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High-Biomass Forests of the Pacific Northwest: Who Manages Them and How Much is Protected?

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Abstract To examine ownership and protection status of forests with high-biomass stores (>200 Mg/ha) in the Pacific Northwest (PNW) region of the United States, we used the latest versions of publicly available datasets. Overlay, aggregation, and GIS-based computation of forest area in broad biomass classes in the PNW showed that the National Forests contained the largest area of high-biomass forests (48.4 % of regional total), but the area of high-biomass forest on private lands was important as well (22.8 %). Between 2000 and 2008, the loss of high-biomass forests to fire on the National Forests was 7.6 % (236,000 ha), while the loss of high-biomass forest to logging on private lands (364,000 ha) exceeded the losses to fire across all ownerships. Many remaining high-biomass forest stands are vulnerable to future harvest as only 20 % are strictly protected from logging, while 26 % are not protected at all. The level of protection for high-biomass forests varies by state, for example, 31 % of all high-biomass federal forests in Washington are in high-protection status compared to only 9 % in Oregon. Across the conterminous US, high-biomass forest covers <3 % of all forest land and the PNW region holds 56.8 % of this area or 5.87 million ha. Forests with high-biomass stores are important to document and monitor as they are scarce, often threatened by harvest and development, and their disturbance including timber harvest results in net C losses to the atmosphere that can take a new generation of trees many decades or centuries to offset.

Keywords Forest biomass · Forest management · Forest conservation · Carbon · Pacific Northwest

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Introduction

Forests are a critical part of the global biological carbon (C) cycle and can contribute to climate stabilization through uptake and storage of atmospheric C in live and dead trees and in soils (Nabuurs et al. 2007; Ryan et al. 2010). With increasing interest in incorporating forest C stores in forest management and climate change mitigation strategies, there is a growing need for improved understanding of spatial distribution of forest biomass across continents, regions, and landscapes. This is because biomass density (the quantity of biomass per unit area, or Mg dry weight per hectare) indicates the amount of C removed from the atmosphere and retained by vegetation and determines the amount of C that is emitted to the atmosphere (as CO_2, CO, and CH_4 through burning and decay) when ecosystems are disturbed (Houghton et al. 2009). The advances in forest monitoring using satellite imagery have been substantial over the past few decades and this technology is moving toward operational readiness for monitoring, reporting, and verification of forest cover, associated C stock, and their change over time (Goetz and Dubayah 2011). Mapping forest biomass has evolved into a major research priority and multiple methods have been proposed (e.g., Gonzalez et al. 2010; Lefsky 2010; Le Toan et al. 2011; Cartus et al. 2012). Biomass maps derived from

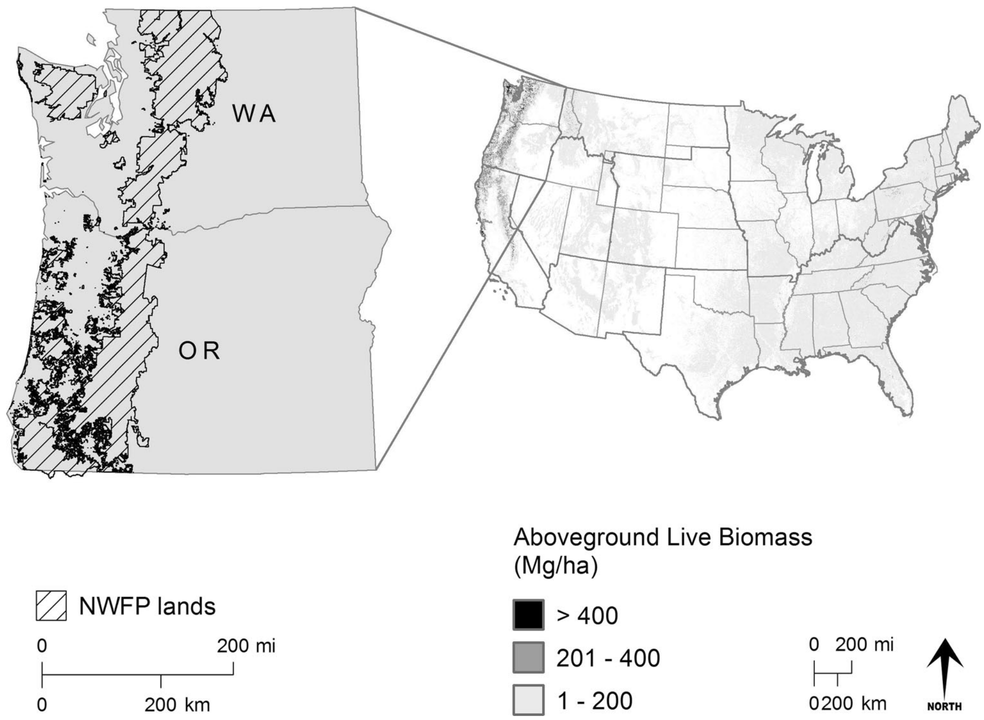

Fig. 1 Forest biomass classes across the conterminous United States as derived from the aggregated version of NBCD2000 dataset with location of study area in the Pacific Northwest and lands managed under Northwest Forest Plan

