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Washington's Forest Resources, 2007–2016: 10-Year Forest Inventory and Analysis Report

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Technical Editors

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Cover photo: Mountain stream running through a moist forest of western redcedar, Douglas-fir, and western hemlock near Desolation Peak in North Cascades National Park, Washington. Photo by Jessica Deans.

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Abstract

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The Forest Inventory and Analysis (FIA) program reports on the status and trends of Washington's forest resources, producing comprehensive updates every 5 years. This report provides detailed estimates of forest area, tree species composition and distribution, volume, biomass, carbon, standing dead trees and down wood, and understory vegetation on forest land for the state of Washington. It also includes estimates of annual growth, mortality, and removals on forest land. Estimates are based on inventory data collected on 6,112 forested FIA plots in Washington between 2007 and 2016. There are 22.5 million forested acres in Washington covering about half the state's land area. Washington has 9.4 billion live trees on forest land that collectively represent 94.3 billion ft^3 of net volume or 853.3 million Mg of carbon. The majority of this forest volume occurs on the moist west side of the state. Net change in volume on forest land was positive for all ownership groups in western Washington, but negative on National Forest System lands in eastern Washington, especially in wilderness areas. Statewide, net change in volume was 20 ft^3 ac^{-1} yr^{-1} or a total addition to net volume of 415 million ft^3 yr^{-1}.

Keywords: Biomass, carbon, dead wood, FIA, forest change, Forest Inventory and Analysis, forest land, inventory, timber volume, timberland, Washington.

Key Forest Inventory and Analysis (FIA) Statistics, Washington 2007–2016:

- Number of forested plots measured by the FIA program (2007–2016): 6,112
- Estimated total forest area: 22.5 million ac
- Estimated number of live trees: 9.4 billion
- Estimated net live tree volume: 94.3 billion ft^3
- Estimated aboveground live tree biomass: 1.9 billion tons
- Estimated aboveground live tree carbon: 853.3 million Mg
- Estimated annual net change in live tree volume: 490.8 million ft^3

Contents

Background

What Is Forest Inventory and Analysis?

The Forest Inventory and Analysis (FIA) program of the U.S. Forest Service was established in 1928 to provide comprehensive information on the nation's forest resources necessary for economic and forest management planning. Forest inventories were conducted periodically in each state until the Agricultural Research, Extension, and Education Reform Act of 1998 (the Farm Bill) mandated a nationally consistent methodology in which a portion of all plots in each state were measured each year. States in the Pacific Northwest Forest Inventory and Analysis (PNW-FIA) unit are on a 10-year measurement cycle, except in Hawaii and interior Alaska where inventories are conducted on a periodic basis.

How Does FIA Define a Forest?

FIA collects data only in forested areas; therefore, the definition used for forest land affects the estimates produced in each inventory year. The FIA program defines a forest as currently or formerly (within 30 years) at least 10 percent canopy cover of trees of any size and not currently developed for nonforest use. The area must be at least 1 ac in size where a minimum width of 120 ft is maintained. Prior to 2013, the FIA program used stocking tables to define forest based on a minimum of 10-percent stocking rather than canopy cover. This procedural change affects a small percentage of sampled plots, and estimates of forest land area-change between 2002–2006 and 2012–2016 have been adjusted to consistently use the current definition. The PNW-FIA collected information on forested lands using both definitions to allow calibration between estimates.

What are the differences between timberland, reserved forest land, and other forest land?—

- Timberland: Forest land that is producing or is capable of producing crops of industrial wood and not withdrawn from timber utilization by statute or administrative regulation. (Note: Areas qualifying as timberland are capable of producing in excess of 20 ft^3 ac^{-1} yr^{-1} of industrial wood in natural stands. Currently inaccessible and inoperable areas are included.)
- Reserved forest land: Forest land permanently reserved from wood products utilization through statute or administrative designation. Examples include National Forest System (NFS) wilderness areas and national parks and monuments.
- Other forest land: Forest land not capable of producing 20 ft^3 ac^{-1} yr^{-1} of wood, often occurring on sites with poor soils.

What Is in This Report?

This report presents a summary of Washington's forest resources, highlighting key forest characteristics estimated from inventory field plots sampled across the state over the 10-year period from 2007 through 2016. It also includes the first set of remeasurement data from the FIA annual inventory of Washington (plots measured for the second time between 2012 and 2016). Estimates presented here are an update to prior estimates reported in Campbell et al. 2010 and Holgerson et al. 2018 and are based on field measurements of 6,112 forested plots; 2,853 have now been remeasured and can be used to assess change in forest conditions (fig. 1). We present estimates of current forest area, ownership, composition, volume, and distribution, as well as information on growth, mortality, and removals. We also provide information on forest health based on observations of forest pathogens and stands affected by fires, and we include information on understory vegetation and down woody debris in Washington's forests.

An extensive set of 125 summary data tables accompanies this report and can be downloaded from the Web at https://www.fs.fed.us/pnw/pubs/pnw_gtr976-supplement.pdf. These tables provide estimates of forest area, number of trees, volume, biomass, carbon, forest change, NFS summaries, down wood, understory vegetation, tree damages, and timber products output for the state. A complete list of online tables is available at the end of this report.

Where Can I Find Additional Information?

Campbell et al. 2010 and Holgerson et al. 2018 provided detailed information on annual inventory methods and definitions as well as prior forest inventories in Washington. The PNW-FIA website (https://www.fs.fed.us/pnw/rma/) has up-to-date reports and statistics for each state in the PNW-FIA unit and field guides that include PNW-FIA regional variables. Most of the data used in this report are accessible through the Forest Inventory and Analysis Database (PNW-FIADB) application (requires Microsoft Access™)[1], which contains both national core data and regional variables collected only by the PNW-FIA unit.

The main Web page for FIA is at https://www.fia.fs.fed.us/. Links lead to resources such as publications or data and tools. EVALIDator and DATIM are the primary estimation tools that allow users to generate custom summaries from the most recent data in FIADB. Definitions of tables and fields are available in the FIADB user manual (O'Connell et al. 2017), and core FIA field guides contain details on how each data item was collected. A glossary of FIA terms can be found at https://www.nrs.fs.fed.us/fia/data-tools/state-reports/glossary/default.asp.

[1] The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Jessica Deans

Figure 1—Field crews measured 6,112 forested plots in Washington from 2007 to 2016. Measuring a tree diameter in Olympic National Park.

Forest Resources

Importance of Washington's Forests

Known as the Evergreen State, Washington has a rich history of abundant evergreen forests, also called conifers or softwoods. Washington's temperate rainforests contain some of the oldest and tallest trees in the country and store more aboveground biomass than most other forest ecosystems worldwide (Keith et al. 2009). The Evergreen name also references the importance of timber in the state's early history, and the forest products industry continues to be important to Washingtonians, especially those in rural communities. As the state's population grows, so does demand for quality forest recreation opportunities. Ecosystem services and benefits to society provided by forests include timber production, carbon storage, water regulation, aesthetic amenities, recreation, and wildlife (Binder et al. 2017, Boyd and Banzhaf 2007). Forest lands across Washington state are managed to balance these ecosystem services and other priorities.

Forest Area and Composition

Washington currently has an estimated 22,120,300 forested ac (table 1) that cover 52 percent of the state's total land area (excluding census water). Timberland area (the unreserved, productive component of forest land) is estimated at 17,791,200 ac, and reserved forest land covers 3,802,400 ac or approximately 9 percent of the state's land area (fig. 2). Forest surveys in Washington began in the 1930s, and estimates are available for comparison over time, but it is important to note that survey methods and the land included in forest or timberland definitions differed prior to 2000 so trends reflect a combination of real forest changes and sampling artifacts (fig. 3). The dip in forest and timberland area shown in figure 3 during the 1990s is likely affected more by sampling differences than by land use change. Since 2006, forest land area in Washington has decreased by around 50,000 ac, a loss of 0.02 percent annually.[2]

The majority (86 percent) of forest area in Washington occurs as conifer forest types. Hardwood forest types cover 10 percent of forest land, and the remaining 4 percent is nonstocked (forested areas that currently lack 10-percent tree cover, typically because of recent disturbance). Note that forest types refer to the dominant species in a stand but may contain a diverse species mix. Douglas-fir forest types are the most prevalent, covering 8,875,500 ac or 40 percent of all forest land. Fir/spruce/mountain hemlock (17 percent) and hemlock/Sitka spruce (14 percent) also

[2] Gray, A. Unpublished analysis. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331.

Table 1—Area of forest land, by ownership and land status, Washington, 2007–2016

	Land status													
	Unreserved forests						Reserved forests							
	Timberland		Other forest		Total		Productive		Other forest		Total		All forest land	
All Washington ownership	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	Thousand acres													
U.S. Forest Service	5,701.2	40.9	290.1	21.8	5,991.3	35.7	1,776.2	61.4	525.4	55.4	2,301.6	51.0	8,292.8	51.2
Other federal government:														
Bureau of Land Management	46.6	15.2	8.7	7.5	55.3	16.7	—	—	—	—	—	—	55.3	16.7
Departments of Defense or Energy	62.3	19.4	—	—	62.3	19.4	—	—	—	—	—	—	62.3	19.4
National Park Service	—	—	—	—	—	—	1,068.6	41.3	117.4	25.4	1,186.0	39.3	1,186.0	39.3
U.S. Fish and Wildlife Service	—	—	—	—	—	—	93.5	19.8	4.4	5.4	97.8	20.3	97.8	20.3
Other federal	36.8	14.4	—	—	36.8	14.4	20.5	11.8	11.4	8.7	32.0	14.4	68.7	20.4
Total	145.7	28.5	8.7	7.5	154.4	29.4	1,182.5	41.2	133.2	27.0	1,315.7	38.0	1,470.1	43.9
State and local government:														
Local	376.4	46.3	13.3	7.9	389.6	46.9	67.7	20.1	—	—	67.7	20.1	457.4	50.8
State	2,317.5	57.3	16.8	9.4	2,334.3	57.3	106.6	24.5	10.8	8.0	117.4	25.8	2,451.7	53.3
Other public	12.5	8.8	—	—	12.5	8.8	—	—	—	—	—	—	12.5	8.8
Total	2,706.3	71.1	30.0	12.3	2,736.4	71.5	174.4	31.4	10.8	8.0	185.1	32.5	2,921.5	69.1
Corporate private	4,693.3	121.8	66.9	19.2	4,760.2	122.6	—	—	—	—	—	—	4,760.2	122.6
Noncorporate private:														
Nongovernmental conservation or natural resource organizations	190.8	33.5	2.2	2.1	193.0	33.6	—	—	—	—	—	—	193.0	33.6
Unincorporated partnerships, associations, or clubs	24.7	11.0	—	—	24.7	11.0	—	—	—	—	—	—	24.7	11.0
American Indian	1,848.7	95.6	40.7	14.8	1,889.4	96.6	—	—	—	—	—	—	1,889.4	96.6
Individual	2,480.5	102.9	88.1	21.4	2,568.6	104.5	—	—	—	—	—	—	2,568.6	104.5
Total	4,544.7	124.2	131.0	26.0	4,675.7	125.3	—	—	—	—	—	—	4,675.7	125.3
All private	9,238.0	112.8	197.9	32.2	9,435.9	111.7	—	—	—	—	—	—	9,435.9	111.7
All owners	17,791.2	117.2	526.8	41.5	18,317.9	114.0	3,133.0	80.3	669.4	62.1	3,802.4	71.4	22,120.3	119.5

Note: Totals may be off because of rounding; data are subject to sampling error; SE = standard error; — = less than 50 ac was estimated.

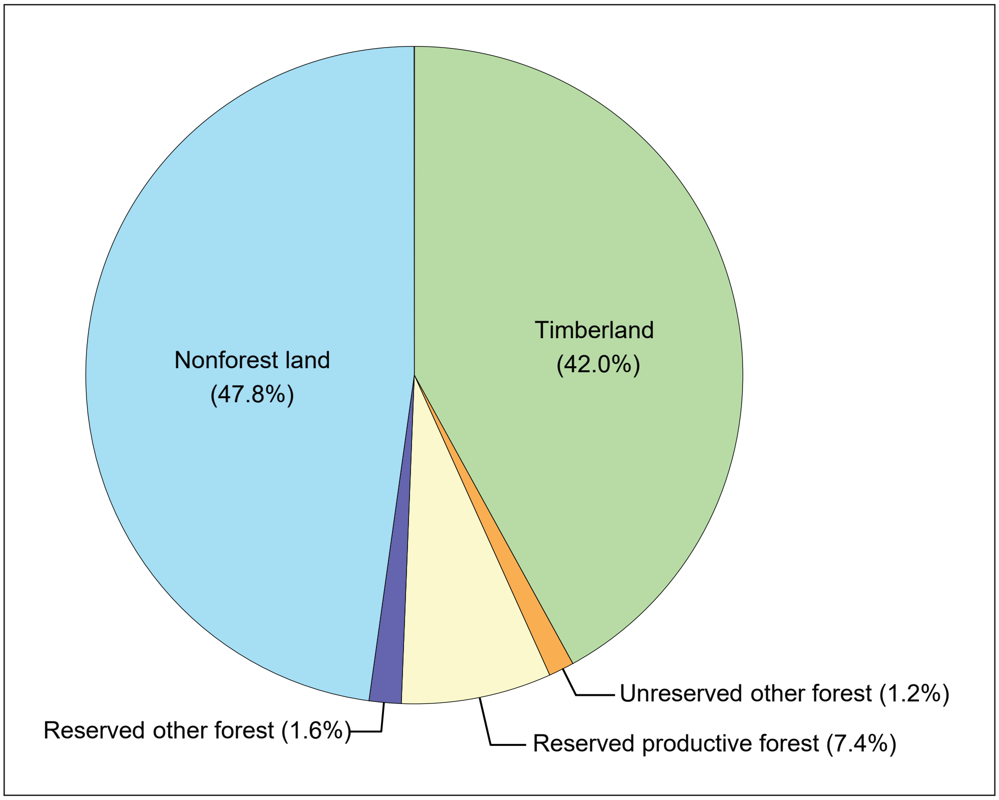

Figure 2—Forest Inventory and Analysis area classification by land class category, Washington, 2007–2016.

