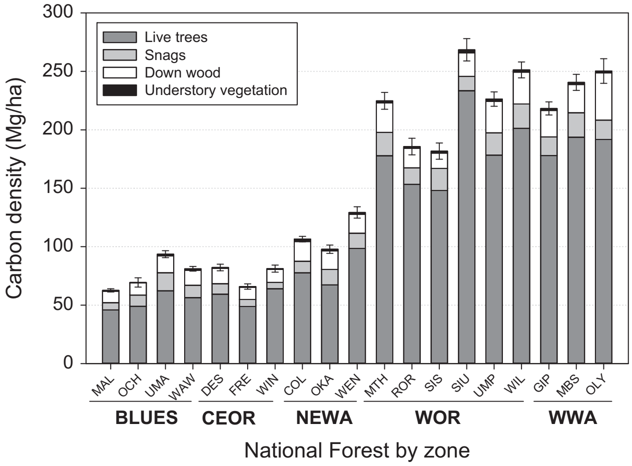

Fig. 2. Mean forestland C density (Mg/ha) on national forests in the Pacific Northwest, by type of C pool and grouped by geographic zone. Standard error bars are for all C pools combined. Abbreviations for National Forests are defined in Table 1 (BLUES = Blue Mountains, CEOR = Central Oregon, NEWA = Northeast Washington, WOR = Western Oregon, WWA = Western Washington).

down dead wood, understory vegetation, and all pools combined was 0.51 ± 0.001, 0.081 ± 0.007, 0.24 ± 0.001, $-0.052 \pm 4.7 \times 10^{-6}$, and 0.77 ± 0.002 Mg/ha/yr, respectively.

Live trees are the drivers of C sequestration and the wood in subsequent pools. The net change in live tree C density was significantly positive ($P < 0.0001$) for unreserved forestland in all zones (Fig. 5). Gross growth was greater and the ratio of mortality to growth was lower in westside zones than in eastside zones on unreserved forestlands. In contrast, the balance between growth and mortality on reserved forestland resulted in net change in live tree C density that was negative for the BLUES zone ($Z = 2.82$, $P = 0.002$), not significantly different from zero for CEOR, NEWA, or WWA ($Z = 1.50$, $P = 0.067$; $Z = 0.11$, $P = 0.46$; $Z = 0.90$, $P = 0.18$, respectively), and positive only for WOR ($Z = 1.76$, $P = 0.039$). On unreserved forestland, 1% (8.9 Tg) of the time 1 C was in trees that were cut by time 2 (0.2%/yr), while 18% of C was in trees that died naturally (including from fire) (Table 5). In contrast, the standing dead tree pool was quite dynamic, with 44% of the C in 1995 being lost to decay and fragmentation by 2002 (6%/yr), yet more than replaced by new mortality. C in new standing dead trees was 76% of the total lost to mortality of live trees, with the remainder ending up directly in the down dead wood pool.

The general patterns of zonal differences in productivity and disturbance were evident in the net changes in C density of the different pools within zone groups. The net increase in C density on westside forests was 1.2 ± 0.09 Mg/ha/yr, with 90% of the increase occurring in the live tree pool (Appendix Fig. A.2). In contrast, the net increase in C density on eastside forests was 0.5 ± 0.04 Mg/ha/yr, with 76% of the increase occurring in the down dead wood pool, reflecting higher rates of disturbance during the measurement period. An alternative summary by state to enable comparison with other studies indicates higher rates of sequestration in Washington than in Oregon, primarily due to the live tree pool (0.99 ± 0.9 and 0.64 ± 0.05 Mg/ha/yr, respectively; Appendix Table A.2).

4. Discussion

This is the first regional C stock and flux assessment for NFS lands based on a probabilistic sample of multiple forest C pools on remeasured plots. By combining these measurements with plot-specific information on management and disturbance events, we were able to assess the importance of different agents of change to C stocks in different parts of the region. We found that C stocks increased on Pacific Northwest national forests between 1995 and 2002, but with substantial variation among zones and reserve status. Harvest and disturbance have had little overall impact on C sequestration.

4.1. Regional drivers of carbon density and flux

C density was substantially greater on westside than on eastside NFS forests, reflecting greater productivity tied to warmer temperatures and greater precipitation. The standing dead tree and down dead wood pools were a larger proportion of total C on eastside than westside forests, reflecting the greater eastside mortality rates we found. Much of this mortality is related to recent outbreaks of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) and western spruce budworm (*Choristoneura occidentalis* Freeman) in eastside forests (Meigs et al., 2011), as well as recent wildfires. The size of the standing dead tree and down dead wood C pools may also reflect regional differences in decomposition rates, which are affected by tree species, piece diameter, and local climate (Harmon et al., 1986).

Reserved forest lands had greater C densities than unreserved forest lands, reflecting a history of low rates of management and natural disturbance. During the 1995–2002 remeasurement period, however, there was no increase in the live tree C pool overall, with losses on eastside reserved lands and slight gains on westside reserved lands. The low sequestration rates on reserved lands are likely due to greater amounts of natural disturbance (on Wilderness in particular) and the lower inherent sequestration found at high elevations and in older (i.e., high C density) forest age classes.