a combination of remote sensing and in situ data not only deliver transparent and current estimates of C stocks but also capture spatial variability necessary for prioritizing areas for conservation and other aspects of policy development and analysis. New remote sensing instruments aim to improve estimates of forest biomass across the globe at sufficient spatial resolution to inform climate change policies and to reduce uncertainty in regional to global scale C budgets (Goetz and Dubayah 2011). Yet, the bulk of policy analysis continues to rely on established forest inventories that deliver non-spatial estimates of forest biomass (e.g., Heath et al. 2011). Improved awareness of strengths and limitations of newly developed biomass maps is needed for effective use of these resources to inform policy development, implementation, and public scrutiny.

The impact of forest management practices on C exchange between forests and the atmosphere tends to increase in proportion to the amount of biomass C on site: while net losses of forest C to the atmosphere occur following any major forest disturbance, these losses are proportionally greater in high-biomass forests. Exceptional levels of C are stored in late-successional forests of the Pacific Northwest (PNW; Smithwick et al. 2002) and southeast Alaska (Leighty et al. 2006), and these forests are among the most C dense ecosystems in the world (Keith et al. 2009). The PNW forests contain substantial remnants of productive, high-biomass old-growth forests (Smithwick et al. 2002; Spies 2004; DellaSala 2011), whereas in other temperate regions these forests have been eliminated for centuries. Protecting biodiversity of late-successional forests was among the primary goals of the Northwest Forest Plan (NWFP) that shifted forest management on ~10 million ha of federal lands in the PNW from predominately timber extraction to ecosystem management and biodiversity conservation (Fig. 1; NWFP 2002; Mouer et al. 2005; DellaSala and Williams 2006). This change in management resulted in a considerable increase in C stores on federal forest lands within the first decade of plan implementation and this trend can be expected to continue into the future if the limits on timber harvest set under the NWFP are maintained (Krankina et al. 2012).

In the U.S., the national forest planning rule and national road map for responding to climate change require the Forest Service to conduct baseline C inventories so that C can be managed as a "multiple use" across the ~80 million ha national forest system (USDA Forest Service 2010; 2012). Monitoring forest C stores is also integral to the development of an emerging C market for private forest lands (e.g., Alig et al. 2010; California Climate Action Registry www.climateregistry.org/ accessed December 17, 2007). The largest national ground-based dataset was developed by the USDA Forest Inventory and Analysis (FIA) Program and used extensively in studies of forest biomass at national, regional, and state levels (Smith 2002; Heath et al. 2011). Summaries of plot data are available at county level (Van Deusen and Heath 2010), but the sampling method is designed to produce averages for large areas rather than characterizing spatial distribution at fine

Table 1 Area estimates of forest biomass classes and disturbances by land ownership class in Oregon and Washington States combined (thousand ha)

Ownership class	Forest area in biomass classes[a]			Forest area disturbed from 2000 to 2008		High-biomass[b] forest area disturbed from 2000 to 2008		Total forest area[c]	Total land area
	Low (1–200 Mg/ha)	High (201–400 Mg/ha)	Very high (>400 Mg/ha)	Fire	Other disturbance	Fire	Other disturbance		
USFS	3,784	2,121	716	628	246	236	35	7,495	10,003
NPS	131	265	156	6	1	4	1	560	865
BLM	288	343	152	26	94	8	48	902	6,511
Other Public	1,149	597	179	51	151	7	69	2,125	5,101
Private	3,108	1,174	163	58	557	6	364	5,061	19,936
Total	**8,459**	**4,499**	**1,366**	**769**	**1,049**	**261**	**518**	**16,142**	**42,416**

[a] Excluding 2000–2008 disturbance

[b] >200 Mg/ha

[c] In year 2000

resolutions needed for local management decisions. The FIA dataset was used in combination with remotely sensed data to map forest biomass across the conterminous USA at 240 m resolution (Blackard et al. 2008) and at 30-m resolution (National Biomass and Carbon Dataset for the year 2000 (NBCD2000); http://www.whrc.org/mapping/nbcd/index.html, accessed November 21, 2012; Kellndorfer et al. 2006, 2013). Both datasets are freely available to the public.

Our objective was to develop and demonstrate a simple method for using the NBCD2000 dataset to map forests with high-biomass stores in the PNW, examine their ownership and protection status, and assess the area of different types of disturbance affecting high-biomass forests between 2000 and 2008. The overall purpose was to provide an example of using newly available spatial datasets to answer some common questions of forest conservation.