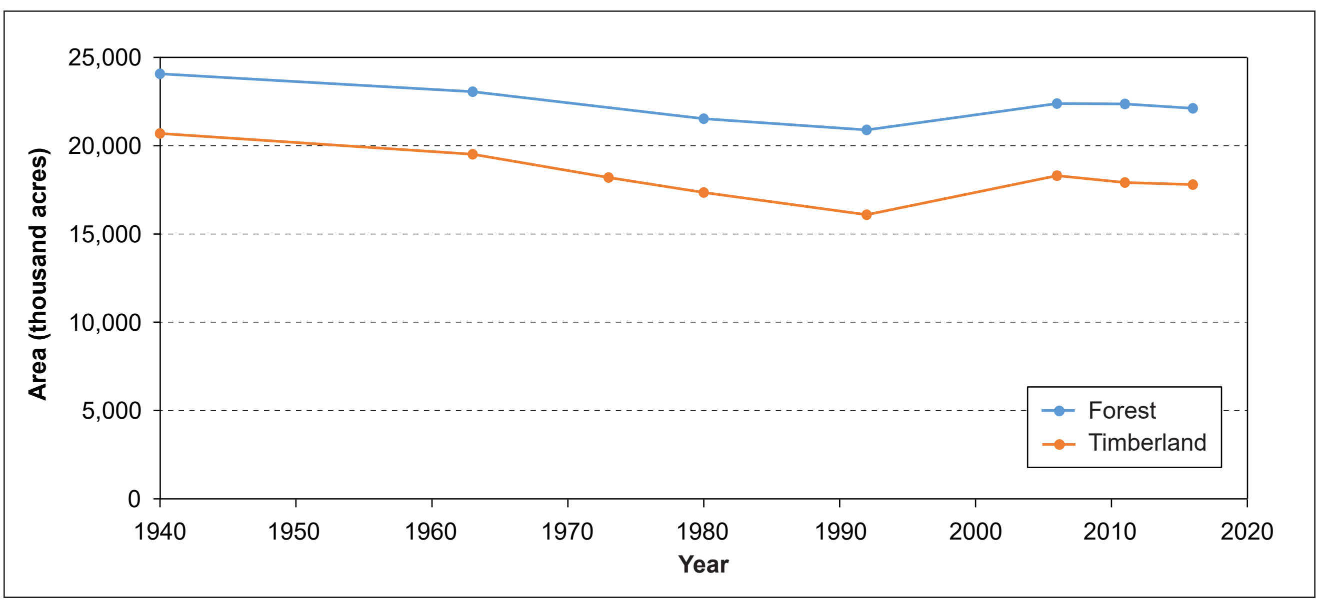

Figure 3—Area of forest land and timberland (thousand acres) by inventory year in Washington, 1940–2016. Note that estimates from 2000 to 2016 are based on the annual inventory design and protocols, while prior estimates were based on periodic inventories that used different designs and methods (Bassett and Choate 1974; Bassett and Oswald 1981a, 1981b, 1982, 1983; Bolsinger et al. 1997; Cowlin and Moravets 1940; Metcalf 1965). Differences shown here represent a combination of real change, wilderness designations that placed timberland into reserved status, and protocol differences over time such as the use of stockability factors during periodic inventories.

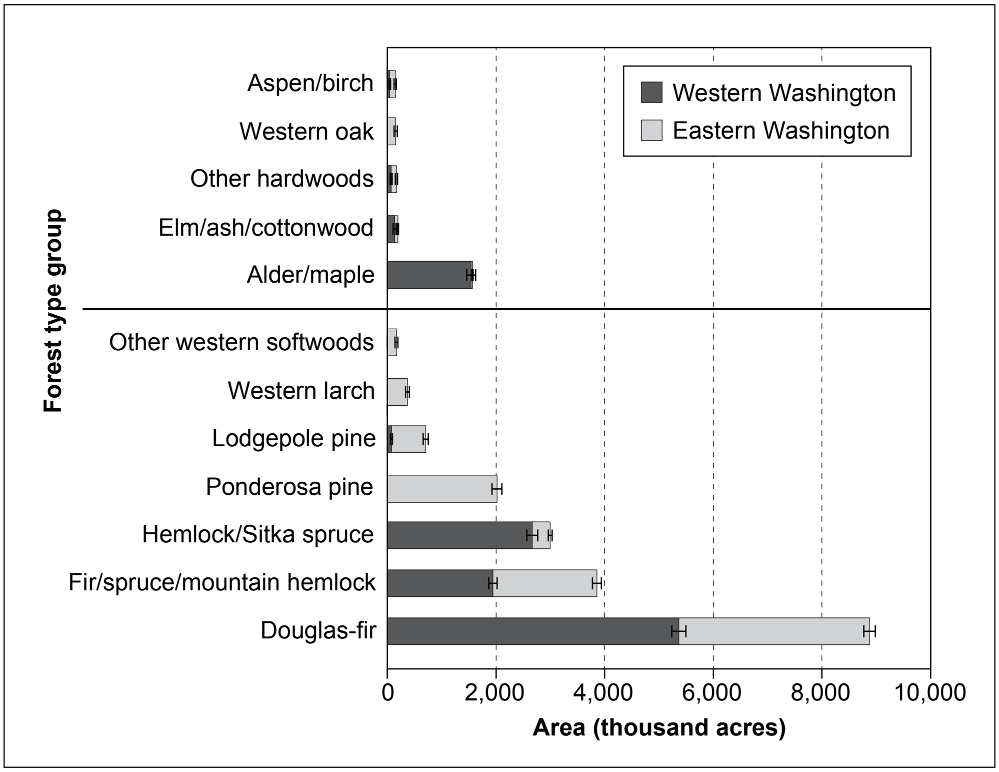

Figure 4—Area of softwood and hardwood forest type groups in eastern and western Washington, 2016.

cover significant forest land area (fig. 4). Western Washington has slightly more forested area (12 million ac) than eastern Washington (10 million ac). Forests west of the Cascade Range crest are dominated by Douglas-fir, hemlock/Sitka spruce, and alder/maple types, while eastern Washington has considerable Douglas-fir but also more than 2 million ac of ponderosa pine forest types. Fir/spruce/mountain hemlock forests grow at high elevations and are evenly distributed between the east and west sides of the Cascade crest (fig. 5).

Forests in Washington encompass a broad range of size and age classes. Species growth habits, forest management, and natural disturbances all affect stem diameter and stand age distributions. Young plantations of Douglas-fir and other species are intensively managed and have high growth rates. Intact old-growth stands dominated by large, old trees with some individuals more than 1,000 years old are also an important component of the state's forests. Two-thirds of Washington's forest area is composed of stands less than 100 years old, but 11 percent (2.4 million ac) is composed of stands greater than 200 years old (fig. 6). Fir/spruce/mountain hemlock (fig. 7) and hemlock/sitka spruce forest types have the largest share of their distributions as older stands, each with more than 20 percent of forested area more than 200 years old (fig. 8).

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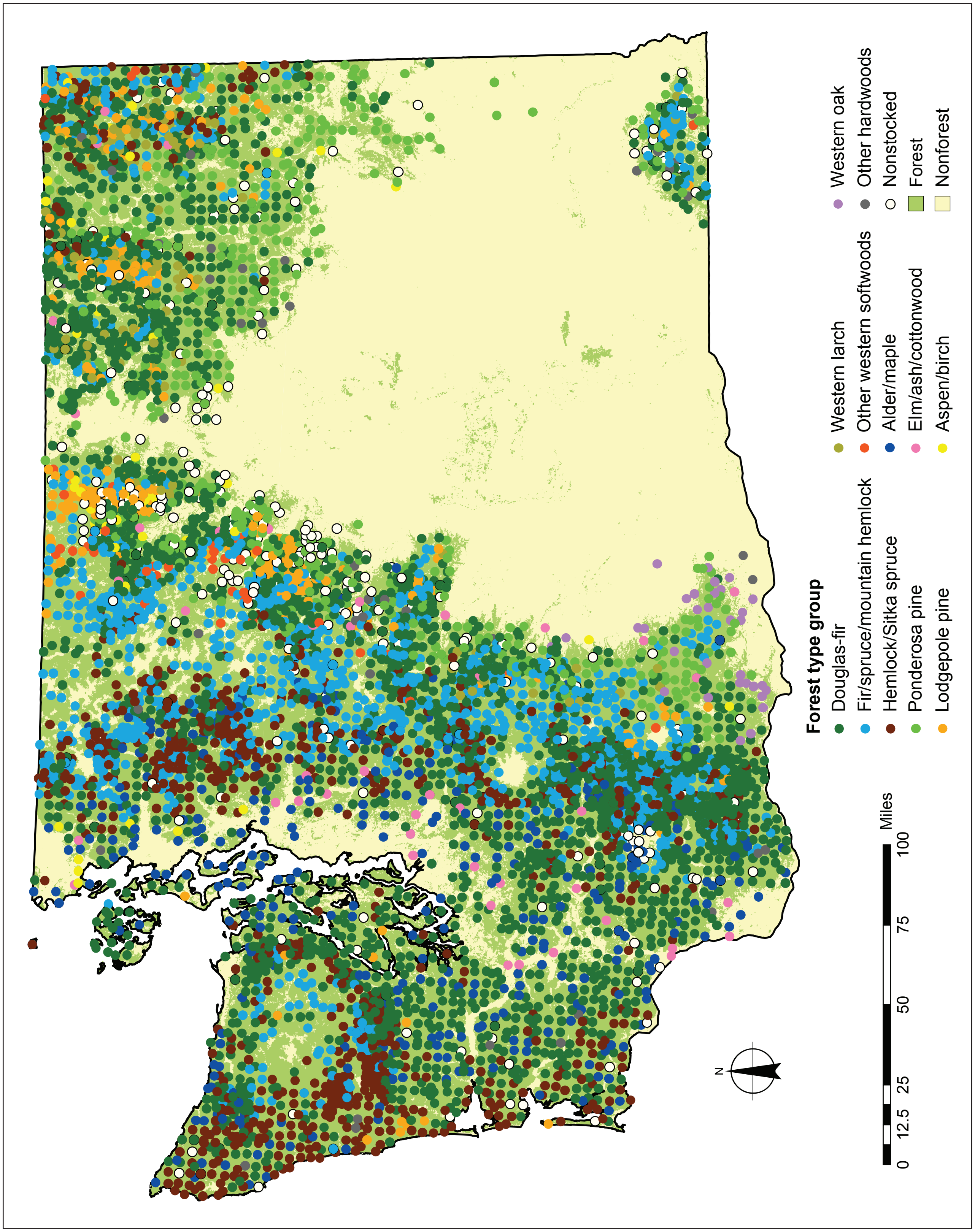

Figure 5—Distribution of forest type groups based on field observations at Forest Inventory and Analysis sample sites, Washington, 2007–2016 (forest/nonforest geographic information system layer: Blackard et al. 2008).

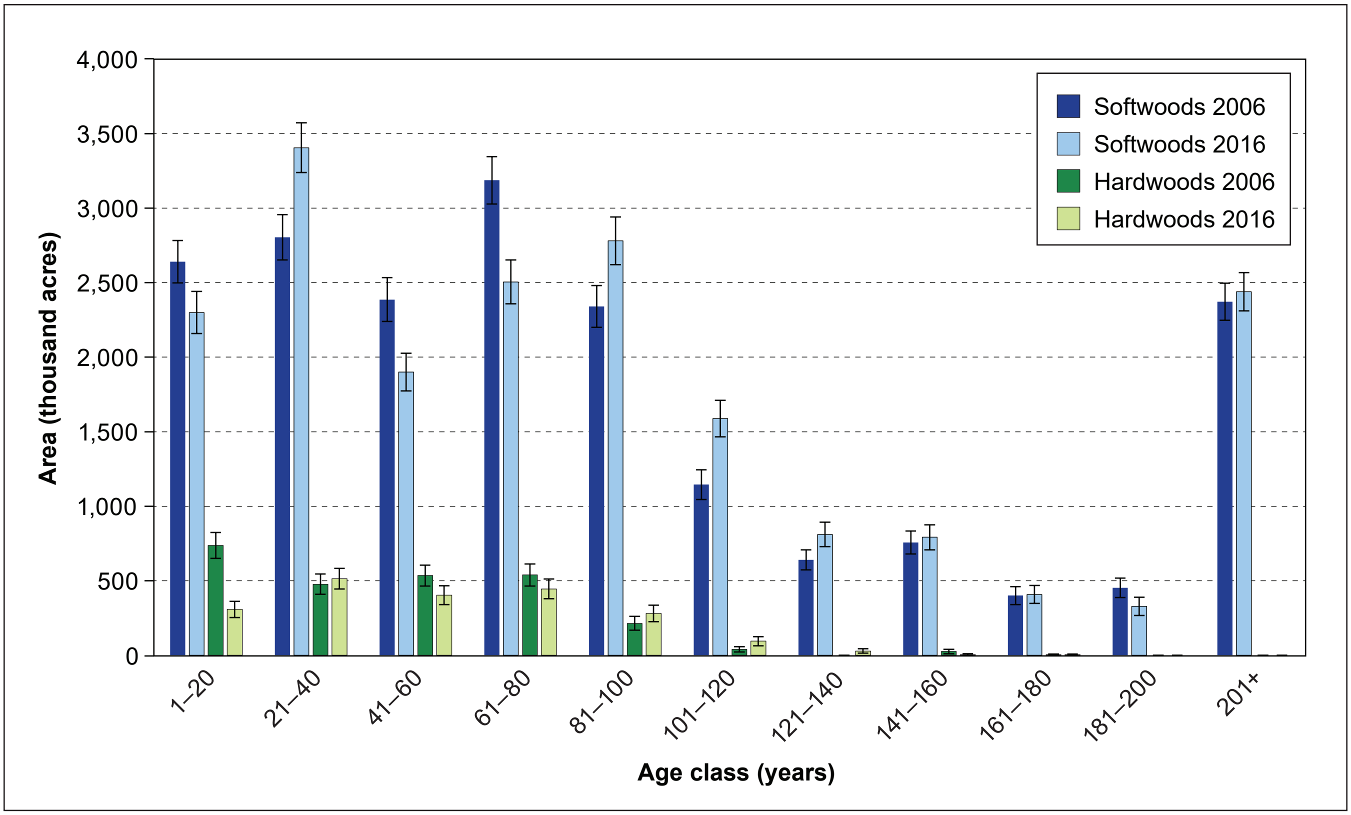

Figure 6—Stand age distribution for softwoods and hardwoods in Washington, 2006 and 2016. To ensure that the estimates are comparable, the 2016 estimates include only plots that were remeasured in 2012–2016. Therefore, they differ from the 2007–2016 estimates discussed elsewhere in this report.