Fire events reduced C stocks during the remeasurement period, but the regional impact was minor (−5.6 Tg), despite affecting a substantial area (1%/yr). On plots affected by fire, the losses in the live tree pool were not fully compensated by increases in the standing dead tree pool (reflecting decay), and down dead wood C pools declined slightly as well. Fire effects on C pools were most prevalent in eastside reserved forests. Most of these lands are at high elevations where weather should be a more important control on fire events than lack of fuel (Littell et al., 2009), but it is also

Table 4
Estimated means and standard errors of carbon stock density (Mg/ha) and proportion of total by carbon pool on forestland by zone on National Forest lands in the Pacific Northwest in 2002.

Component	BLUES			CEOR			NEWA			WOR			WWA		
	Mean	SE	Percent	Mean	SE	Percent	Mean	SE	Percent	Mean	SE	Percent	Mean	SE	Percent
Live tree	53.7	1.0	70	57.6	1.3	75	82.7	2.0	73	181.7	2.7	81	187.5	3.5	80
Standing dead tree	10.3	0.4	13	7.1	0.4	9	12.3	0.5	11	18.5	0.5	8	18.3	1.0	8
Down dead wood	12.0	0.3	16	11.8	0.3	15	16.3	0.5	14	22.5	0.5	10	26.4	0.7	11
Understory vegetation	1.0	0.0	1	0.6	0.0	1	1.6	0.0	1	1.8	0.0	1	1.8	0.0	1
Total	77.0	1.1	100	77.2	1.5	100	113.0	2.4	100	224.5	3.0	100	233.9	4.1	100

Note: BLUES = Blue Mountains, CEOR = Central Oregon, NEWA = Northeast Washington, WOR = Western Oregon, WWA = Western Washington.

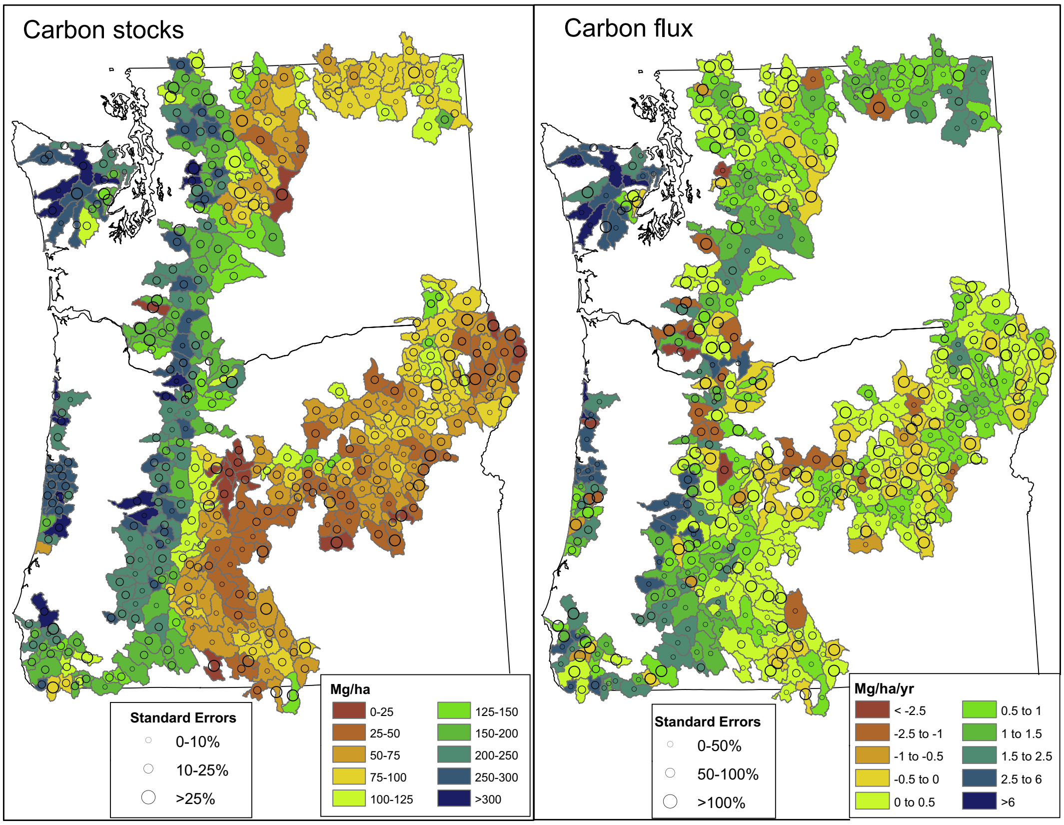

Fig. 3. Mean C stocks (left) and flux (right) on national forest lands by 5th-order watershed in the Pacific Northwest. C in live trees, dead trees, down dead wood, and live understory vegetation on forest and nonforest lands is included. Only watersheds with at least 5 plots in the sample are shown; the median number of plots per watershed was 23. Circle sizes indicate the standard error of the estimate for each watershed.