Study Area and Methods

The study area encompasses 42.4 million ha in two states, Oregon (OR) and Washington (WA), that together form the Forest Service's Pacific Northwest Region (Fig. 1; Table 1). Within this region, we examined the area covered by the NWFP and its land-use allocations in greater detail. The overall approach relies on using the latest versions of publicly available spatial datasets for overlay, aggregation, and GIS-based computation of forest area in broad biomass classes across a range of categories that characterize ownership, land-use allocations, disturbance, and protection status of forest lands.

The primary source of data for mapping forest biomass classes was the NBCD2000 dataset (Kellndorfer et al. 2006, 2013). The dataset represents live aboveground biomass of trees with >5 in (12.7 cm) diameter at breast height (DBH) in 30 m pixels. Biomass values in NBCD2000 dataset were predicted using statistical fusion of several data sources, including high-resolution InSAR data acquired from the 2000 Shuttle Radar Topography Mission (SRTM); optical remote sensing data from the Landsat ETM+ sensor (three seasons); USGS National Land Cover Dataset 2001 (NLCD 2001); LANDFIRE (existing vegetation type; USGS 2011); USGS National Elevation Dataset; and USDA FIA data (Kellndorfer et al. 2006; 2013). The biomass values were estimated for each pixel and then averaged at a "stand" patch level (~2 ha average). The standard error of biomass values based on bootstrap validation with USDA FIA plot data is ±139 Mg/ha.

We used the values from NBCD2000 dataset within the PNW study region to assign the 30-m pixels to four biomass classes: <1 Mg/ha (labeled non-forest), 1–200 Mg/ha

(Low Biomass), 201–400 Mg/ha (High Biomass), and >400 Mg/ha (very high biomass). We chose these broad biomass classes because of the high-estimated standard error of the source biomass dataset. Classification breaks were chosen to separate the total forest area into comparable parts with all biomass classes represented within each ownership class. Furthermore, 200 Mg/ha in aboveground live tree biomass approximates the biomass store common for harvest-age productive Douglas-fir (*Pseudotsuga menziesii*) stands (Krankina et al. 2012), the regional average of inventory plots on USDA FS forestlands (Heath et al. 2011), and the lower range of biomass in old-growth forests, while 400 Mg/ha approximates the mid-range for old-growth stands (Smithwick et al. 2002; Keith et al. 2009). In addition to the primary 30-m resolution NBCD2000 dataset, we also used an aggregated version of this dataset at 240-m resolution (http://www.whrc.org/mapping/nbcd/index.html; accessed November 21, 2012) to characterize the share of PNW high-biomass forest area in the nationwide total (Fig. 1; Online Resource 2).

Because NBCD2000 reflects the distribution of biomass circa year 2000, we updated our biomass class map by removing all pixels identified as disturbed in LANDFIRE 2008 dataset (http://landfire.cr.usgs.gov/viewer/; accessed August 31, 2012; and obtained on DVD from Heather Kreilick hkreilick@usgs.gov). The Vegetation Disturbance layer for 1999–2008 provides spatial information on vegetation transitions at 30-m resolution, including disturbance year, type, and severity of disturbance derived mainly from Landsat TM/ETM and MODIS data (Vogelmann et al. 2011; USGS 2012). To characterize the impact of disturbance on high-biomass forests, we computed the disturbed area by biomass class with separation of "fire" from other disturbance types that were examined in aggregate (Table 1). This update of our biomass class map accounts for losses of high-biomass forest to various kinds of disturbance but does not reflect recruitment of high-biomass forests with tree growth over time. We acknowledge this bias but could not eliminate it as the required spatial data are not readily available.

USDA FIA plot-level biomass data were used to assess the accuracy of our updated biomass class map, i.e., the agreement of field-based estimates of forest biomass from FIA plots with assignment of corresponding map pixels to biomass classes. The FIA plot data are publically available (http://www.fia.fs.fed.us/tools-data/, accessed December 5, 2013) with the exception of precise plot location coordinates. FIA staff has unrestricted access to the plot location coordinates and the co-author who is a FIA staff member (Mikhail Yatskov) used plot coordinates to identify mapped biomass class for each FIA plot. This was the only step that relied on data not publicly available.