More than 9.3 billion individual live trees (excluding seedlings less than 1 inch diameter at breast height [d.b.h.]) make up Washington's 22 million forested acres. This amounts to 424 trees per forested acre on average. True firs and Douglas-fir each account for more than 2.1 billion trees, collectively making up nearly half (46 percent) of all trees in the state. Western hemlock accounts for 19 percent. Lodgepole pine and red alder are more frequent among the smaller diameter classes, while western redcedar makes up a larger proportion of diameter classes above 40 inches d.b.h. (fig. 9).

Figure 7—Twenty-five percent of fir/spruce/mountain hemlock stands in Washington are more than 200 years old, such as this stand on the Gifford Pinchot National Forest.

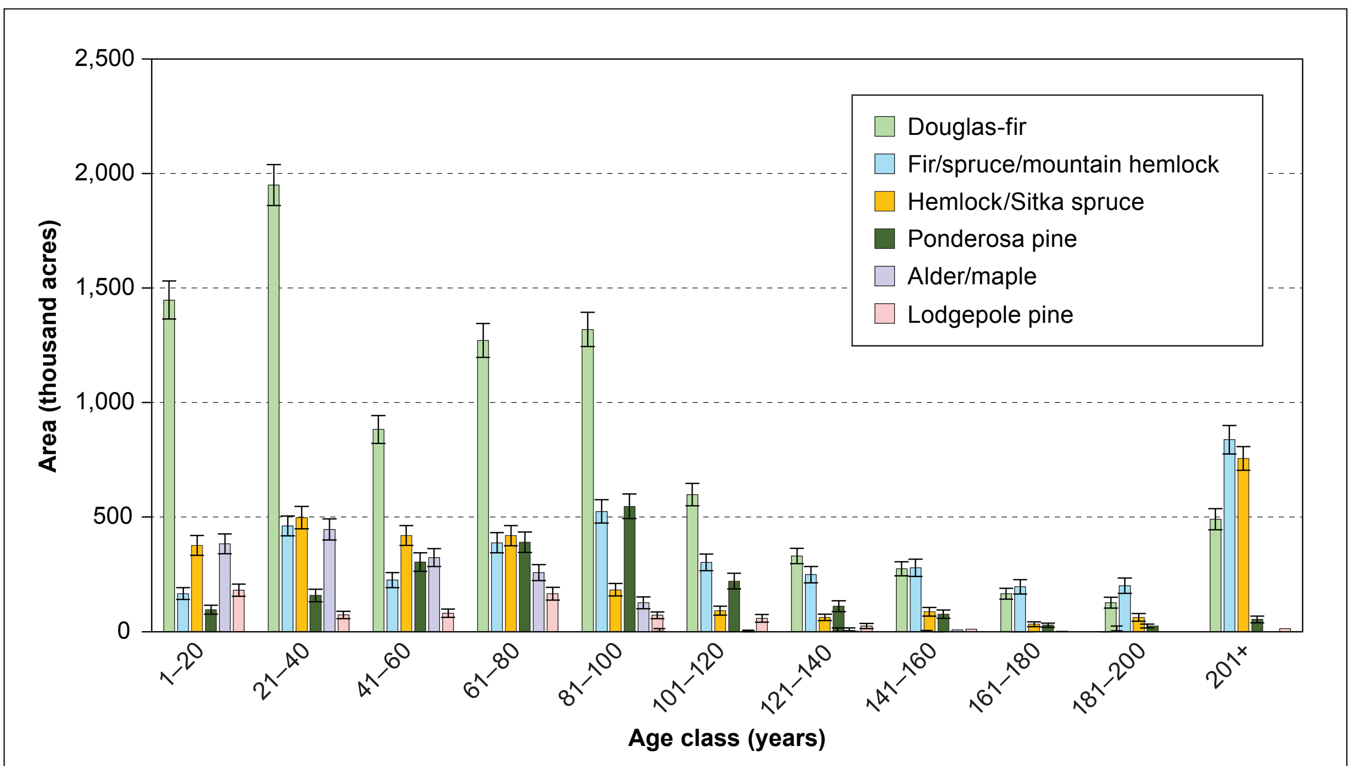

Figure 8—Stand age distributions of the six forest types with the greatest forest land area in Washington, 2007–2016.

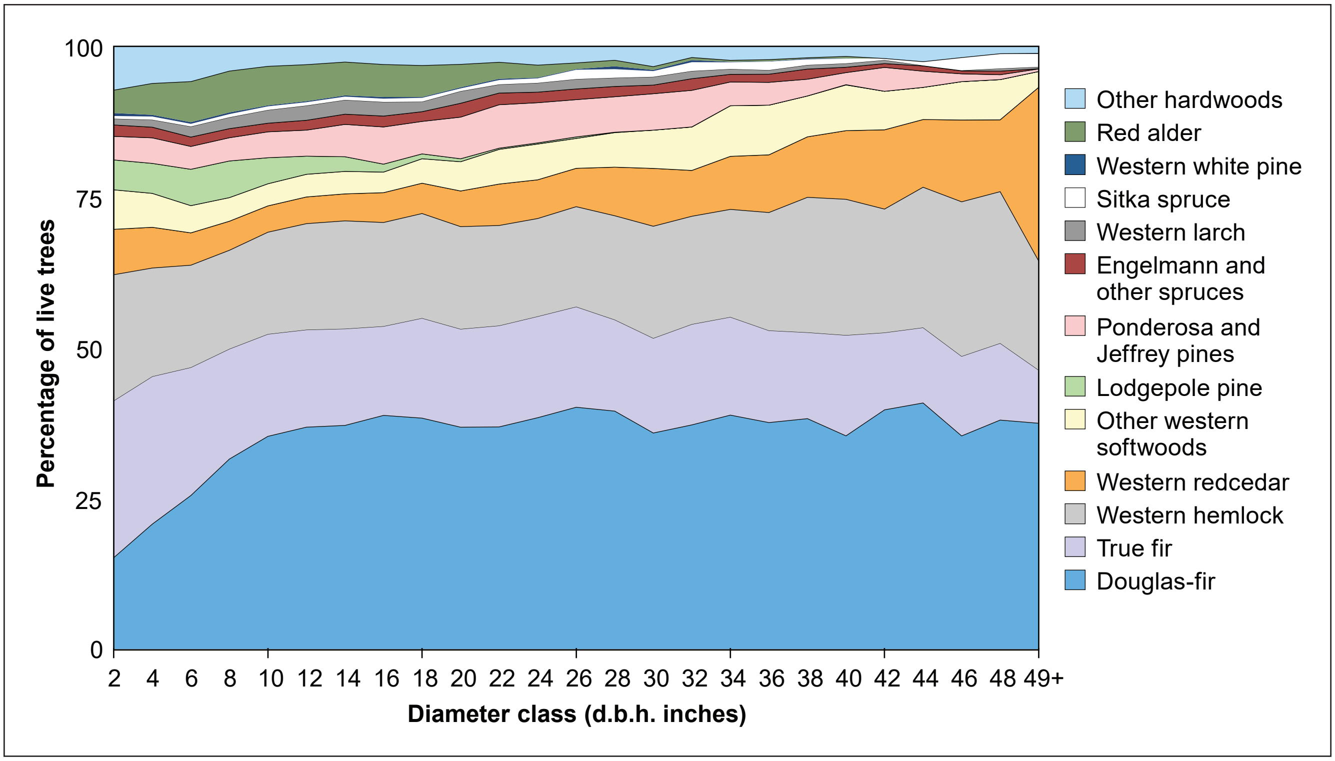

Figure 9—Proportional species composition for individual trees on forest land by diameter class, Washington 2007–2016. Value shown on the horizontal axis represents the midpoint of the 2-inch diameter class, i.e., 6 inches refers to trees with diameters of 5 to 6.9 inches. d.b.h. = diameter at breast height.

Forest Ownership

Forest land in Washington State is distributed among a variety of private forest owners and public land management agencies (table 1; fig. 10). Fifty-seven percent is publicly administered (fig. 11), while more than 9 million ac (43 percent) are held privately. Half of Washington's private forests are owned by corporations that tend to manage their land more intensively, with timber harvest as a primary objective. Therefore, average stand age and tree diameters tend to be less on corporate private lands. For example, average live tree net volume is 2,857 ft^3 ac^{-1} on private forest lands compared to 4,263 ft^3 ac^{-1} across all forest land. Noncorporate private owners include families and individuals, American Indian tribes, various partnerships, and nongovernmental organizations. The National Woodland Owner Survey, a partnership of the FIA program, provides information on the history and future of private forest management in Washington and throughout the United States; visit https://www.fia.fs.fed.us/nwos/ for more information of this program.

Major public forest land managers in Washington include the NFS, National Park Service, and Washington Department of Natural Resources (WDNR). The NFS covers more than 8 million forested acres in Washington and carries 42 percent of the state's live tree net volume. More than two-thirds of NFS land is

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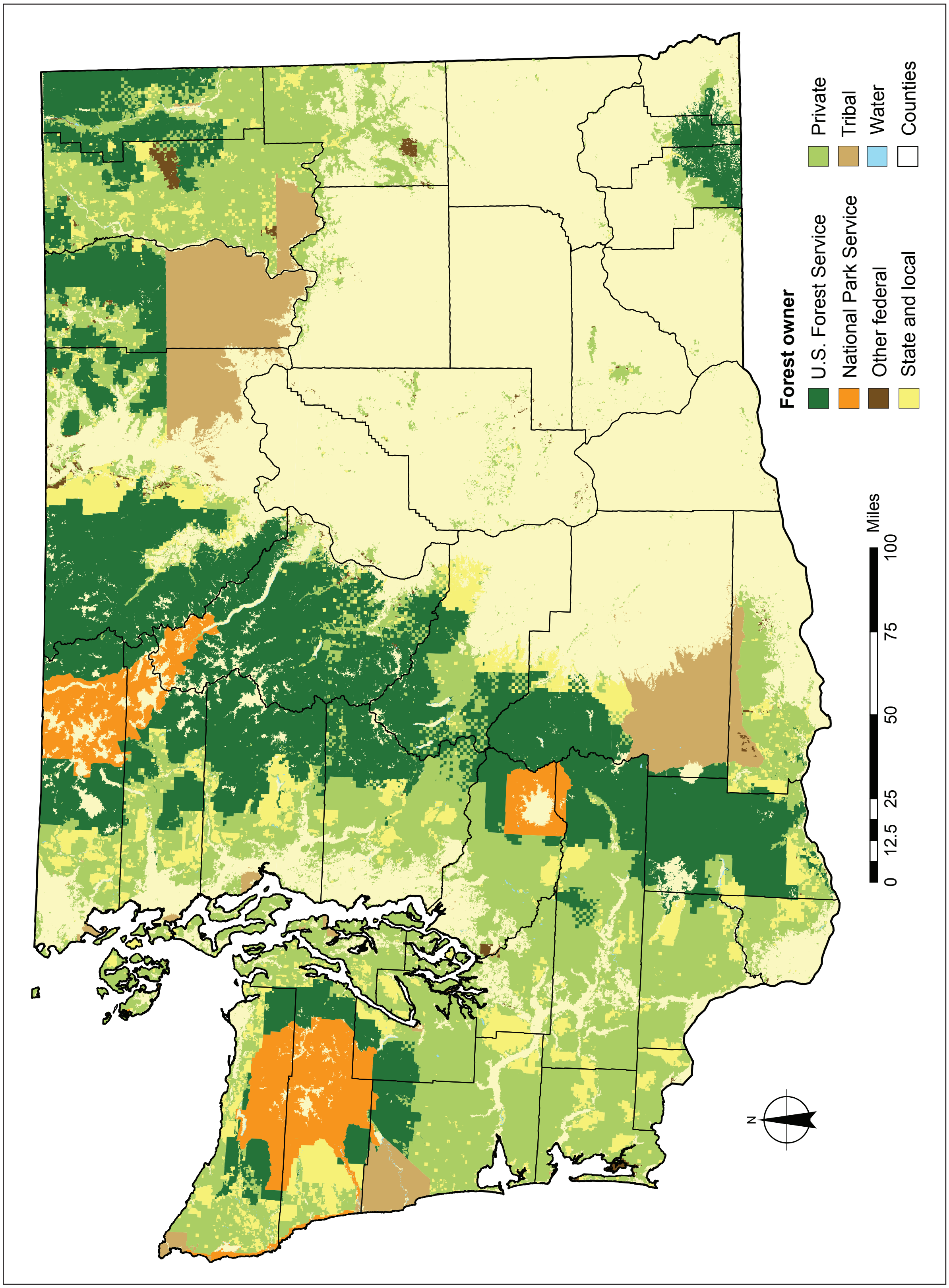

Figure 10—Washington forest ownership categories (forest/nonforest geographic information system layer: Blackard et al. 2008, ownership polygon: Bureau of Land Management, Oregon/Washington State Office).

Figure 11—Collecting field measurements on public forest land on the Olympic Peninsula managed by the Washington Department of Natural Resources.

classified as productive timberland, while 28 percent is in designated reserves such as wilderness areas and Wild and Scenic River corridors. Olympic, Mount Rainier, and North Cascades National Parks, which have a mission of wilderness preservation, make up 5 percent of the state's forest land yet contain 12 percent of its live tree net volume. Eleven percent of Washington's forest area is in state forests managed by WDNR. The 2.1 million ac of working forests on state trust land are managed to provide habitat, clean water, and revenue to support public schools and other beneficiaries (WDNR 2018a).

Forest ownership patterns differ east and west of the Cascade crest (fig. 12). Private corporations are the largest forest owner in western Washington, closely followed by the NFS. Half of eastern Washington's forest land is managed by federal agencies, mostly in the NFS. Private noncorporate landowners own 30 percent of eastern Washington forest land. These landowners, primarily American Indian tribes and families or individuals, manage their forests for a wide variety of objectives.