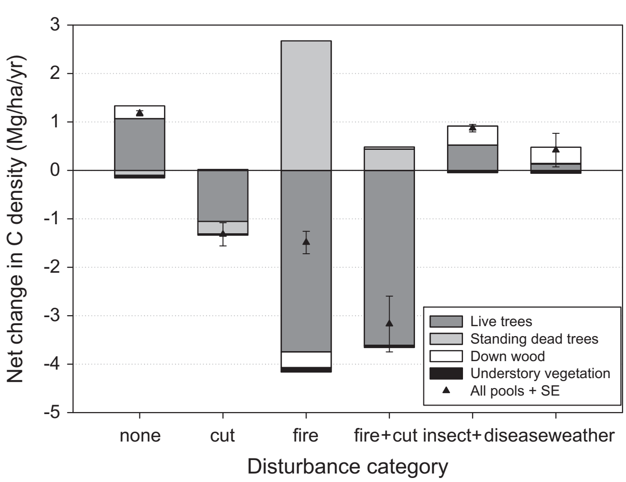

Fig. 4. Net annual change in C density by pool and all pools on forested national forest lands combined by disturbance category. Standard error bars are for total flux.

possible that in some areas, forests have higher C density and are burning more severely than in the past due to decades of fire suppression. Higher fire incidence in east-side Wilderness areas is to be expected given greater prevalence of lightning strikes east of the Cascades and less aggressive (or no) suppression measures in Wilderness due to an increased appreciation of the beneficial role of fire in forest ecosystems (e.g., Agee, 1993). Beyond the effects of fire on C, the desirability of fire effects on forests depends on the severity and patch sizes of fire incidents and the ability of vegetation to regenerate and recover (Stephens et al., 2013). Despite apparent increases in fire incidence in the west (Westerling et al., 2006), fire has not had a substantial impact on C stocks in this region during this period.

Harvest activities on NFS lands affected less than 1% of the area and removed less than 0.2% of the live tree C outside reserved areas per year, reflecting the recent management focus on partial cutting in younger stands. Although the C in trees that are removed in cutting activities is not immediately lost to the atmosphere, estimating their contribution to C flux with the atmosphere requires accounting for residence and decay times in different harvested wood C pools (Skog, 2008), which is beyond the scope of this study. As harvest rates have declined on NFS lands since 1990 (Donnegan et al., 2008; Campbell et al., 2010), live tree pools have increased from growth, and mortality has also added to the standing dead tree and down dead wood C pools. Future efforts to restore east-side forests by reducing density to reduce fire severity could result in overall declines in C stocks over time.

C flux was also affected by the type of pool, ownership change, and watershed location. Although the standing dead tree C pool was 12% of the size of the live tree C pool, it was more dynamic, with 57% as much C moving in and out of the pool. This appears to be in agreement with other studies that found standing dead tree fall rates of 4–7%/yr, and half-lives between death and snag fall ranging 6–11 years among species in the west (Harmon et al., 1986; Landram et al., 2002). Ownership change between NFS and other owners was a minor component in area and C change at the regional level, although likely important for management units where many land exchanges occurred (e.g., Wenatchee National Forest). Similarly, changes among owner groups and between forest and nonforest land use were minor components of C flux on non-NFS lands in Oregon in the 1990s (Gray et al., 2014). Although our finding that the highest rates of C sequestration were in

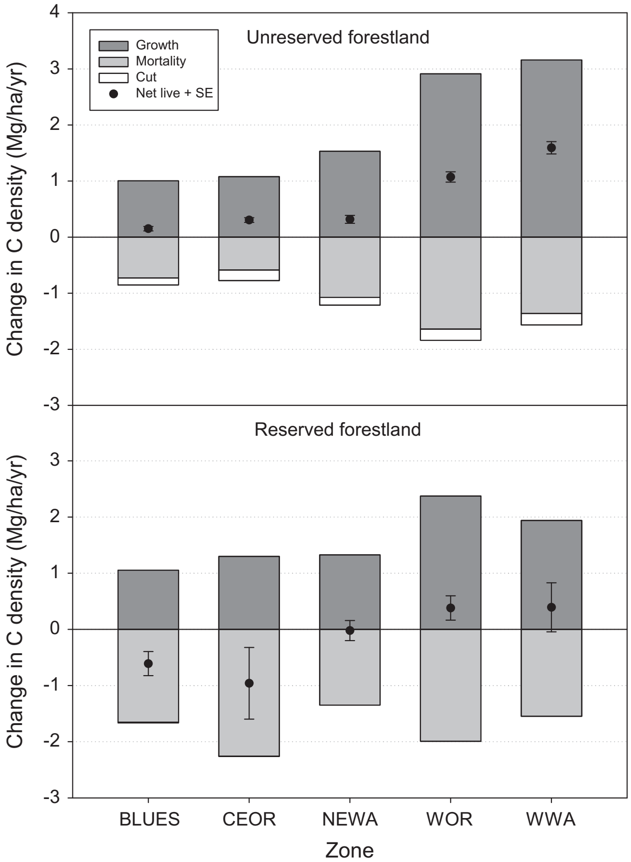

Fig. 5. Net annual change in live tree C density and components of change on forestland by national forest zone and reserve status. Standard error bars are for net live tree flux. (BLUES = Blue Mountains, CEOR = Central Oregon, NEWA = Northeast Washington, WOR = Western Oregon, WWA = Western Washington).