Forest inventory plots are distributed across all ownerships on a hexagonal grid with one plot being roughly representative of 2,400 ha of land area (Bechtold and Patterson 2005). Plots are re-measured on 10-year cycles to track the land-use change over time as well as changes in biomass, plant species composition, parameters associated with disturbances, and other factors represented by more than 300 collected variables (Smith 2002). Our FIA dataset included 11,887 plots measured during a 10-year cycle that started in 2001. For the reference dataset, we selected a subset of 3,339 plots that were not disturbed since last inventory cycle and were measured between 2008 and 2010. The latter criterion was added to make sure that plot measurements used in our accuracy assessment were not among those used to develop the NBCD2000 dataset (Kellndorfer et al. 2006; 2013) and to minimize the time difference between FIA plot measurements in the field and the biomass class map which was updated to year 2008. We then removed from our reference dataset the plots that were not measured in the field and plots where the proportion of forest cover was <90 % to eliminate plot observations with ambiguous attribution to a specific biomass class. The resulting dataset included 2,898 plots; in each of them live aboveground biomass (Mg/ha) for trees >12.7 cm DBH was estimated from field measurements using regional biomass equations (Zhou and Hemstrom 2010). These estimates were assigned to circles with a radius of 56.4 m (1 ha area) that were overlaid with our updated biomass class map using ArcGIS 10.1. For each circle, we calculated the area that belonged to different classes on our biomass map. The circles where the majority biomass class occupied <90 % of the total area were dropped from the set and the remaining 2,226 plots were used to evaluate the performance of the biomass class map. We constructed a confusion matrix and calculated accuracy metrics, including the error of omission (exclusion) and commission (inclusion) for each class, the overall agreement, and chance-corrected agreement (Kappa, Cohen 1960; See Online Resource 1 for details).

To characterize the current protection status and ownership of high-biomass forests, we used the Protected Areas Database of the United States (PADUS), version 1.2. (US Geological Survey, Gap Analysis Program (GAP), http://gapanalysis.usgs.gov/padus/download/, accessed November 21, 2012). PAD-US is an inventory of marine and terrestrial protected areas that are defined as being dedicated to the preservation of biological diversity and to other natural, recreation ,and cultural uses, managed for these purposes through legal or other effective means (National Gap Analysis Program 2011). For our analysis, we examined two sets of variables: GAP Status Code (values range from 1 to 4 in decreasing levels of protection) and Ownership class that included National Park Service (NPS), US Forest Service (USFS), Bureau of Land Management (BLM), and Other Public (including other federal, state, country, and Native

Table 2 Forest area and biomass classes on Northwest Forest Plan land allocations within Oregon and Washington (thousand ha)

State	NWFP Land-use allocation[a]	Total land area	Forest area (≥1 Mg/ha)	High-biomass forest area[b]		
				Total	IRA[c]	GAP 1 and 2 status
Oregon	AW/CR	854.2	704.5	361.6	39.3	256.3
	LSR	1,383.8	1,123.8	740.1	103.4	34.7
	Matrix	1,675.3	1,343.9	817.1	34.3	2.0
	State total	3,913.4	3,172.2	1,918.8	177.0	293.1
Washington	AW/CR	1,880.6	1,219.9	828.0	39.7	760.5
	LSR	976.5	802.5	566.4	220.9	22.2
	Matrix	720.1	516.5	295.4	58.5	6.5
	State total	3,577.4	2,538.9	1,689.8	319.0	789.2
Grand total		7,490.8	5,711.1	3,608.6	496.1	1,082.2

[a] Administratively Withdrawn/ Congressionally Reserved (AW/CR); late-successional reserves (LSR); after Mouer et al. (2005)

[b] >200 Mg/ha; high biomass and very high biomass classes combined

[c] Inventoried roadless areas

American lands). We assumed that lands not classified into these four categories were Private. In addition, we examined overlap between high-biomass forests and Inventoried Roadless Areas (IRA; http://sagemap.wr.usgs.gov/ftp/unitedstates/USFS/ira_us_dd.htm, accessed November 21, 2012) to determine how well this administrative category can contribute to protection of high-biomass forests in our study area. The intent of the 2001 roadless area conservation rule is to provide lasting protection for these roadless areas in the context of multiple-use management, primarily for the purpose of "watershed and ecosystem health" (USDA Forest Service 2000). Most of these areas are concentrated in the western United States and Alaska. Finally, we examined the extent of high-biomass forests within the NWFP land-use allocations (http://www.reo.gov/gis/data/gisdata/index.htm, accessed June 13, 2012). The NWFP record of decision divided federal land into seven land-use allocations of varying levels of protection; Mouer et al. (2005) combined or further split some allocations and we used these generalized land-use categories for our study area (Table 2).

To characterize the current protection status of high-biomass forests, we used polygon data on ownership, disturbance (between 2000 and 2008), land management allocations, and protection status as masks in the Spatial Analyst Toolbox within ArcGIS 10.1 to extract the biomass class map for each land category of interest. We then computed the area of biomass classes using Zonal Statistics tool in the Spatial Analyst Toolbox.