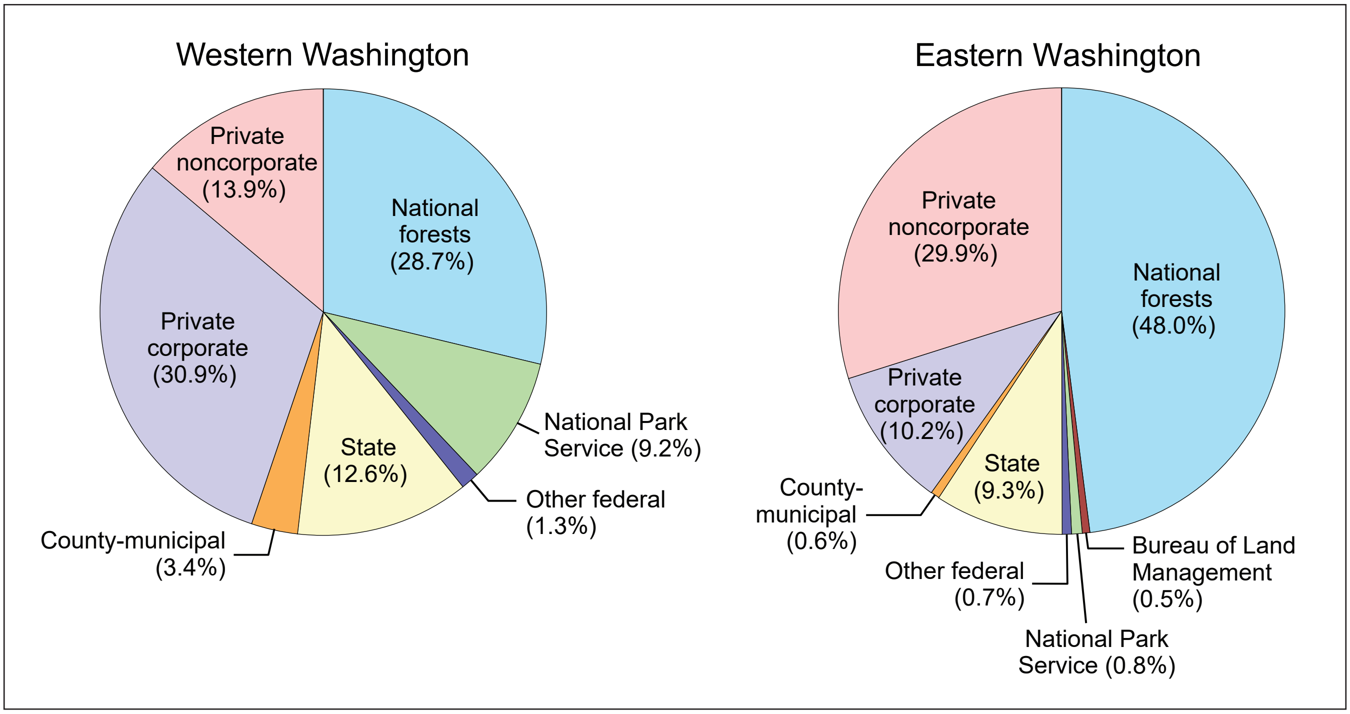

Figure 12—Percentage of forest land by owner group in western and eastern Washington, 2007–2016.

Forest Volume

FIA volume estimates are typically calculated by species, using measurements of a tree's diameter and height (Woodall et al. 2011). Forest volume provides a direct measure of standing timber availability and serves as the basis for estimates of change such as growth, removals, and mortality.

Live tree net volume has remained essentially constant over the past 10 years; estimates in 2006 and 2016 were around 94 billion ft^3. Although total volume has remained fairly constant, the share of volume in the highest volume species (Douglas-fir) has increased from 37 to 42 percent (fig. 13). Ten- to 20-inch diameter classes contain the most live tree volume because of the sheer number of trees in this d.b.h. range. Both Douglas-fir and western redcedar have considerable volume in trees larger than 49 inches d.b.h (1,789 and 1,170 million ft^3, respectively) (fig. 14). Roughly three-fourths of live tree volume is in productive timberlands, while the remaining fourth is in reserved areas. More than 50 percent of live tree volume is on federally managed lands (table 2). Volume per acre varies considerably across and within forest types because of site characteristics and histories of stand disturbance or management. Statewide, forest volume averages 4,263 ft^3 ac^{-1}. Hemlock/ Sitka spruce forest types average 7,548 ft^3 ac^{-1} and tend to contain some of the largest, oldest trees in the state (fig. 15).

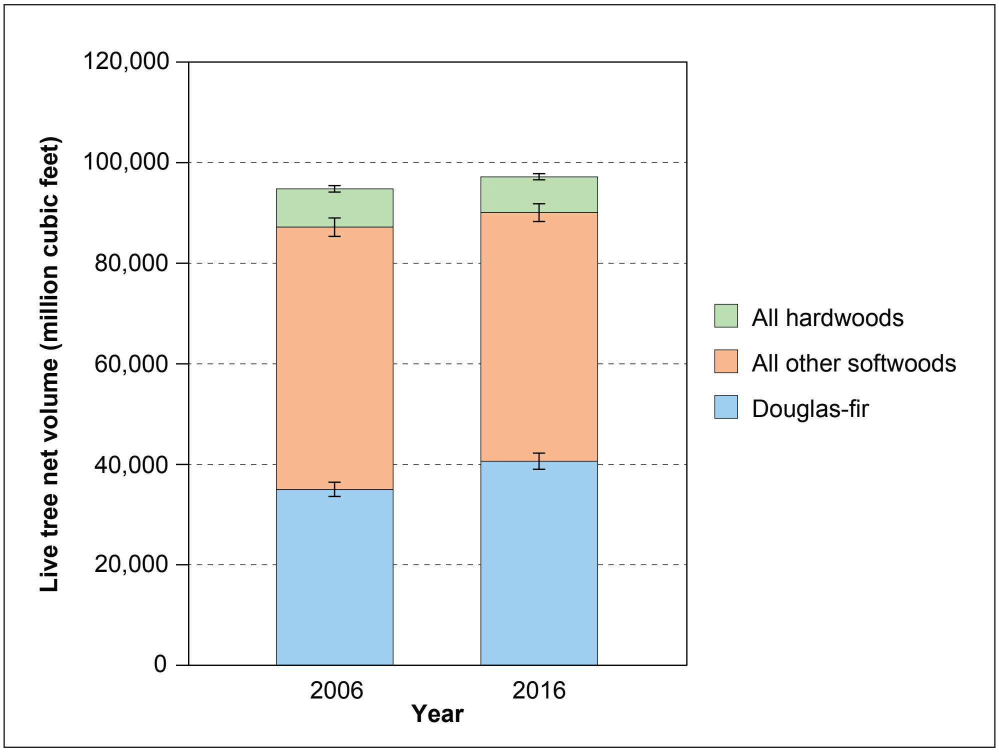

Figure 13—Live tree net volume of softwoods and hardwoods in Washington, 2006 and 2016. To ensure that the estimates are comparable, the 2016 estimates include only plots that were remeasured in 2012–2016. Therefore, they differ from the 2007–2016 estimates discussed elsewhere in this report.

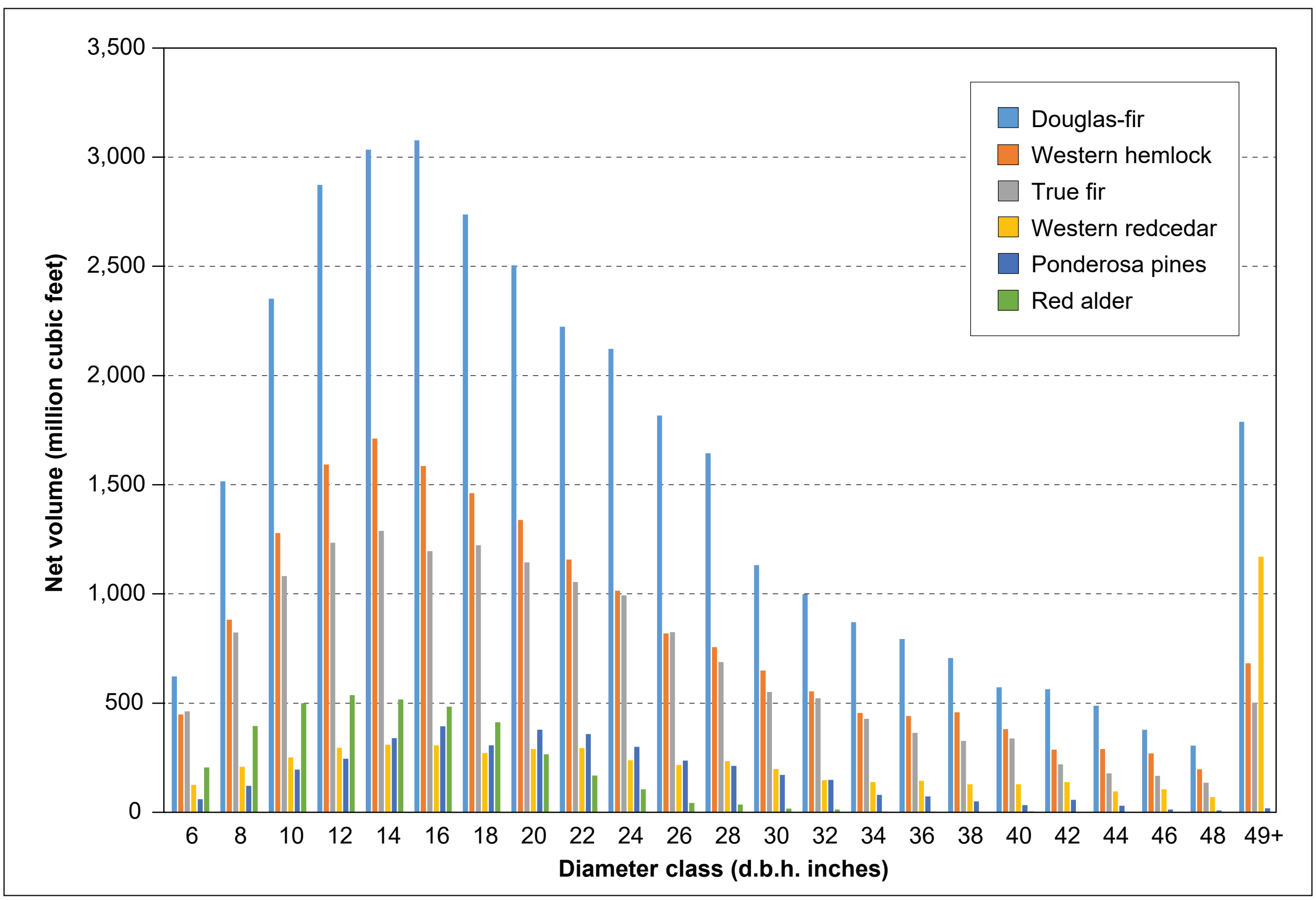

Figure 14—Diameter-class distribution of live tree net volume on forest land, six highest volume species groups, Washington, 2007–2016. d.b.h. = diameter at breast height.

Table 2—Net volume of live trees[a] on forest land, by ownership and land status, Washington, 2007–2016

	Land status													
	Unreserved forests						Reserved forests							
	Timberland		Other forest		Total		Productive		Other forest		Total		All forest land	
Ownership	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
							Million cubic feet							
U.S. Forest Service	28,021.5	389.6	526.1	63.6	28,547.6	385.3	10,217.3	587.9	1,166.3	231.6	11,383.7	573.3	39,931.3	667.7
Other federal government:														
Bureau of Land Management	119.8	53.6	4.4	3.8	124.2	53.7	—	—	—	—	—	—	124.2	53.7
Departments of Defense or Energy	422.6	155.6	—	—	422.6	155.6	—	—	—	—	—	—	422.6	155.6
National Park Service	—	—	—	—	—	—	10,894.9	537.3	446.4	153.0	11,341.3	518.5	11,341.3	518.5
U.S. Fish and Wildlife Service	—	—	—	—	—	—	484.0	121.6	0.9	1.1	484.9	121.5	484.9	121.5
Other federal	297.5	129.0	—	—	297.5	129.0	214.1	122.8	54.6	41.6	268.7	128.5	566.2	182.1
Total	839.8	208.6	4.4	3.8	844.2	208.6	11,592.9	540.0	501.9	156.4	12,094.9	514.8	12,939.1	551.4
State and local government:														
Local	2,045.4	312.3	57.8	39.8	2,103.2	314.6	340.0	118.3	—	—	340.0	118.3	2,443.2	334.7
State	11,080.1	505.8	54.9	39.8	11,135.0	506.1	806.7	220.2	10.4	8.6	817.1	220.5	11,952.1	506.6
Other public	68.2	59.3	—	—	68.2	59.3	—	—	—	—	—	—	68.2	59.3
Total	13,193.8	589.4	112.7	56.3	13,306.4	590.8	1,146.7	249.6	10.4	8.6	1,157.1	249.8	14,463.5	598.0
Corporate private	13,648.3	549.8	101.7	41.0	13,750.0	551.1	—	—	—	—	—	—	13,750.0	551.1
Noncorporate private:														
Nongovernmental conservation or natural resource organizations	540.8	129.0	9.3	8.9	550.1	129.3	—	—	—	—	—	—	550.1	129.3
Unincorporated partnerships, associations, or clubs	195.3	99.6	—	—	195.3	99.6	—	—	—	—	—	—	195.3	99.6
American Indian	4,643.2	347.2	66.0	47.7	4,709.2	350.0	—	—	—	—	—	—	4,709.2	350.0
Individual	7,627.8	460.7	127.0	40.2	7,754.8	461.7	—	—	—	—	—	—	7,754.8	461.7
Total	13,007.1	556.9	202.3	63.0	13,209.4	558.6	—	—	—	—	—	—	13,209.4	558.6
All private	26,655.4	649.4	304.0	75.0	26,959.4	649.2	—	—	—	—	—	—	26,959.4	649.2
All owners	68,710.5	906.0	947.1	113.3	69,657.6	903.1	22,957.0	836.3	1,678.7	279.6	24,635.6	810.0	94,293.2	1,169.9

Note: Totals may be off because of rounding; data are subject to sampling error; SE = standard error; — = less than 50,000 ft^3 was estimated.
[a] Includes all live trees ≥1 inch diameter at breast height, consisting of growing stock, rough cull, and rotten cull tree classes.