Table 5
Total live and standing dead tree carbon stores, components of change between 1995 and 2002, and standard errors by reserved status on forest land.[a]

Component	Unreserved forest		Reserved forest		All forest	
	Total	SE	Total	SE	Total	SE
Live tree C (10^{12} g)						
1995	747.6	6.9	258.5	7.5	1006.0	9.7
Growth	89.0	0.9	26.0	0.7	115.0	1.1
Mortality	−50.7	1.2	−27.4	2.2	−78.2	2.5
Cut	−8.9	0.8	0.0	0.0	−8.9	0.8
2002	777.0	6.9	257.0	7.7	1033.9	9.8
Standing dead tree C (10^{12} g)						
1995	78.9	1.1	33.8	1.3	112.8	1.7
Recruitment	38.0	1.0	21.8	2.0	59.8	2.2
Decay + Loss	−33.2	0.6	−16.3	0.9	−49.6	1.1
2002	83.7	1.3	39.3	1.9	123.0	2.3

[a] Existing and newly-designated reserved lands included in reserved category.

westside forests was expected, the high variation in C flux within zones and watersheds suggests the role of local factors. The role of stand-level attributes like disturbance history, stand age, tree size, and species composition on patterns of C flux by pool is the topic of additional study.

4.2. Comparing carbon estimates

Research on forest C has been very active in recent decades, and has involved a wide range of methods and metrics. Some assessments have built detailed ecosystem models from intensive studies of a few sites to simulate different management or disturbance regimes (e.g., Harmon et al., 2009). Others have linked physiological or ecosystem models to climate models and classified satellite imagery to assess changes in C stocks at regional levels (e.g., Turner et al., 2011; Krankina et al., 2012). Some of these use single-date data from forest inventories and other plot datasets to initialize and parameterize their models. Others are based directly on inventory data and apply models or relationships from other studies to estimate pools and processes not measured in the inventories (e.g., Jenkins et al., 2001; Hudiburg et al., 2009).

We estimated C sequestration of 6.0 ± 0.3 Tg/yr on NFS lands, or 20% of the 29.5 Tg C/yr emitted from fossil fuel combustion in Oregon and Washington in 2011 (U.S. Environmental Protection Agency, 2013). Our estimated sequestration rate of 0.77 ± 0.002 Mg/ha/yr on all NFS forest land is substantially lower than Zheng et al.'s (2011) satellite change-detection modeled estimates for Oregon and Washington of 3.3 and 3.7 Mg/ha/yr, respectively. It is unlikely that the non-NFS lands in Oregon are making up the difference between these estimates, given a measured annual sequestration rate of 0.08 ± 0.12 Mg/ha/yr in the live tree pool in the 1990s (Gray et al., 2014). One possible reason for the difference is that selecting a single dominant forest type and age class for a county based on inventoried tree density resulted in a younger, faster-growing type than the true mean. In addition, Zheng et al. (2011) used values from idealized growth and yield tables—which usually assume full stocking with no exogenous mortality—for their assessment; a comparison of wood volume and live tree C density with stand age indicates many of the values in these tables were higher than found in current inventory data (Tables A.3 and A.4).

Our estimate of C sequestration of 1.2 ± 0.09 Mg/ha/yr on westside NFS lands is within the range of estimates of a physiologically-based model tied to remote sensing change for all ownerships in western Oregon and the coastal Northwest of 1.0–1.5 Mg/ha/yr (Law et al., 2004; Turner et al., 2011). The national Greenhouse Gas Inventory (GHGI, based on FIA data and modeled parameters) estimated sequestration rates of 0.30 and 0.75 Mg/ha/yr for all ownerships in Oregon and Washington, respectively (U.S. Environmental Protection Agency, 2013), likely reflecting low productivity on east-side forests and low sequestration on non-federal lands (Gray et al., 2014).

Our estimate of aboveground live tree C density on NFS lands (88.4 Mg/ha) was 19% lower than the FIA-based estimate in Heath et al. (2011), despite close agreement on area of forestland. The difference is because they used generalized biomass equations based on tree diameter (Jenkins et al., 2003), while we applied the Component Ratio Method (CRM) algorithms now used for the GHGI (Heath et al., 2009; Woodall et al., 2011). Similar differences were also found in Domke et al. (2012). The CRM method is based on local volume equations that use DBH and height, and applies biomass ratios from Jenkins et al. (2003) to the non-merchantable tree components (Woodall et al., 2011). Our values are in line with the non-soil state-wide C density estimates in the GHGI report (U.S. Environmental Protection Agency, 2013), and the related PNW NFS-specific report (USDA Forest Service, in press), as would be expected from applying the same tree C calculation methods to independent inventories overlapping in time.

Many of the forest C assessments attempt to describe C flux through estimates of net primary productivity (NPP) and ecosystem respiration. However several ecosystem components, particularly below-ground NPP, respiration, and decomposition, are difficult to measure. Thus results from a few detailed studies are often extrapolated to other sites and regions. It is just as valid and potentially much simpler to estimate C flux as the simple difference in C stocks measured at two points in time to estimate Net Ecosystem Carbon Balance (NECB, Chapin et al., 2006). While this still requires the use of models and estimates for hard-to-measure C pools (see below), there may be fewer assumptions involved for monitoring C flux, and less reliance on parameters assigned from a few study sites to coarse geographic and plant community groupings. Of course NPP-based methods are quite valuable for trying to understand effects of new conditions, either climatic, disturbance, or management, or the mechanisms behind observed changes.