Results

The assessment of accuracy of our biomass class map with ground measurements on FIA plots indicated that 85.8 % of plots in our sample were mapped correctly with a Kappa value of 65.9 % (Online Resource 1). A large portion of FIA plots with biomass values close to the lower limit of

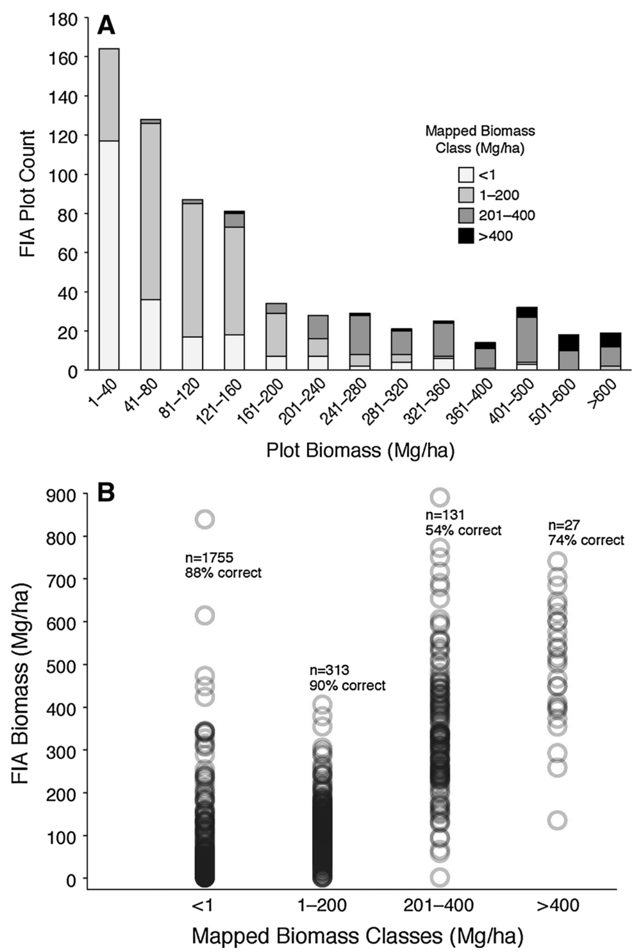

Fig. 2 Agreement between NBCD2000 dataset and biomass estimates for FIA plots in the Pacific Northwest study area: **a** FIA plot counts by mapped biomass classes and **b** distribution of forest biomass values in FIA plots across mapped biomass classes in NBCD2000 dataset

Low-Biomass Class were mapped as non-forest (assigned biomass values <1 Mg/ha in NBCD2000 dataset): among plots with field-based biomass estimates of 1–40 Mg/ha, 77 % were incorrectly assigned to <1 Mg/ha class, while among the plots with biomass ranging from 80 to 200 Mg/ha <25 % were similarly misclassified (Fig. 2a). For the high-biomass class (201–400 Mg/ha), omission and commission errors were well balanced, but in the very high-biomass Class (>400 Mg/ha), the error of omission (71 %) was greater than that of commission (25.9 %, Online Resource 1); in other words—the Very High-Biomass Class (>400 Mg/ha) was under-reported in our biomass class map. The distribution of plot-level biomass values by mapped biomass class demonstrates the degree of biomass class separation and confusion (Fig. 2b). Because of significant confusion between the two high-biomass classes, we opted to report most results for the combined high-biomass class (>200 Mg/ha). Within the combined high-biomass class, 88.6 % of FIA plots were classified correctly and the overall accuracy of three-class biomass map was higher—88.0 %, Kappa 71.0 % (Online Resource 1). Where the results for the very high-biomass class are reported, they likely reflect under-estimation of the area for this class and may have lower overall accuracy.

The total area of mapped forest cover in our PNW study area is 16.1 million ha (Table 1, Online Resource 3) which is generally consistent but lower than the forest area estimate for OR and WA reported by Smith et al. (2001): 51,612000 acres or 20.9 million ha. The definition of forest cover used in this study (≥1 Mg/ha aboveground live tree biomass) is different from definition adopted in the FIA program (Smith et al. 2001); therefore, these area estimates are not directly comparable. The map-based estimate of forest cover excluded forest area disturbed from 2000 to 2008; this combined with the inclusion of lands without tree cover within FIA definition of forest likely accounts for most of the difference in estimates.