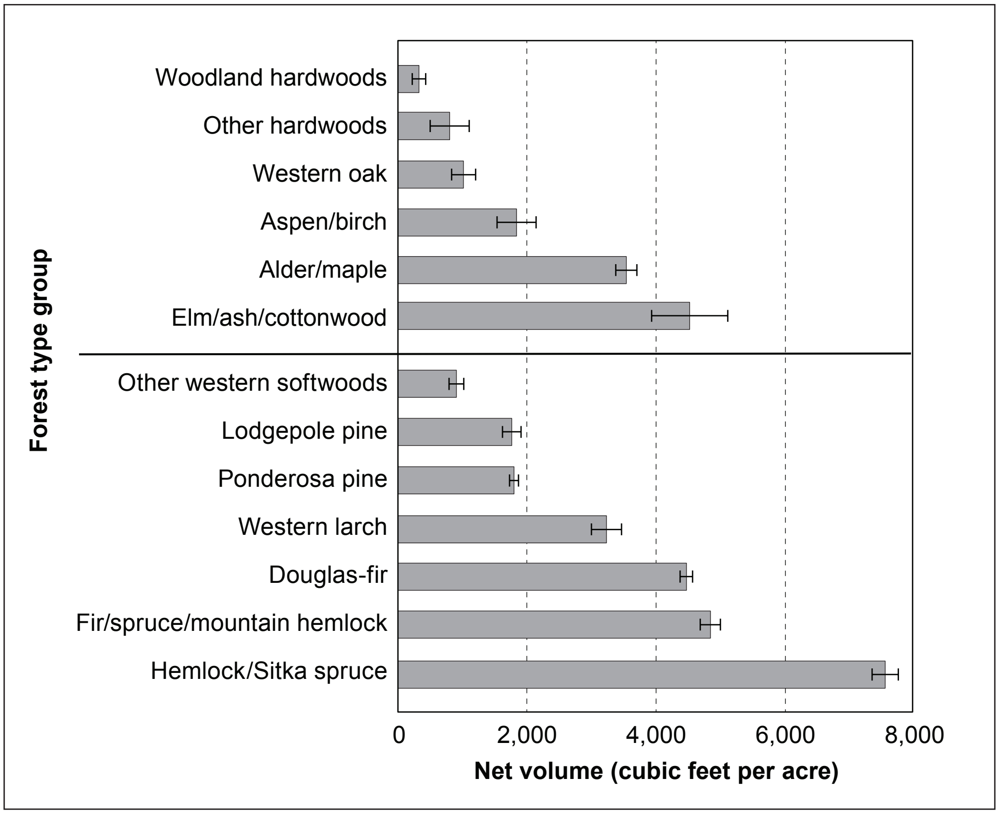

Figure 15—Average net live tree volume per acre on forest land by forest type group, Washington, 2007–2016.

Forest Biomass and Carbon Storage

Forests in Washington have 1,882 million tons of aboveground live tree biomass plus an additional 232 million tons in standing dead trees. More than 40 percent of live tree biomass is on NFS land and 29 percent is on private forest land. Conifer species account for 92 percent of biomass statewide, with 42 percent of all live biomass in Douglas-fir forest types (fig. 16). The moist west side of the state holds 73 percent of live tree biomass despite forest area being relatively equal east and west of the Cascade crest.

Carbon mass of live trees is proportional to biomass; on average, tree boles and coarse roots are assumed to be 50 percent carbon by dry weight (Chapin et al. 2002, Fahey et al. 2005). Carbon mass is used to determine forest carbon stocks and the flux of carbon between atmospheric and terrestrial carbon pools. In Washington, there are 854 million Mg of aboveground carbon[3] stored in live trees (table 3). Large-diameter

[3] Metric units are used for carbon mass to remain consistent with accepted accounting practices.

Jessica Deans

Figure 16—The vast majority of Washington's forest biomass is in conifers such as this stand in Olympic National Park.

Table 3—Aboveground carbon mass[a] of live trees[b] on forest land, by ownership and land status, Washington, 2007–2016

	Land status													
	Unreserved forests						Reserved forests							
	Timberland		Other forest		Total		Productive		Other forest		Total		All forest land	
Ownership	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	Thousand megagrams													
U.S. Forest Service	254,720.1	3,313.6	5,152.1	605.5	259,872.2	3,265.8	89,781.0	5,012.2	11,292.7	2,048.7	101,073.7	4,849.6	360,945.9	5,631.3
Other federal government:														
Bureau of Land Management	1,132.1	462.6	54.2	49.8	1,186.3	464.5	—	—	—	—	—	—	1,186.3	464.5
Departments of Defense or Energy	3,668.2	1,337.4	—	—	3,668.2	1,337.4	—	—	—	—	—	—	3,668.2	1,337.4
National Park Service	—	—	—	—	—	—	97,064.3	4,710.0	4,384.0	1,439.7	101,448.4	4,549.6	101,448.4	4,549.6
U.S. Fish and Wildlife Service	—	—	—	—	—	—	4,300.5	1,063.6	16.9	21.0	4,317.4	1,062.8	4,317.4	1,062.8
Other federal	2,415.2	1,050.2	—	—	2,415.2	1,050.2	2,031.3	1,168.2	428.6	326.3	2,460.0	1,204.8	4,875.1	1,598.3
Total	7,215.4	1,758.6	54.2	49.8	7,269.6	1,759.2	103,396.2	4,748.8	4,829.6	1,460.7	108,225.7	4,530.4	115,495.4	4,821.8
State and local government:														
Local	17,945.1	2,709.5	467.9	310.5	18,413.0	2,725.4	3,055.1	1,042.5	—	—	3,055.1	1,042.5	21,468.2	2,905.7
State	98,329.4	4,311.7	489.4	344.9	98,818.9	4,313.0	7,131.7	1,928.8	148.6	110.0	7,280.3	1,933.2	106,099.2	4,310.8
Other public	586.5	485.3	—	—	586.5	485.3	—	—	—	—	—	—	586.5	485.3
Total	116,861.0	5,035.3	957.4	464.1	117,818.4	5,044.7	10,186.8	2,187.5	148.6	110.0	10,335.5	2,191.2	128,153.8	5,100.3
Corporate private	127,366.2	4,788.8	884.2	319.5	128,250.3	4,796.1	—	—	—	—	—	—	128,250.3	4,796.1
Noncorporate private:														
Nongovernmental conservation or natural resource organizations	5,202.4	1,196.8	102.8	98.7	5,305.2	1,200.9	—	—	—	—	—	—	5,305.2	1,200.9
Unincorporated partnerships, associations, or clubs	1,619.4	828.3	—	—	1,619.4	828.3	—	—	—	—	—	—	1,619.4	828.3
American Indian	42,421.3	3,061.0	649.5	440.7	43,070.8	3,088.9	—	—	—	—	—	—	43,070.8	3,088.9
Individual	69,237.8	3,961.0	1,576.6	450.4	70,814.4	3,978.7	—	—	—	—	—	—	70,814.4	3,978.7
Total	118,480.9	4,809.5	2,329.0	637.3	120,809.8	4,832.7	—	—	—	—	—	—	120,809.8	4,832.7
All private	245,847.0	5,512.4	3,213.1	711.5	249,060.2	5,510.3	—	—	—	—	—	—	249,060.2	5,510.3
All owners	624,643.6	7,651.5	9,376.8	1,044.2	634,020.4	7,619.9	203,364.0	7,242.8	16,270.9	2,518.5	219,634.9	6,988.9	853,655.2	9,942.5

Note: Totals may be off because of rounding; data are subject to sampling error; SE = standard error; — = less than 50 Mg was estimated.

[a] Total aboveground carbon mass of the tree from ground to tip, includes stem wood, bark, and branches; calculated by applying a factor of 0.5 to aboveground biomass estimated from regional biomass equations, and converting to metric units. Convert megagrams of carbon to tons of biomass by multiplying by 2.204586. The result will be approximate because of rounding.

[b] Includes all live trees ≥1 inches diameter at breast height, consisting of growing stock, rough cull, and rotten cull tree classes.

trees are less numerous than small-diameter trees, but store a large fraction of the carbon in Washington's forests; roughly one-third is stored in trees with a d.b.h. greater than 25 inches. Private forests store 29 percent of aboveground live tree carbon, while the NFS stores 42 percent. The tree species with the most live tree carbon is Douglas-fir (323 million Mg). Forest carbon density is concentrated on the west side of the Cascades with Jefferson, Clallam, San Juan, Skamania, and Snohomish Counties having the highest aboveground live tree carbon per hectare (fig. 17). The forest type group with the highest carbon density is hemlock/Sitka spruce, which averages 169 Mg per hectare. Among hardwoods, elm/ash/cottonwood forest types are the most carbon dense with 95 Mg live tree carbon per hectare. Other federal lands (excluding the NFS) have the highest average aboveground live tree carbon density at 194 Mg per hectare, not surprising owing to the greater number of large old trees preserved in national parks. This compares to an average of 65 Mg per hectare on private forest lands.

Standing dead trees[4] (snags) and down dead wood (also referred to as down woody material) are two additional components of aboveground forest biomass and carbon storage. These components are key to any comprehensive inventory of forest carbon pools; although they are dynamic, they contribute considerably to aboveground carbon stocks. Washington has 105 million Mg of carbon in standing dead trees (table 4) and 157 million Mg of carbon in down wood. The total amount of carbon mass and its distribution among the aboveground pools varies as stands age (fig. 18). Total aboveground woody carbon increases with stand age. The proportion in down wood is highest in very young stands that have typically undergone disturbance resulting from natural causes or harvest activity. Stands 40 to 120 years old average a fairly stable distribution among the three pools, while the proportion of aboveground carbon held in standing dead trees increases in stands over 120 years old.

Standing dead tree biomass is lowest in private ownerships, averaging 3.6 and 4.6 tons ac^{-1} in corporate and noncorporate holdings, respectively. Federal lands have significantly higher standing dead tree densities, with 16.0 and 23.7 tons ac^{-1} on NFS and other federal lands. Biomass of down wood can be highly spatially variable, but on average, it is highest in national parks (24.7 tons ac^{-1}) and lowest in private noncorporate ownerships (9.3 tons ac^{-1}).

FIA also calculates carbon storage using the component ratio method (Heath et al. 2009, O'Connell et al. 2017), which estimates belowground carbon and divides the aboveground tree carbon into distinct components. Live trees and saplings make up almost 70 percent of the total woody carbon, mostly in boles (fig. 19).

[4] Standing dead tree number, biomass, and carbon reported include all trees at least 5 inches diameter at breast height (d.b.h.). Beginning in 2016, FIA began measuring standing dead trees 1 inch d.b.h. or greater, but data for the dead sapling size class are not yet available.

Marin Palmer

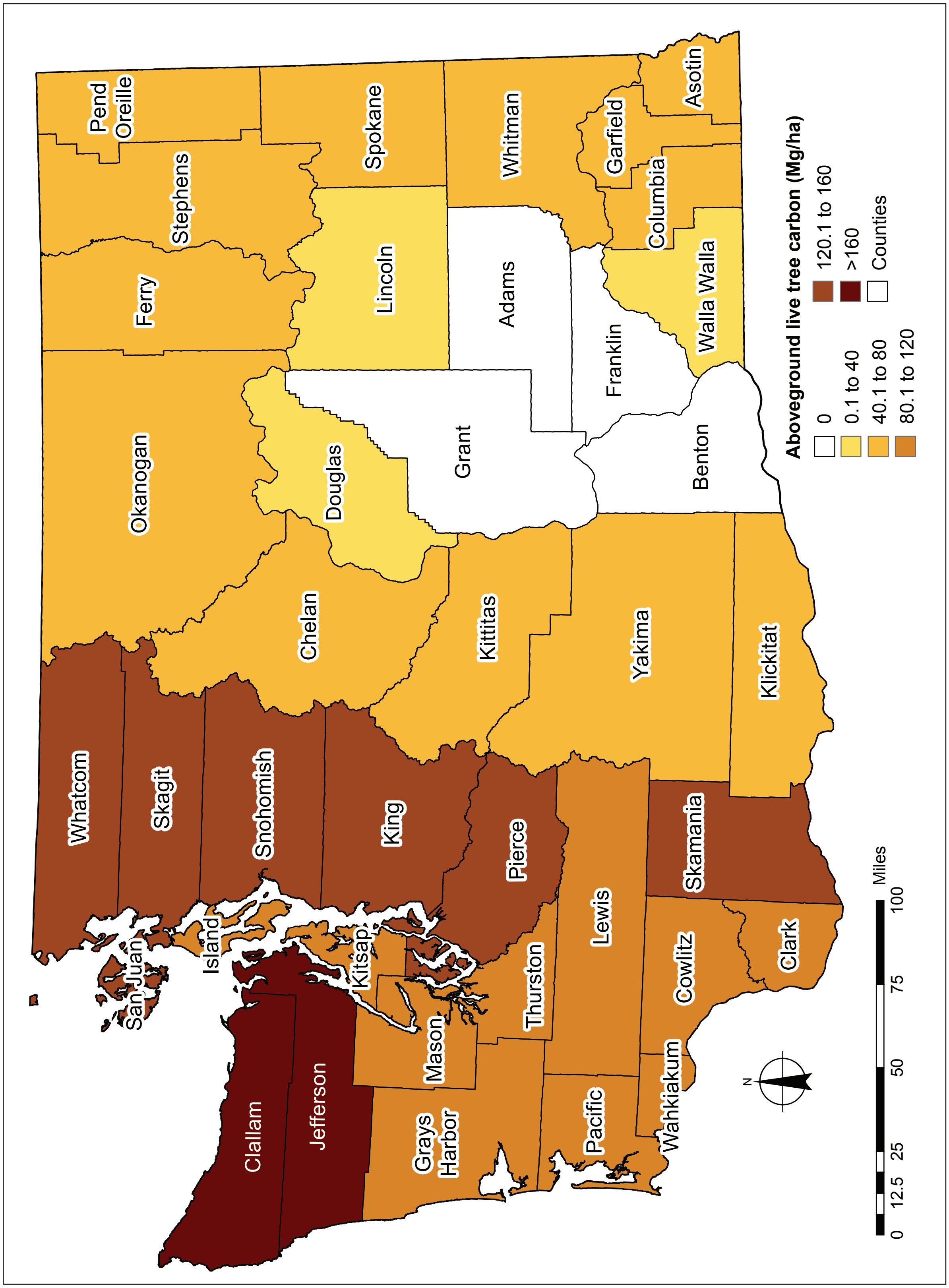

Figure 17—Average aboveground live tree carbon (megagrams per hectare) by county, Washington, 2007–2016.