Studies of disturbance effects are often limited to the specific locations and conditions of the events studied. For example, prescribed burns are rarely done in the high-severity season when fires affect the most area, limiting their scope of inference. Retrospective studies rarely have prior data, requiring a number of assumptions. Inventory data on the other hand cover the range of current conditions, including prescribed treatments, wildfire, and their interactions with other agents of disturbance. One of the advantages of working with an unbiased inventory sample of a region is that the range of conditions is sampled in proportion to their abundance. This can also be a disadvantage when the goal is to limit variation to assess potential causality of specific types of events. Another complication with inventory data is that regional estimates are a mean value for a defined period of time. The effect of events occurring during the remeasurement period (e.g., the 200,000 ha Biscuit Fire in 2002 in southwest Oregon) is dampened because some plots in the affected area were measured before the event and some after. Being able to update plot attributes to a specific point in time to account for changes (i.e., with models tied to events detected from satellite imagery) is desirable, but complicated because it is necessary to account for growth of existing trees, ingrowth of new trees, and background rates of mortality on all plots, not just the ones that were disturbed. Being able to correctly identify disturbance severity for effects of partial harvest, moderate fire, or combined fire and harvest in remotely sensed images is an active area of research. We expect the timeliness and comprehensiveness of future C change estimates to improve as this research matures.

This study was based on a unique dataset of remeasured inventory plots on Pacific Northwest region NFS lands, post-stratified with satellite imagery to improve the precision of the estimates. The current annualized FIA inventories, which began in 2001, will provide similar data on all forest lands in the U.S., with consistent and comprehensive tracking of changes in tree and land status. To meet information needs of regional FIA program partners, most inventories include measurements beyond the national core procedures, including understory vegetation, down dead wood and forest floor, and nonforest on NFS lands in the west. Our study predates the current FIA surveys, and thus our results extend the time frame for which forest C trends on NFS lands may be developed from ground-based surveys.

4.3. Carbon estimation gaps

Estimating the C content of a forest ecosystem and its changes over time is not a simple matter, even when ground-based measurements are available for multiple pools at two (or more) points in time. C estimates are based on applying a large number of equations and constants, some of which are based on scant information (e.g., branch and root biomass equations, decay-class wood density constants). Even the equations with the most empirical data behind them, for volume of tree boles, in many cases are based on geographically-limited samples of trees in particular types of stands, which could introduce bias when applied to trees across a region. Tree biomass estimates can be calculated from nationally-generalized equations (Jenkins et al., 2003), or component ratios applied to merchantable volume (Woodall et al., 2011), or selected local equations from specific studies (Zhou and Hemstrom 2009), but their accuracy for regional applications is unknown. When available, application of tree biomass equations based on a large, well-distributed sample can result in model-related errors that are much lower than the sampling errors (Ståhl et al., 2014).

In this study, soils were not measured and flux of soil C was not considered, with the assumption that short-term changes are small. However it is clear that mineral soil C can be affected by intense disturbances like hot fires (Bormann et al., 2008). Regional assessments of soil C are fairly general (e.g., soil maps and chronosequences) and provide no information about change. The FIA program does have a soil protocol that has been implemented on subsets of plots across the U.S. (O'Neill et al., 2005), but there appears to be little consensus among soil scientists about how to measure regional forest soil C stocks and monitor change (AN Gray, pers. obs.).

Forest floor measurements were not made in the NFS inventories used in this study but are available for current FIA inventories in the Pacific Northwest. Calculations using duff and litter depth data indicate an additional 121 Tg C stored in the forest floor on NFS forest lands (13.3 Mg/ha; data not shown). This substantial amount of C (10% of the other estimated pools) is affected by disturbance and succession (Giesen et al., 2008; Meigs et al., 2009), so having data on future changes in this pool will be important. We are also missing measurements of stumps left by tree cutting and of standing dead trees that decay to less than breast height in the NFS inventory as well as in current FIA inventories. Given that coarse root biomass alone averaged 20% of total tree biomass in our study, it is likely that stumps and their roots are a substantial C pool, particularly in managed stands. Likewise, we do not have inventory measurements of fine roots. Fine roots are thought to scale with stand leaf area index (LAI) and soil moisture regime, and their estimated contribution to C stocks does not exceed 1 Mg/ha, and is 0.5 Mg/ha or less for well-stocked stands (Van Tuyl et al., 2005).

In our study, the standard errors presented in the results were all associated with sampling error. Sampling error is essentially a function of sample size or in our case the area over which attributes are estimated; the smaller the area, the greater the error as a proportion of the estimate. The errors introduced by the models and parameters used to calculate C from the field measurements were not included. In many cases this information is not available, because validation with unbiased, well-distributed samples have not been done. Based on some model error information and assumptions concerning the distribution of uncertainties, the 95% confidence interval for annual C flux on forest ecosystems for the U.S. as a whole was calculated as ±16% of the estimate (U.S. Environmental Protection Agency, 2013). Whether this level of error is acceptable or not likely depends on the application, e.g., estimating general trends vs. trading C credits of specific value. Future development of regional-scale parameters for estimating different C pools would provide more confidence in calculations of C stocks and flux.

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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.2014.05.015.

References

Agee, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.

Barrett, T.M., 2006. Optimizing efficiency of height modeling for extensive forest inventories. Can. J. For. Res. 36, 2259–2269.