High-Biomass Forests Distribution and Losses—Total forest area that was disturbed from 2000 to 2008 was 1.82 million ha or 1.25 % per year on average. With disturbed forest area excluded, high-biomass (>200 Mg/ha) forest area was 5.87 million ha or 41 % of the total forest area, while very high-biomass forests occupied 1.37 million ha or 10 % (Table 1). These high-biomass forests represent a large proportion of all high-biomass forests nation wide (Fig. 1; Online Resource 2). The aggregated version of NBCD2000 used at the national scale suggests that within the conterminous United States, the PNW region holds 56.8 % of forest area with biomass >200 Mg/ha and as much as 77.2 % of forest area with biomass >400 Mg/ha. The coarser resolution of the national dataset (240 m) may have resulted in omission of high-biomass forests where they occur in dispersed small patches and this hampers comparison of high-biomass forest areas in different parts of the country. However, the scarcity of high-biomass forests and their extreme overall concentration in western United States is evident: high-biomass forest occupies <3 % of all forest land in conterminous US, and the PNW and Pacific Southwest regions combined hold 89 % of those forests (Fig. 1; Online Resource 2).

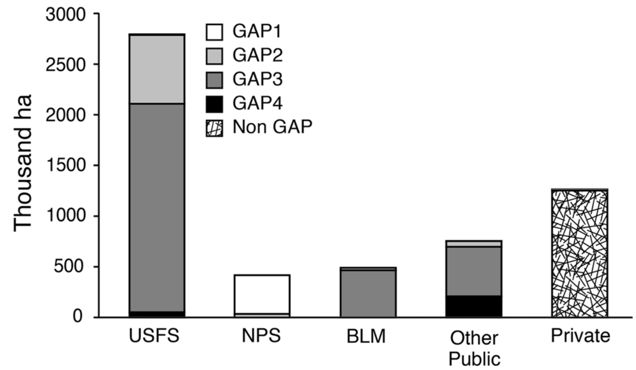

Fig. 3 High-biomass (>200 Mg/ha) forest area distribution by ownership and GAP status for the Pacific Northwest study area

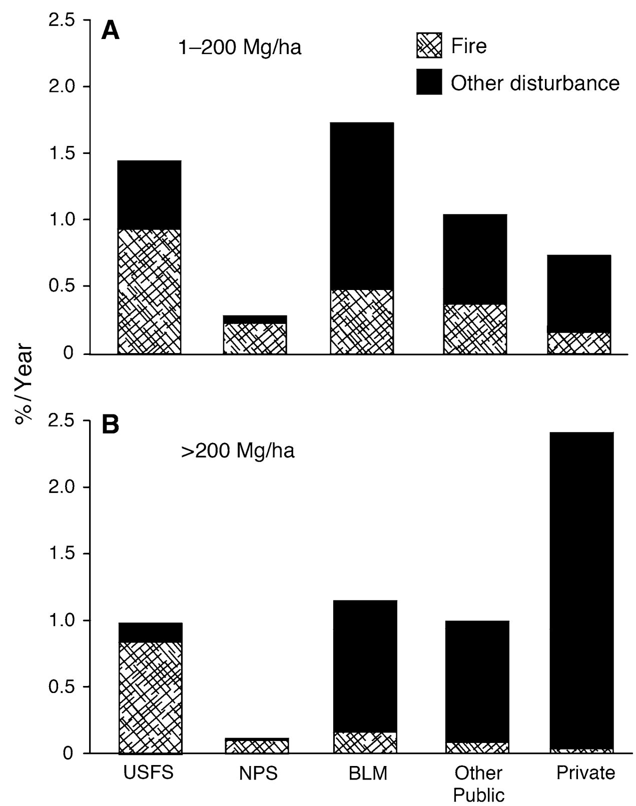

Fig. 4 Average annual disturbance rates for forests in the Pacific Northwest study area between 2000 and 2008: **a** low-biomass forests; **b** high-biomass forests

Among ownership types in the PNW, USFS lands (primarily National Forests) contained the largest area of high-biomass forests (48.4 % of regional total), but private lands contained a significant portion of high-biomass forest as well (22.8 %; Table 1; Fig. 3). More than half of very high-biomass area was on USFS lands, while the share of other four ownership classes was 11–13 % in each. As a fraction of total forest area in an ownership class, the proportion of high-biomass forest area was the largest on NPS and BLM lands (76.6 and 68.1 %, respectively), while on private lands, the proportion of high-biomass forest was relatively low (38.6 %) with only 3.7 % in >400 Mg/ha class (Table 1; Fig. 3).

On NPS land, the proportion of forest area disturbed by all factors between 2000 and 2008 was only 0.16 % per year on average, other ownership classes had much higher disturbance rates (Fig. 4). On USFS lands, fire was the dominant disturbance factor, while other types of disturbance played a much greater role in all other ownerships. The loss of high-biomass forest stands to disturbance both in terms of total area (Table 1) and as a proportion of area in 2000 (Fig. 4) was smaller than the loss of low-biomass forest area with one important exception: on private lands, the loss of high-biomass forest was four times greater than low-biomass forests. The loss of private high-biomass forests between 2000 and 2008 was 21.3 % (364,000 ha) and was mostly associated with non-fire disturbance (primarily logging). The loss of high-biomass forests to fire on USFS lands was 7.6 % of their area in year 2000 (236,000 ha). Overall, the area of high-biomass forest logged on private lands exceeded the total area burned across all ownerships (Table 1). Among public ownerships, the rate of forest loss was greatest on BLM lands (1.25 % per year in high-biomass forest; Fig. 4), mostly to non-fire disturbance (logging). Across all ownerships, the average annual rate of disturbance of high-biomass forest was 1.32 % with fire responsible for about one-third of this loss.