Table 4—Aboveground carbon mass[a] of dead trees[b] on forest land, by ownership and land status, Washington, 2007–2016

	Land status													
	Unreserved forests						Reserved forests						All forest land	
	Timberland		Other forest		Total		Productive		Other forest		Total			
Ownership	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
							Thousand megagrams							
U.S. Forest Service	37,343.9	924.1	1,115.6	162.1	38,459.5	926.5	19,325.0	1,693.1	2,564.3	634.5	21,889.3	1,709.3	60,348.8	1,928.7
Other federal government:														
Bureau of Land Management	122.7	77.8	16.2	19.0	138.9	80.0	—	—	—	—	—	—	138.9	80.0
Departments of Defense or Energy	214.4	84.8	—	—	214.4	84.8	—	—	—	—	—	—	214.4	84.8
National Park Service	—	—	—	—	—	—	13,619.0	989.3	731.0	250.2	14,349.9	972.9	14,349.9	972.9
U.S. Fish and Wildlife Service	—	—	—	—	—	—	358.4	130.9	—	—	358.4	130.9	358.4	130.9
Other federal	213.7	105.7	—	—	213.7	105.7	371.7	258.6	148.2	112.8	519.9	278.3	733.6	297.7
Total	550.8	156.1	16.2	19.0	566.9	157.2	14,349.1	997.0	879.2	268.4	15,228.3	969.7	15,795.2	978.7
State and local government:														
Local	1,568.7	340.1	21.0	13.8	1,589.7	340.4	225.6	99.6	—	—	225.6	99.6	1,815.2	353.9
State	9,212.6	789.0	11.0	8.3	9,223.6	788.9	768.6	244.7	2.3	2.7	770.9	244.6	9,994.5	806.3
Other public	6.6	4.7	—	—	6.6	4.7	—	—	—	—	—	—	6.6	4.7
Total	10,787.9	856.1	32.0	16.1	10,819.8	856.1	994.2	263.6	2.3	2.7	996.5	263.5	11,816.3	874.4
Corporate private	7,579.8	486.8	54.8	29.7	7,634.5	487.1	—	—	—	—	—	—	7,634.5	487.1
Noncorporate private:														
Nongovernmental conservation or natural resource organizations	391.5	126.5	—	—	391.5	126.5	—	—	—	—	—	—	391.5	126.5
Unincorporated partnerships, associations, or clubs	71.6	40.6	—	—	71.6	40.6	—	—	—	—	—	—	71.6	40.6
American Indian	5,286.7	618.6	138.7	81.3	5,425.5	623.1	—	—	—	—	—	—	5,425.5	623.1
Individual	3,697.2	341.6	56.2	23.8	3,753.4	342.2	—	—	—	—	—	—	3,753.4	342.2
Total	9,447.0	699.8	194.9	84.7	9,642.0	703.5	—	—	—	—	—	—	9,642.0	703.5
All private	17,026.8	804.7	249.7	89.7	17,276.5	806.8	—	—	—	—	—	—	17,276.5	806.8
All owners	65,709.3	1,481.4	1,413.4	187.0	67,122.8	1,483.8	34,668.2	1,982.4	3,445.8	689.0	38,114.0	1,982.7	105,236.8	2,457.2

Note: Totals may be off because of rounding; data are subject to sampling error; SE = standard error; — = less than 50 Mg was estimated.
[a] Total aboveground carbon mass of the tree from ground to tip, includes stem wood, bark, and branches; calculated by applying a factor of 0.5 to aboveground biomass estimated from regional biomass equations, and converting to metric units. Convert megagrams of carbon to tons of biomass by multiplying by 2.204586. The result will be approximate because of rounding.
[b] Includes all dead trees ≥ 5 inches diameter at breast height; smaller dead trees were not measured in this inventory.

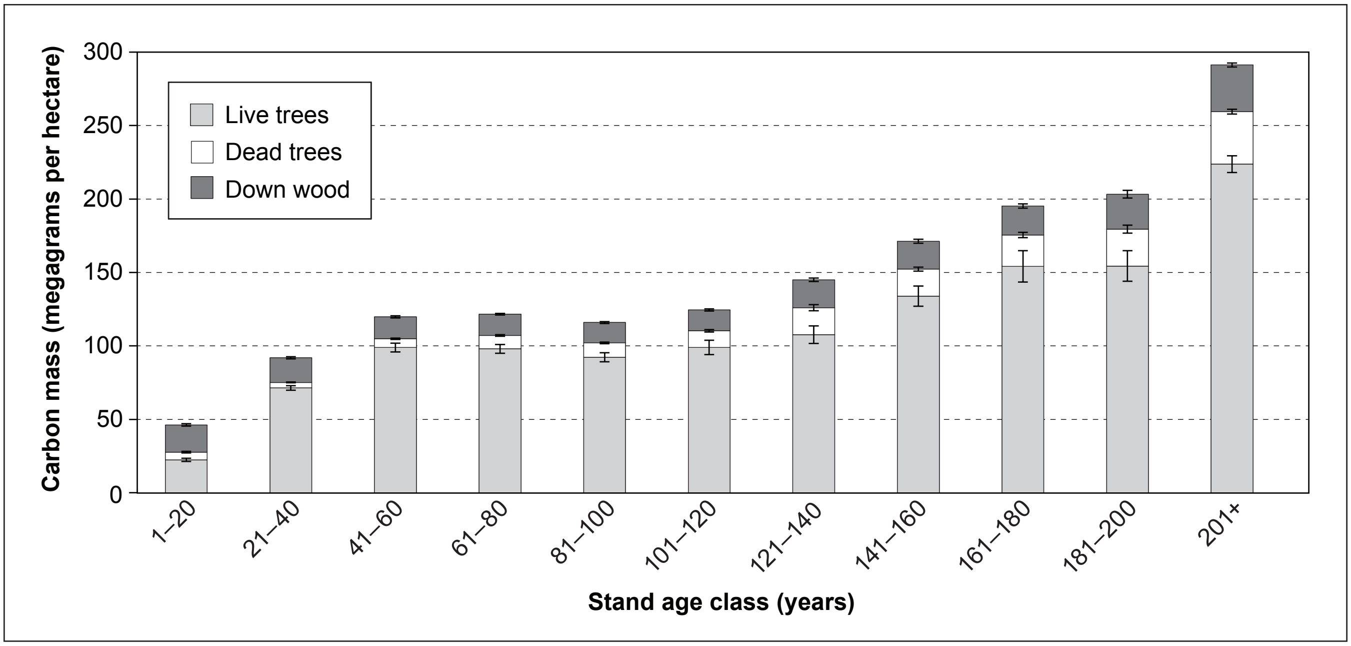

Figure 18—Average aboveground carbon mass per hectare on forest land, by stand age class, Washington, 2007–2016.

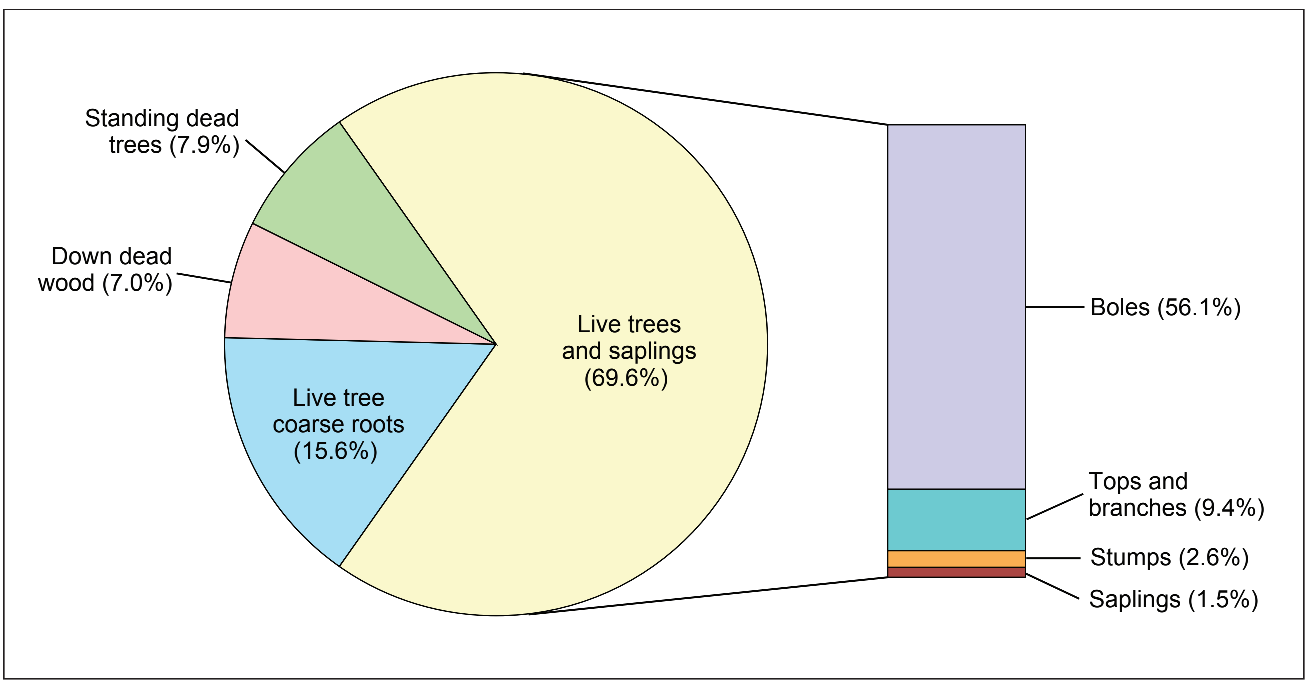

Figure 19—Distribution of woody tree carbon components on forest land, Washington, 2007–2016. Live tree carbon is subdivided into saplings (at least 1 but less than 5 inches diameter at breast height [d.b.h.]) and trees (at least 5 inches d.b.h.). Note that shrubs represent another component of woody carbon not directly measured by Forest Inventory and Analysis or reported here.

Research Application: Carbon Flux in the Pacific Northwest

Andy Gray

Forests store large amounts of carbon, but it is not fully understood how a forest's storage capacity fluctuates as stands age or respond to disturbance. Forests in Oregon and Washington currently store an estimated 2,100 million Mg of carbon and accumulate carbon at a rate of 7 million Mg per year (an increase of 0.3 percent per year) (Gray and Whittier 2016, Watts et al. 2017). In effect, forests are accumulating the equivalent of 24 percent of the carbon emissions from fossil fuel combustion in Oregon and Washington.

National Forest System (NFS) lands in Oregon and Washington are storing 63 percent of their maximum carbon storage capacity for their respective plant association zone and productivity class, which is greatest in the oldest forests. However, maturing younger forests and small trees (e.g., less than 150 years and less than 40 inches in diameter) accumulate carbon at a faster rate per acre compared to older forests and large trees (fig. 20). Thus the management objectives and harvest and disturbance levels on the landscape determine whether

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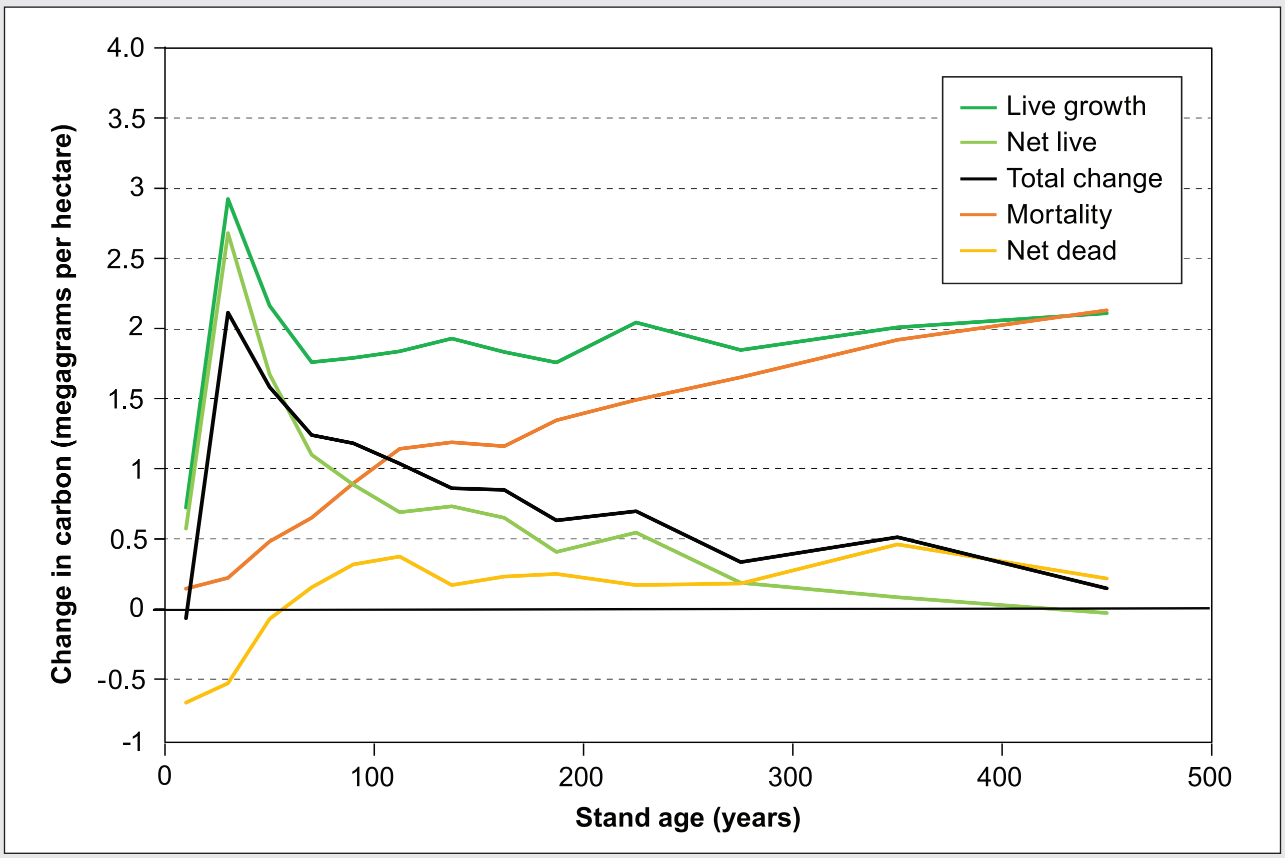

Figure 20—The carbon storage capacity of a Pacific Northwest forest fluctuates throughout its lifetime because of tree growth and mortality. Live tree carbon storage rates peak early in stand development, but this growth is offset by tree mortality as the stand ages. In young stands, the amount of carbon stored in dead wood decreases, but it increases at low rates in older stands.

carbon is stored in forests or in products as well as its rates of accumulation.