Bormann, B.T., Homann, P.S., Darbyshire, R.L., Morrissette, B.A., 2008. Intense forest wildfire sharply reduces mineral soil C and N: the first direct evidence. Can. J. Forest Res. 38, 2771–2783.

Campbell, S., Waddell, K., Gray, A., 2010. Washington's Forest Resources, 2002 to 2006. Gen. Tech. Rep. PNW-800. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 189 p.

Chapin, F.S., Woodwell, G.M., Randerson, J.T., Rastetter, E.B., Lovett, G.M., Baldocchi, D.D., Clark, D.A., Harmon, M.E., Schimel, D.S., Valentini, R., Wirth, C., Aber, J.D., Cole, J.J., Goulden, M.L., Harden, J.W., Heimann, M., Howarth, R.W., Matson, P.A., McGuire, A.D., Melillo, J.M., Mooney, H.A., Neff, J.C., Houghton, R.A., Pace, M.L., Ryan, M.G., Running, S.W., Sala, O.E., Schlesinger, W.H., Schulze, E.D., 2006. Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems 9, 1041–1050.

Cochran, W.G., 1977. Sampling Techniques, third ed. John Wiley & Sons, New York.

Coops, N.C., Ferster, C.J., Waring, R.H., Nightingale, J., 2009. Comparison of three models for predicting gross primary production across and within forested ecoregions in the contiguous United States. Remote Sens. Environ. 113, 680–690.

Coulston, J.W., Nelson, K., Woodall, C.W., Meriwether, D., Reams, G.A., 2012. The climate change performance scorecard and carbon estimates for national forests. Gen. Tech. Rep. NRS-P-105. USDA Forest Service, Northern Research Station, Newtown Square, PA, pp. 170–176.

Domke, G.M., Woodall, C.W., Smith, J.E., Westfall, J.A., McRoberts, R.E., 2012. Consequences of alternative tree-level biomass estimation procedures on U.S. forest carbon stock estimates. For. Ecol. Manage. 270, 108–116.

Donnegan, J., Campbell, S., Azuma, D., 2008. Oregon's forest resources, 2001–2005: five-year Forest Inventory and Analysis report. Gen. Tech. Rep. PNW-GTR-765. USDA Forest Service, Pacific Northwest Research Station, Portland, OR. 186 p.

Dunham, P.A., Weyermann, D.L., Azuma, D.L., 2002. A comparison of stratification effectiveness between the National Land Cover Data set and photointerpretation in western Oregon. Gen. Tech. Rep. NC-230. USDA Forest Service North Central Research Station, St. Paul, MN, 63–68.

Eidenshink, J., Schwind, B., Brewer, K., Zhu, Z.-L., Quayle, B., Howard, S., 2007. A project for monitoring trends in burn severity. Fire Ecol. 3, 3–21.

Franklin, J.F., Dyrness, C.T., 1973. Natural Vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 417 p.

Giesen, T.W., Perakis, S.S., Cromack, K., 2008. Four centuries of soil carbon and nitrogen change after stand-replacing fire in a forest landscape in the western Cascade Range of Oregon. Can. J. For. Res. 38, 2455–2464.

Gonzalez, M., Augusto, L., Gallet-Budynek, A., Xue, J.M., Yauschew-Raguenes, N., Guyon, D., Trichet, P., Delerue, F., Niollet, S., Andreasson, F., Achat, D.L., Bakker, M.R., 2013. Contribution of understory species to total ecosystem aboveground and belowground biomass in temperate *Pinus pinaster* Ait. forests. For. Ecol. Manage. 289, 38–47.

Gray, A.N., Whittier, T.R., Azuma, D.L., 2014. Estimation of above-ground forest carbon flux in Oregon: adding components of change to stock-difference assessments. Forest Sci. 60, 317–326.

Hall, F.C., 1998. Pacific Northwest ecoclass codes for seral and potential natural communities. Gen. Tech. Rep. PNW-418. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 290 p.

Hanson, E.J., Azuma, D.L., Hiserote, B.A., 2002. Site Index Equations and Mean Annual Increment Equations for Pacific Northwest Research Station Forest Inventory and Analysis Inventories, 1985–2001. Res. Note PNW-533. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 24 p.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack Jr., K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133–302.

Harmon, M.E., Moreno, A., Domingo, J.B., 2009. Effects of partial harvest on the carbon stores in douglas-fir/western hemlock forests: a simulation study. Ecosystems 12, 777–791.

Harmon, M.E., Woodall, C.W., Fasth, B., Sexton, J., Yatkov, M., 2011. Differences between standing and downed dead tree wood density reduction factors: a comparison across decay classes and tree species. Res Pap NRS-15. USDA Forest Service Northern Research Station, Newtown Square, PA. 40 p.

Hayes, D.J., Turner, D.P., Stinson, G., McGuire, A.D., Wei, Y., West, T.O., Heath, L.S., de Jong, B., McConkey, B.G., Birdsey, R.A., Kurz, W.A., Jacobson, A.R., Huntzinger, D.N., Pan, Y., Post, W.M., Cook, R.B., 2012. Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data. Glob. Change Biol., 1282–1299.

Heath, L.S., Hansen, M., Smith, J.E., Miles, P.D., Smith, B.W., 2009. Investigation into calculating tree biomass and carbon in the FIADB using a biomass expansion factor approach. In: McWilliams, W., Moisen, G., Czaplewski, R., comps. Forest Inventory and Analysis (FIA) Symposium 2008; October 21–23, 2008; Park City, UT. Proc. RMRS-P-56CD. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO. 26 p.