Protection Status of High-Biomass Forests in the PNW—NWFP lands in OR and WA contained 3.6 million ha of high-biomass forest or 61.5 % of the regional total (Table 2). This area was somewhat greater in OR than in WA, but high-biomass area within IRAs and in high-protection GAP status (Gap 1 and 2) was much greater in WA. For example, 31 % of all high-biomass forest lands in WA were in high-protection GAP status compared to only 9 % in OR. Fire was the primary disturbance factor within NWFP lands and fire losses of high-biomass forest between 2000 and 2008 totaled 217,000 ha, while all other factors combined accounted for 74,000 ha loss. However, the average rate of high-biomass forest loss to disturbance on NWFP lands was 0.83 % per year—lower than 2.37 % per year on private lands or 1.32 % per year regional average rate (Fig. 4).

IRAs contained 496,000 ha or 17.5 % of all high-biomass forest lands in USFS ownership in our study area (Table 2) and 132,000 ha or 18.4 % of very high-biomass forests. GAP status information was available only for public lands and primarily reflected the ownership status of high-biomass forests (Fig. 3). High-biomass forest lands with GAP1 status were concentrated on NPS lands, while GAP2 and three occurred mainly on USFS forest lands (with GAP3 prevailing). On other public ownerships, high-biomass forests were in GAP3 and four status (Fig. 3). Across all ownerships, only 20 % of high-biomass forest had strict protection from logging under GAP 1 or 2 status, while 26 % were in GAP4 or no-GAP status receiving little to no protection.

Discussion

The mapping of forest biomass has improved greatly in past decades with increasing use of satellite and aircraft remote sensing. NBCD2000 dataset appears to represent the full range of biomass values better than the Blackard et al. (2008) dataset, where over-estimation of low biomass values and under-estimation of high biomass were reported. Conversely, NBCD2000 assigned biomass values <1 Mg/ha to majority of pixels that coincide with FIA plots with biomass ranging from 1 to 40 Mg/ha; thus under-reporting the area of forest with low-biomass (Fig. 2). For stands with very high-biomass, NBCD2000 tends to under-estimate biomass (Online Resource 1; Fig. 2).

The accuracy metrics in our analysis indicate a moderate level of agreement between the updated biomass class map (Online Resource 3) and the reference data (85.6 % overall agreement for 4-class biomass map, 88.0 % with High Biomass and very high biomass classes combined; Online Resource 3). This suggests that the aggregation of pixel-level biomass values into broad classes served to mitigate the problem of high error in the source NBCD2000 dataset and the map can be considered robust. Yet, at the pixel or stand level, the accuracy of large-area datasets remains inadequate for effective operational monitoring of C stocks (Houghton et al. 2009; Goetz and Dubayah 2011). In the future, the combined use of passive optical remote sensing with light detection and ranging (LiDAR) instruments and the new generation of radar sensors is widely expected to improve the accuracy of biomass maps and meet the needs of forest C monitoring (Gonzalez et al. 2010; Lefsky 2010; Le Toan et al. 2011; Goetz and Dubayah 2011). Nevertheless, currently available biomass maps can provide useful information on patterns of spatial distribution and abundance or scarcity of high-biomass forests over large areas and their losses due to disturbance (Fig. 1; Online Resource 2, 3). Combined with data on land-use designations and protection status of forest lands, the available biomass maps can help assess the ownership status and the extent to which high-biomass forests are protected versus those vulnerable to future harvests.

Our results are broadly consistent with earlier studies that used remote sensing methods to assess the area of mature, old-growth, and large-diameter forests (LDF) in the PNW and their loss to disturbance (Strittholt et al. 2006; Healey et al. 2008). However, the focus on biomass rather than stand age (Strittholt et al. 2006) or stand structure (Healey et al. 2008) makes our results more relevant to planning C management in forest ecosystems as part of climate change mitigation policies (USDA Forest Service 2010, 2012). It is also a likely reason for differences in results. For example, Strittholt et al. (2006) report that 26 % of old-growth forest were strictly protected (GAP1 and GAP2), whereas only 20 % of high-biomass forest were similarly protected (Tables 1, 2; Fig. 3). Furthermore, the loss of LDF across all ownerships during the period following implementation of the NWFP was reported by Healey et al. (2008) at 0.73 % annually, whereas our estimate of high-biomass forest loss to disturbance was nearly twice as high (1.32 % per year), primarily because of logging on private lands. Thinning has become a major type of logging on NWFP lands, and thinned stands were presumed to retain their LDF status (Healey et al. 2008) but thinning significantly reduces forest biomass store. Clearly, the NWFP offers less protection for high-biomass forests compared to LDF or old growth, especially for the most productive stands that can reach 200 Mg/ha biomass level when they are relatively young (~40 years old). Protecting high-biomass forest may be a greater challenge as it presents a more direct conflict with economic gains from timber harvest than protection of old growth, especially old growth with relatively low biomass stores.