Wildfires on NFS lands resulted in a loss of 0.8 million Mg per year during the study period 1993 to 2007 (11 percent of the net increase in carbon across the region). Most of this loss occurred in wilderness areas east of the Cascade Range, where, until recently, wildfires had been suppressed for several decades. In contrast, changes in land use from forested to nonforested lands had three times the impact on regional carbon stores compared to wildfire. Land use change resulted in an estimated net loss of 2.4 million Mg of carbon per year, equivalent to 25 percent of the net increase in carbon across the region. Although the area of juniper forests increased in Oregon, this did not offset the conversion of Douglas-fir forests, which store more carbon per acre than juniper forests, to residential or agricultural uses in both Oregon and Washington. Research is continuing on how much carbon is being stored in Pacific Northwest forests and how that is changing with management and disturbance.

Literature cited—

Gray, A.N.; Whittier, T.R.; Harmon, M.E. 2016. Carbon stocks and accumulation rates in Pacific Northwest forests: role of stand age, plant community, and productivity. Ecosphere. 7: e01224. http://treesearch.fs.fed.us/pubs/52237.

Watts, A.; Gray, A.N.; Whittier, T.R. 2017. There's carbon in them thar hills: but how much? Could Pacific Northwest forests store more? Science Findings 195. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 6 p. http://treesearch.fs.fed.us/pubs/53931.

Forest Productivity

Timber Resources and Forest Productivity

The Pacific Northwest contains some of the world's most productive forest land. Forest products contribute to Washington's economy and are especially important in rural areas. Three billion board feet (BBF) Scribner of timber were harvested from Washington forests in 2016. Most of this volume (84 percent) came from western Washington, and 77 percent of total harvested volume came from private and tribal lands (WDNR 2017). Washington is the second largest lumber producer in the country; the state's forest products industry provides 42,000 direct jobs plus an additional 64,000 forestry-related jobs that collectively generate $5.2 billion in annual wages (WFPA 2018). This industry is especially important in rural counties with a large proportion of forest land.

Lumber mills in Washington processed or exported more than 3.1 BBF of timber in 2016 (fig. 21). Most (86 percent) of the logs received by Washington mills came from Washington forests, while the rest came from Oregon, other states or British Columbia. Douglas-fir contributed 60 percent and hemlock contributed 25 percent of the lumber volume. Although the number of mills has declined since 2006, total production levels have remained steady (Smith and Larson 2017).

T. Robillard

Figure 21—Lumber mills such as the Wilkins, Kaiser & Olsen sawmill in Carson, Washington, processed or exported more than 3.1 billion board feet of timber in Washington during 2016.

Growing-stock or sawtimber volumes on timberland are one measure of the current stock of standing timber for a region, and monitoring growing stocks over time is essential for sustained yield. Timberland volume alone is not a direct measure of timber availability or future harvest levels because forest management objectives differ widely among landowners, and timber harvests are driven by a variety of market factors in addition to log supply. In Washington, growing-stock volume on timberland is currently 68.7 billion ft^3. It is difficult to compare estimates from FIA's annual inventory with those produced prior to 2000 because each used different definitions of timberland and merchantable timber. In general, growing-stock volume decreased during the post-World War II housing boom and has steadily increased since harvest rates on federal lands sharply declined in the 1990s (fig. 22).

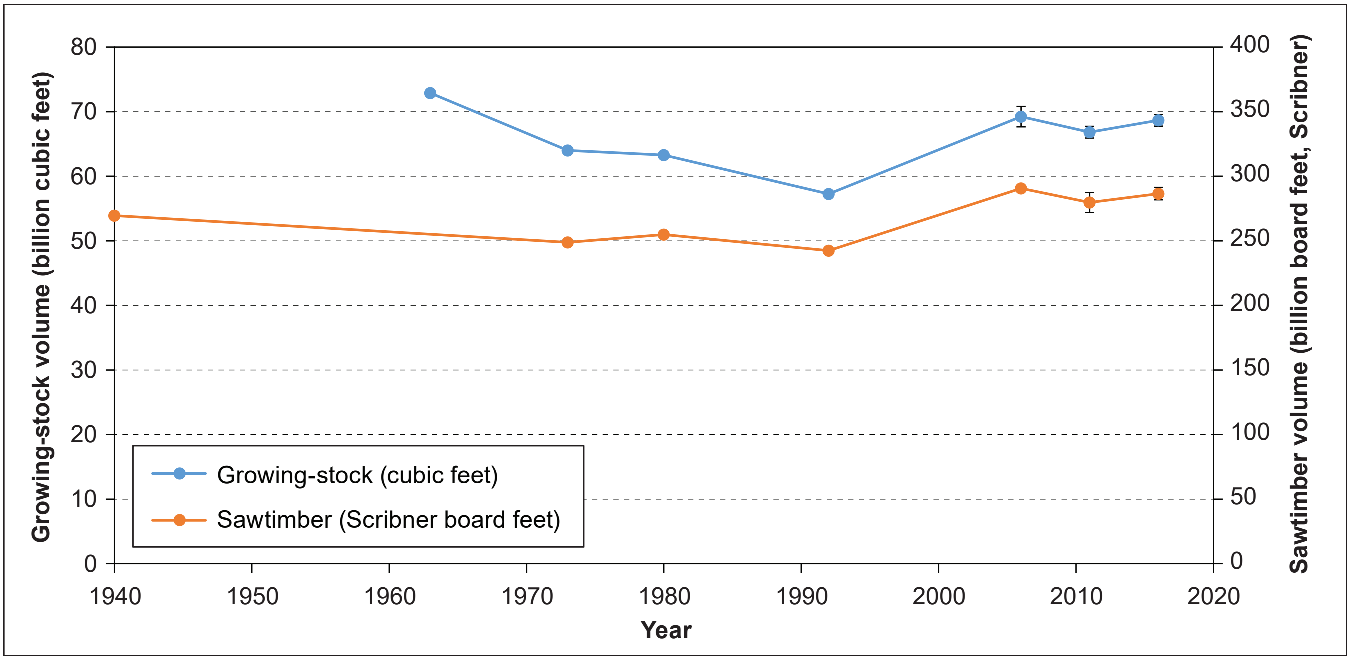

Figure 22—Growing-stock (billion cubic feet) and sawtimber (billion board feet, Scribner) volumes on unreserved timberland by inventory year in Washington, 1942–2016. Note: estimates from 2000–2016 are based on the annual inventory design and protocols, while prior estimates were based on periodic inventories that used different designs and methods (Bassett and Choate 1974; Bassett and Oswald 1981a, 1981b, 1982, 1983; Bolsinger et al. 1997; Cowlin and Moravets 1940; Metcalf 1965). Not all inventory years reported each estimate (growing-stock or Scribner sawtimber). Differences shown here represent a combination of real change and protocol differences over time, such as the use of stockability factors during periodic inventories and updated volume equations.

Timberlands in Washington currently hold 59.9 billion ft^3 or 286.5 BBF Scribner of live sawtimber trees. Sawtimber trees include only the sound portion of commercial species meeting minimum sawlog size. Douglas-fir (44 percent), western hemlock (19 percent), true firs (12 percent), ponderosa and Jeffery pines (6 percent), western redcedar (5 percent), and red alder (4 percent) contribute the most sawtimber volume (fig. 23). Western Washington holds 70 percent of sawtimber volume and eastern Washington holds 30 percent. Statewide, sawtimber tree volume per acre of timberland averages 16,105 board feet Scribner. There is considerable variation among owner groups with an average of 10,744 board feet Scribner per acre on private lands and more than 26,788 board feet Scribner per acre on non-NFS federal lands (fig. 24).

FIA also estimates the site productivity class (Hanson et al. 2003) for each forested condition. Site productivity class is an indicator of a forest stand's potential productivity based on mean annual increment at culmination, and stands are classified as being of low productivity (capable of producing 20 to 84 ft^3 ac^{-1} yr^{-1}),

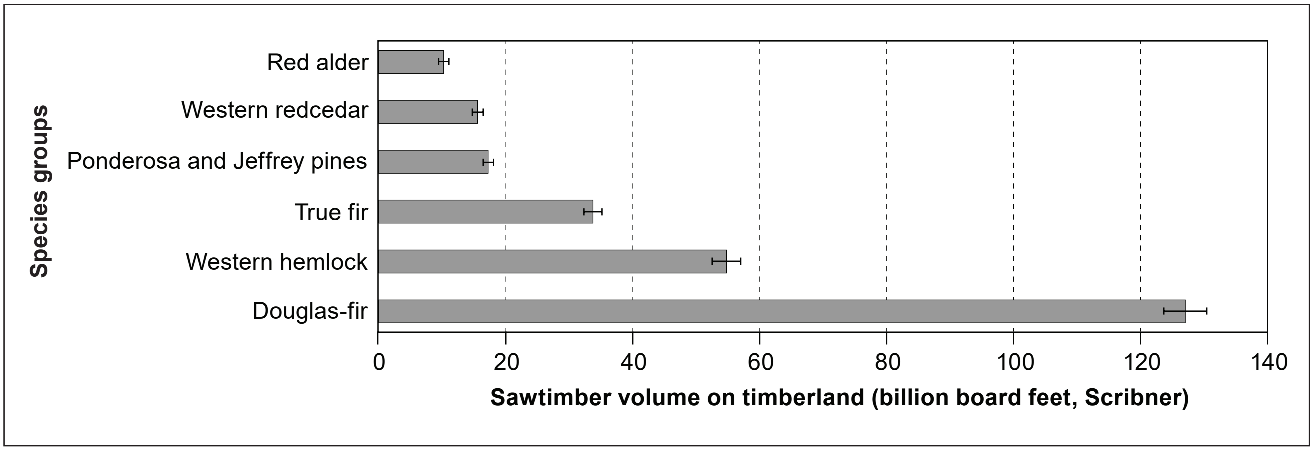

Figure 23—Scribner board-foot volume found on timberland by species group (six highest volume species groups), Washington, 2007–2016.

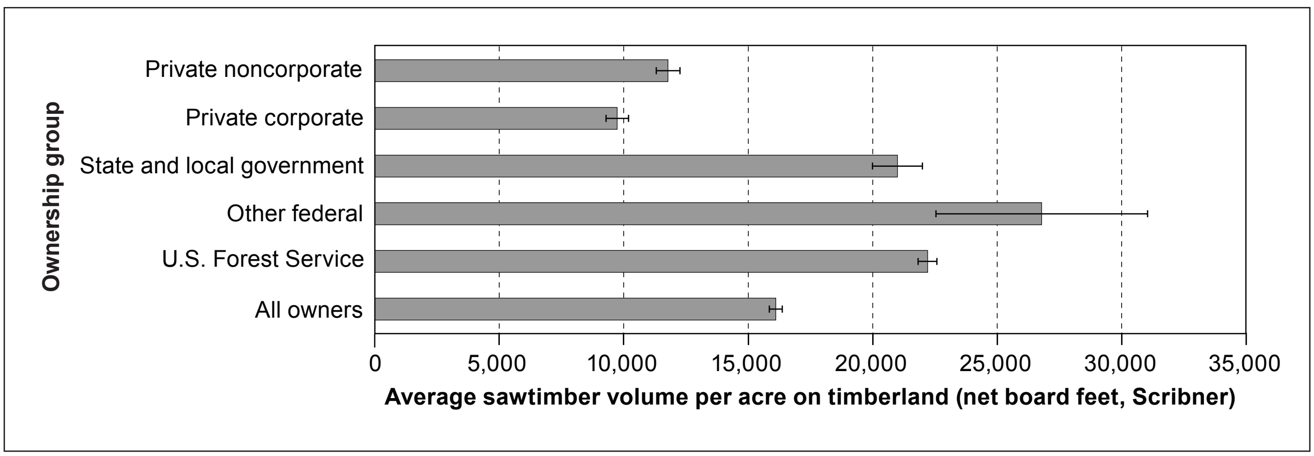

Figure 24—Average sawtimber tree volume per acre of timberland by ownership group (net board feet, Scribner), Washington, 2007–2016.

medium productivity (85 to 164 $ft^3\ ac^{-1}\ yr^{-1}$), or high productivity (at least 165 $ft^3\ ac^{-1}\ yr^{-1}$), or as nonproductive (incapable of producing at least 20 $ft^3\ ac^{-1}\ yr^{-1}$). Twenty percent of Washington forest land area is classified as high productivity and another 39 percent is medium productivity. Most of the high-productivity sites are located on the west side of the state, with the highest productivity areas concentrated along the Pacific Coast (fig. 25). One-half of the high-productivity sites hold Douglas-fir forest types, and another 30 percent hold hemlock/Sitka spruce types. Alder/maple and hemlock/Sitka spruce forest types tend to be found on medium- or high-productivity sites, while ponderosa pine is restricted to low- or medium-productivity sites (fig. 26).