Heath, L.S., Smith, J.E., Woodall, C.W., Azuma, D., Waddell, K.L., 2011. Carbon stocks on forestland of the United States, with emphasis on USDA Forest Service ownership. Ecosphere 2, 1–21.

Henderson, J.A., 2009. Modeled potential natural vegetation zones of Washington and Oregon. USDA Forest Service. <http://ecoshare.info/2010/02/28/waor-washingtonoregon/>.

Homer, C., Huang, C., Yang, L., Wylie, B., Coan, M., 2004. Development of a 2001 national landcover database for the United States. Photogramm. Eng. Remote Sens. 70, 829–840.

Hudiburg, T., Law, B., Turner, D.P., Campbell, J., Duane, M., 2009. Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. Ecol. Appl. 19, 163–180.

Hurteau, M.D., Hungate, B.A., Koch, G.W., North, M.P., Smith, G.R., 2013. Aligning ecology and markets in the forest carbon cycle. Front. Ecol. Environ. 11, 37–42.

IPCC Core Writing Team, Pachauri, R.K., Reisinger, A. (Eds.), 2007. Climate Change 2007: Synthesis Report Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Jenkins, J.C., Birdsey, R.A., Pan, Y., 2001. Biomass and NPP estimation for the mid-Atlantic region (USA) using plot-level forest inventory data. Ecol. Appl. 11, 1174–1193.

Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2003. National-scale biomass estimators for United States tree species. For. Sci. 49, 12–35.

Krankina, O.N., Harmon, M.E., Schnekenburger, F., Sierra, C.A., 2012. Carbon balance on federal forest lands of Western Oregon and Washington: the impact of the Northwest Forest Plan. For. Ecol. Manage. 286, 171–182.

Landram, F.M., Jr., W.F.L., Atzet, T., 2002. Demography of standing dead trees in eastside pine forests of California. Gen. Tech. Rep. PSW-181. USDA Forest Service Pacific Southwest Research Station, Albany, CA, 605–620.

Law, B.E., Turner, D., Campbell, J., Sun, O.J., Van Tuyl, S., Ritts, W.D., Cohen, W.B., 2004. Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. Glob. Change Biol. 10, 1429–1444.

Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecol. Appl. 19, 1003–1021.

MacLean, C.D., 1972. Photo Stratification Improves Northwest Timber Volume Estimates. Research Note PNW-150. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 16 p.

Malmsheimer, R.W., Bowyer, J.L., Fried, J.S., Gee, E., Izlar, R.L., Miner, R.A., Munn, I.A., Oneil, E., Stewart, W.C., 2011. Managing forests because carbon matters: integrating energy, products, and land management policy. J. For. 109, S7–S48.

Max, T.A., Schreuder, H.T., Hazard, J.W., Oswald, D.D., Teply, J., Alegria, J., 1996. The Pacific Northwest region vegetation and inventory monitoring system. Res. Pap. PNW-493. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 22 p.

McKinley, D.C., Ryan, M.G., Birdsey, R.A., Giardina, C.P., Harmon, M.E., Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., Murray, B.C., Pataki, D.E., Skog, K.E., 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecol. Appl. 21, 1902–1924.

Means, J.E., Hansen, H.A., Koerper, G.J., Alaback, P.B., Klopsch, M.W., 1994. Software for computing plant biomass–BIOPAK users guide. Gen. Tech. Rep. PNW-340. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 184 p.

Meigs, G.W., Donato, D.C., Campbell, J.L., Martin, J.G., Law, B.E., 2009. Forest fire impacts on carbon uptake, storage, and emission: the role of burn severity in the eastern cascades, Oregon. Ecosystems 12, 1246–1267.

Meigs, G.W., Kennedy, R.E., Cohen, W.B., 2011. A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. Remote Sens. Environ. 115, 3707–3718.

Mitchell, S.R., Harmon, M.E., O'Connell, K.E.B., 2009. Forest fuel reduction alters fire severity and long-term carbon storage in three Pacific Northwest ecosystems. Ecol. Appl. 19, 643–655.

North, M.P., Hurteau, M.D., 2011. High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest. For. Ecol. Manage. 261, 1115–1120.

O'Neill, K.P., Amacher, M.C., Perry, C.H., 2005. Soils as an Indicator of Forest Health: A Guide to the Collection, Analysis, and Interpretation of Soil Indicator Data in the Forest Inventory and Analysis Program. Gen. Tech. Rep. GTR-258. USDA Forest Service North Central Research Station, St. Paul, MN. 53 p.

Olsen, A.R., Sedransk, J., Edwards, D., Gotway, C.A., Liggett, W., Rathbun, S., Reckhow, K.H., Young, L.J., 1999. Statistical issues for monitoring ecological and natural resources in the United States. Environ. Monit. Assess 54, 1–45.

Olson, C.M., Martin, R.E., 1981. Estimating Biomass of Shrubs and Forbs in Central Washington Douglas-Fir Stands. Research Note PNW-380. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 5 p.

Pan, Y.D., Birdsey, R.A., Fang, J.Y., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S.L., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333, 988–993.