While the biomass maps used in this analysis have been available to the public for some time, to our knowledge they have not been used for a quantitative assessment of the area of high-biomass forests and their protection status. The development of approaches and methods for spatial data analysis, like the one presented here, is needed so that forest managers and interest groups can extract pertinent information from available biomass maps. The established FIA sampling methods and analysis tools target broad-scale averages (Van Deusen and Heath 2010; Heath et al. 2011) and cannot deliver adequate characterization of the spatial distribution of forests across the range of biomass values. Forests with high-biomass stores are important to document as they are scarce (Fig. 1, Online Resource 2) and often threatened by harvest and development. The disturbance of high-biomass forests especially timber harvest results in net C losses to the atmosphere that can take a new generation of trees many decades or centuries to offset (e.g., Houghton et al. 2009; Krankina et al. 2012). Yet, protection of high-biomass forests and their C stocks is not among options for managing C on forest lands proposed by the national road map for responding to climate change (USDA Forest Service 2010), the Pacific Coast Action Plan on Climate and Energy (http://www.pacificcoastcollaborative.org/Documents/Pacific%20Coast%20Climate%20Action%20Plan.pdf, accessed December 9, 2013), or The President's Climate Action Plan (http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf, accessed December 9, 2013). Our biomass class map (Online Resource 3) can help identify critical gaps in protection of high-biomass forests in the PNW, better target future conservation programs related to C stores and climate change mitigation efforts, and support the inclusion of high-biomass forest protection in the set of climate change mitigation options on forest lands.

Availability of data on spatial distribution of high-biomass forests could have improved the effectiveness of forest conservation under the NWFP. The NWFP was an important step forward in protecting late-successional habitat for threatened species (e.g., Mouer et al. 2005; DellaSala and Williams 2006) and, as a side benefit, resulted in active C sequestration on federal forest lands (Turner et al. 2011; Krankina et al. 2012). However, there is a surprising discrepancy in protection level of high-biomass forests in OR and WA and overall limited protection from harvest (GAP3, GAP4 or no-GAP) for ~70 % of high-biomass forests managed under NWFP (Table 2). Among publicly owned forest lands, BLM has the highest concentration of high-biomass forests (Fig. 3), which were harvested at a higher rate compared to other public ownerships in 2000–2008 (Fig. 4). Many of the remaining high-biomass forests on BLM lands are designated for logging under recent proposals for expanded timber harvest on NWFP lands (e.g., DeFazio et al. 2012; Wyden 2013).

The vulnerability of old-growth forest to wildland fire on USFS lands has dominated the debate on future conservation strategies in the PNW (Spies et al. 2006; DellaSala and Williams 2006; Healey et al. 2008). This debate largely overlooked the impact of ongoing logging on public lands, yet logging accounts for a greater loss of high-biomass forest than fire on BLM lands and in the other public lands category that includes state and tribal forests (Table 1; Fig. 4). While not all harvested high-biomass forests are old growth, this continued harvest on public lands depletes the cohort of stands where old-growth characteristics can develop over time. In addition, fire and other natural disturbances in high-biomass forests transfer C from live biomass into dead biomass pool, but the total C store on site remains high, while logging moves C off-site leaving a greatly reduced total C store on forest land (Krankina and Harmon 2006).

Significant portions of high-biomass forests in the PNW that are vulnerable to additional losses are privately owned (Fig. 3). The biomass class map can help identify areas where privately owned high-biomass forests are concentrated and where targeted conservation incentives for private owners may be effective in protecting the diverse ecosystem services provided by high-biomass forests, especially long-term C storage (Foley et al. 2009). Studies of the effect of C price on private forest owner behavior in Western OR showed that even at a low C price some extension of harvest rotation can be expected (Im et al. 2007; Alig et al. 2010). In addition to slowing the losses of high-biomass forests and reducing associated C emissions, significant net sequestration of C can be expected from postponing harvest of relatively young and productive high-biomass forests on private lands (Krankina and Harmon 2006; Foley et al. 2009; Ryan et al. 2010). The incentives to postpone harvest can also help inform stakeholder's importance of protecting high-carbon forests for purposes of climate change mitigation.

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