Scott, C.T., Bechtold, W.A., Reams, G.A., Smith, W.D., Westfall, J.A., Hansen, M.H., Moisen, G.G., 2005. Sample-based estimators used by the forest inventory and analysis national information management system. Gen. Tech. Rep. SRS-80. USDA Forest Service Southern Research Station, Asheville, NC, pp. 43–67.
Skog, K.E., 2008. Sequestration of carbon in harvested wood products for the United States. For. Prod. J. 58, 56–72.
Smith, J.E., Heath, L.S., Woodbury, P.B., 2004. How to estimate forest carbon for large areas from inventory data. J. For. 102, 25–31.
Smith, W.B., Miles, P.D., Perry, C.H., Pugh, S.A., 2009. Forest resources of the United States, 2007. Gen. Tech. Rep. WO-78. USDA Forest Service Washington Office, Washington, DC 336 p.
Sprugel, D.G., 1983. Correcting for bias in log-transformed allometric equations. Ecology 64, 209–210.
Ståhl, G., Heikkinen, J., Petersson, H., La, J.R., Holm, S., 2014. Sample-based estimation of greenhouse gas emissions from forests-a new. approach to account for both sampling and model errors. For. Sci. 60, 3–13.
Stephens, S.L., Agee, J.K., Fule, P.Z., North, M.P., Romme, W.H., Swetnam, T.W., Turner, M.G., 2013. Managing forests and fire in changing climates. Science 342, 41–42.
Turner, D.P., Ritts, W.D., Law, B.E., Cohen, W.B., Yang, Z., Hudiburg, T., Campbell, J.L., Duane, M., 2007. Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. Biogeoscience 4, 597–612.
Turner, D.P., Ritts, W.D., Yang, Z.Q., Kennedy, R.E., Cohen, W.B., Duane, M.V., Thornton, P.E., Law, B.E., 2011. Decadal trends in net ecosystem production and net ecosystem carbon balance for a regional socioecological system. For. Ecol. Manage. 262, 1318–1325.
U.S. Environmental Protection Agency, 2013. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2011. Environmental Protection Agency, Office of Atmospheric Programs, Washington, DC. <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html>.
USDA Forest Service, 2002. Current Vegetation Survey. Version 2.04. unpublished manual available from USDA Forest Service, Pacific Northwest Region, Natural Resource Inventory, Portland, OR.
USDA Forest Service, 2006. 2006 field instructions for the annual inventory of Washington, Oregon, and California. USDA Forest Service, Pacific Northwest Research Station, Portland, OR, p. [Irregular pagination]. <http://www.fs.fed.us/pnw/fia/local-resources/pdf/field_manuals/2006_field_manual.pdf>.
USDA Forest Service, 2011. National roadmap for responding to climate change. FS-957B. USDA Forest Service, Washington, DC. <http://www.fs.fed.us/climatechange/pdf/Roadmapfinal.pdf>.
USDA Forest Service, in press. Baseline assessment of forest carbon stocks including harvested wood products–USDA Forest Service, Pacific Northwest Region. Washington, DC.
USDA Natural Resources Conservation Service, USDI Geological Survey, US Environmental Protection Agency, 2013. The Watershed Boundary Dataset. <http://datagateway.nrcs.usda.gov>.
Van Tuyl, S., Law, B.E., Turner, D.P., Gitelman, A.I., 2005. Variability in net primary production and carbon storage in biomass across Oregon forests – an assessment integrating data from forest inventories, intensive sites, and remote sensing. For. Ecol. Manage. 209, 273–291.
van Wagner, C.E., 1968. The line-intersect method in forest fuel sampling. For. Sci. 14, 20–26.
Vose, J.M., Peterson, D.L., Patel-Weynand, T., 2012. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-870. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 265 p.
Waddell, K.L., Hiserote, B., 2005. The PNW-FIA Integrated Database, Version 2.0. USDA Forest Service Pacific Northwest Research Station, Forest Inventory and Analysis program, Portland, OR. <http://www.fs.fed.us/pnw/fia/publications/data/data.shtml>.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western US forest wildfire activity. Science 313, 940–943.
Woodall, C.W., Heath, L.S., Domke, G.M., Nichols, M.C., 2011. Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. USDA Forest Service Northern Research Station, Newtown Square, PA. 30 p.
Woodall, C.W., Monleon, V.J., 2008. Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA program. Gen. Tech. Rep. NRS-22. USDA Forest Service Northern Research Station, Newtown Square, PA. 68 p.
Woodall, C.W., Monleon, V.J., 2010. Estimating the quadratic mean diameters of fine woody debris in forests of the United States. For. Ecol. Manage. 260, 1088–1093.
Woodbury, P.B., Smith, J.E., Heath, L.S., 2007. Carbon sequestration in the US forest sector from 1990 to 2010. For. Ecol. Manage. 241, 14–27.
Zar, J.H., 1984. Biostatistical Analysis. Prentice-Hall Inc., Englewood Cliffs, NJ.
Zheng, D.L., Heath, L.S., Ducey, M.J., Smith, J.E., 2011. Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001. Environ. Res. Lett. 6, 0140212.
Zhou, X., Hemstrom, M., 2009. Estimating aboveground tree biomass on forest land in the Pacific Northwest: a comparison of approaches. Res Pap PNW-584. USDA Forest Service Pacific Northwest Research Station, Portland, OR. 18 p.