Marin Palmer

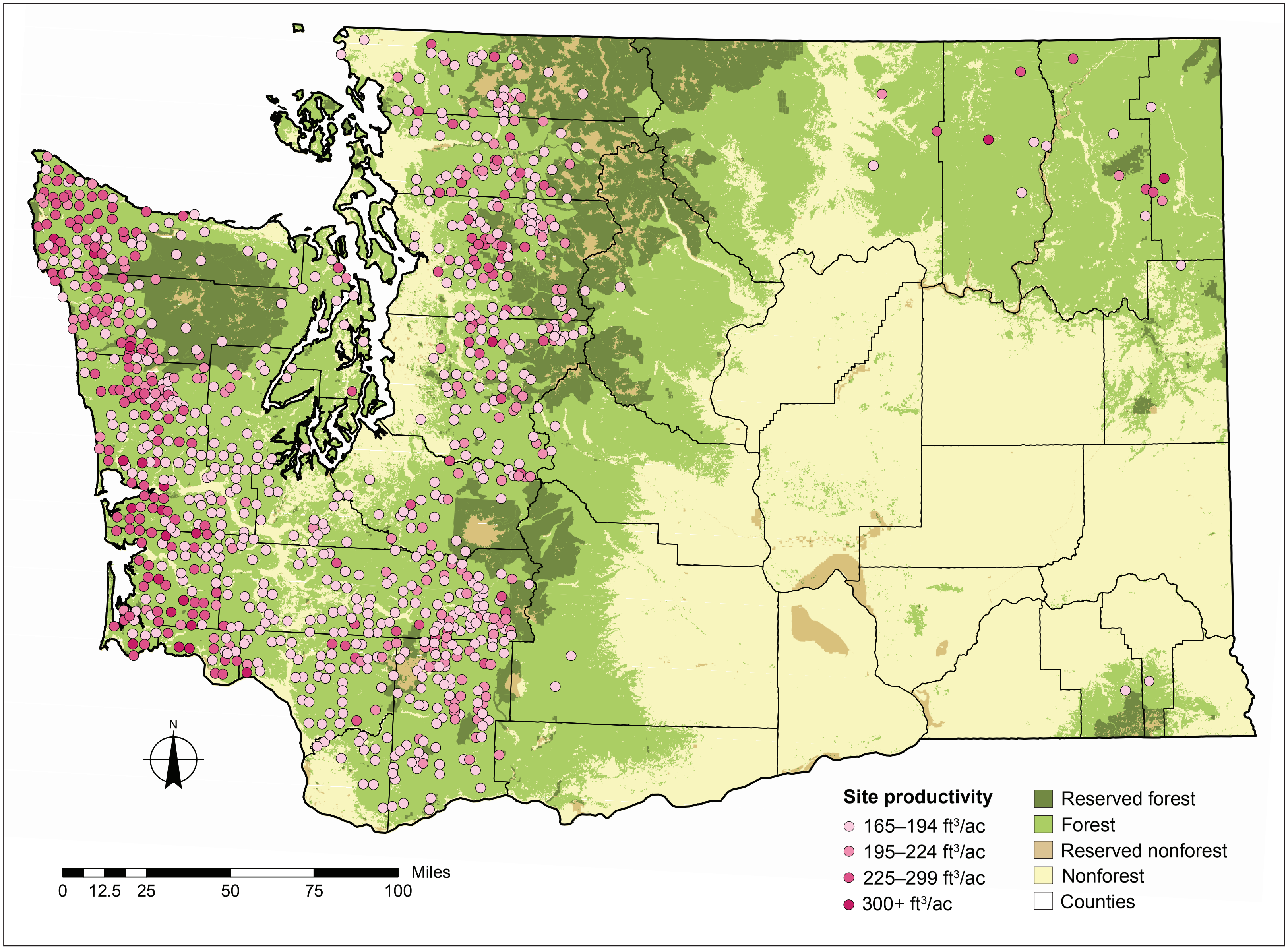

Figure 25— Forest Inventory and Analysis plots on highly productive sites, Washington, 2007–2016. One hundred and ninety-seven plots were classified as capable of at least 225 ft^3 ac^{-1} yr^{-1}, and 780 plots capable of 165 to 224 ft^3 ac^{-1} yr^{-1} growth (forest/nonforest geographic information system layer: Blackard et al. 2008).

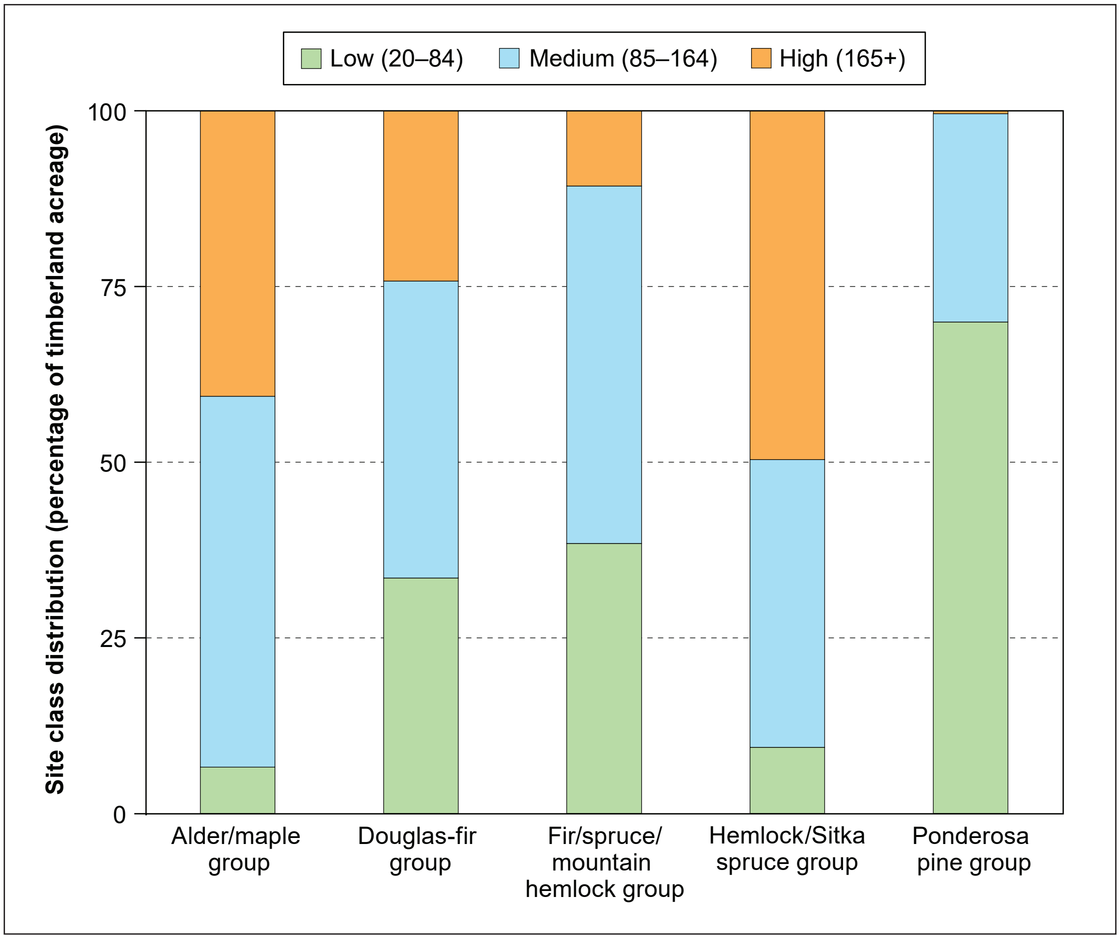

Figure 26—Timberland site class distribution (ft^3/ac mean annual increment) for major forest type groups, Washington, 2007–2016.

Average Annual Growth, Removals, and Mortality

Growth, removals, and mortality (GRM) estimates provide a detailed accounting of changes in forest composition over time based on repeated measurements of individual trees. FIA's landscape-level sampling design covers all forest land ownerships, with the same plots and trees measured each 10-year cycle; GRM estimates represent average annual rates over the entire measurement cycle. The GRM estimates in this report include 2,853 forested plots initially installed in 2002–2006 that were remeasured in 2012–2016, 50 percent of the Washington FIA grid. As the second cycle is completed through 2021, the estimates reported here are not expected to change substantially, but their precision will improve.

Annual gross growth in Washington averaged 105 ft^3 ac^{-1} yr^{-1} statewide and was almost three times greater in western Washington than eastern Washington (table 5). Net change (defined as gross growth minus mortality and harvest removals) was

Table 5 — Average annual volume (cubic feet per acre) growth, removals, and mortality on forest land by ownership group, Washington, 2002–2006 and 2012–2016

	Ownership group																	
	National forest												Private					
	Timberland		Reserved		Low productive		Total national forest		Other federal		State and local government		Corporate		Noncorporate		Total private		All owners	
	Total	SE	Total	SE	Total	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
	Cubic feet per acre per year																			
All Washington:																				
Growth	95.5	2.0	63.1	5.3	27.9	5.1	84.3	2.1	91.9	7.9	135.3	5.7	145.0	5.3	85.6	4.0	117.1	3.3	105.4	1.8
Mortality	55.9	2.6	73.0	13.1	28.8	7.4	60.0	4.2	77.8	9.6	41.7	4.5	18.1	2.3	26.2	2.8	21.9	1.8	42.7	2.0
Removals	6.0	1.2	—	—	—	—	4.1	0.8	2.3	2.0	68.1	16.1	117.4	13.2	28.1	6.3	75.4	7.6	42.6	3.9
Net change	33.6	3.5	-9.9	13.9	-0.9	7.9	20.1	4.7	11.8	11.3	25.5	18.0	9.5	15.1	31.4	7.5	19.8	8.8	20.1	4.8
Eastern Washington:																				
Growth	58.1	1.6	48.7	5.0	22.2	5.1	54.1	1.8	57.5	12.4	50.1	4.7	63.5	5.0	55.3	3.0	57.3	2.6	55.0	1.5
Mortality	57.0	3.4	104.2	22.5	30.7	9.0	69.2	6.8	53.5	14.3	34.8	7.8	7.8	1.6	24.7	3.5	20.8	2.8	46.2	3.6
Removals	4.6	1.0	—	—	—	—	3.2	0.7	11.8	11.8	23.0	8.4	61.5	13.9	20.1	4.1	29.8	4.6	15.9	2.1
Net change	-3.5	4.0	-55.5	22.5	-8.6	9.0	-18.2	6.9	-7.8	15.2	-7.8	11.6	-5.8	14.9	10.5	5.8	6.7	5.7	-7.0	4.2
Western Washington:																				
Growth	147.9	4.1	82.4	10.6	40.0	11.0	126.9	4.4	99.3	9.0	178.6	7.3	164.1	6.1	156.1	9.4	162.2	5.1	148.1	3.0
Mortality	54.4	3.8	31.0	5.7	24.6	13.0	47.1	3.1	83.0	11.3	45.2	5.6	20.6	2.9	29.6	4.3	22.8	2.4	39.6	2.1
Removals	8.0	2.6	—	—	—	—	5.5	1.8	0.2	0.2	90.9	24.0	130.5	16.0	46.6	18.6	109.7	13.0	65.3	7.0
Net change	85.5	6.1	51.4	11.5	15.4	14.7	74.3	5.5	16.0	13.2	42.5	26.4	13.0	18.3	79.9	20.2	29.6	14.7	43.2	8.1

Note: Totals may be off because of rounding; data are subject to sampling error; SE = standard error; — = less than 0.005 ft^3 per acre was estimated.

positive for all ownership groups in western Washington, meaning that these forests are adding tree volume each year; however, in eastern Washington, net change was negative on NFS lands and only significantly positive on noncorporate private lands (fig. 27). Reserved NFS lands showed the highest volume losses, with mortality exceeding growth by 56 ft^3 ac^{-1} yr^{-1}. Statewide, net change in volume was 20 ft^3 ac^{-1} yr^{-1} or a total addition to net volume of 415 million ft^3 yr^{-1} (fig. 28, table 6). Mortality rates are highest on other federal lands in western Washington (83 ft^3 ac^{-1} yr^{-1}) and in eastern Washington NFS reserves (104 ft^3 ac^{-1} yr^{-1}), comparable to average mortality rates statewide of 43 ft^3 ac^{-1} yr^{-1}. On both sides of the state, harvest removals on corporate private land (117 ft^3 ac^{-1} yr^{-1}) are more than triple that of any other owner group.

Mortality rates (ratios of average annual mortality to original standing net volume) give an estimate of the tree volume lost each year to a variety of natural agents such as fire, insects, disease, weather, or competition. The average annual mortality rate in Washington, in terms of tree volume, is 1.0 percent. Engelmann and other spruces, lodgepole pine, and western white pine species groups have the highest mortality rates, 4.8, 4.5, and 2.3 percent, respectively (fig. 29). Most Engelmann spruce mortality was caused by insects and fire. Insects tended to affect larger Engelmann spruce trees, accounting for 32 percent of mortality trees but 64 percent of mortality volume, whereas fire killed smaller individuals (50 percent of trees but only 23 percent of mortality volume). Mortality in lodgepole pine trees was mainly caused by insects (45 percent), fire (39 percent), or disease (7 percent), with similar trends in volume losses to mortality. Mountain pine beetle (*Dendroctonus ponderosae*) and several other beetles frequently attack lodgepole pine. The mortality rate for a given species can be an indicator of forest health but is also highly dependent of each species' life history or average stand age.

Net growth is a better indicator of whether growth is offsetting mortality losses. Net growth, in forestry terms, is defined as the gross growth minus mortality losses. Engelmann and other spruces and lodgepole pine have negative annual net growth rates (-3.2 and -2.8 percent, respectively) owing to the annual mortality of each group exceeding gross growth. The six highest volume species groups are all adding volume at rates between 1.5 and 2.4 percent annually, with the exception of true fir owing to a higher mortality rate. Sitka spruce and other western hardwood species groups demonstrate the highest net growth rates (fig. 30).

Most removals (75 percent or 754 million ft^3 annually) occur on private forest land (including tribal lands), of which 84 percent occur in western Washington and 16 percent east of the Cascades. An additional 21 percent of annual removals come from land managed by state and local entities, and 4 percent of removals occur on

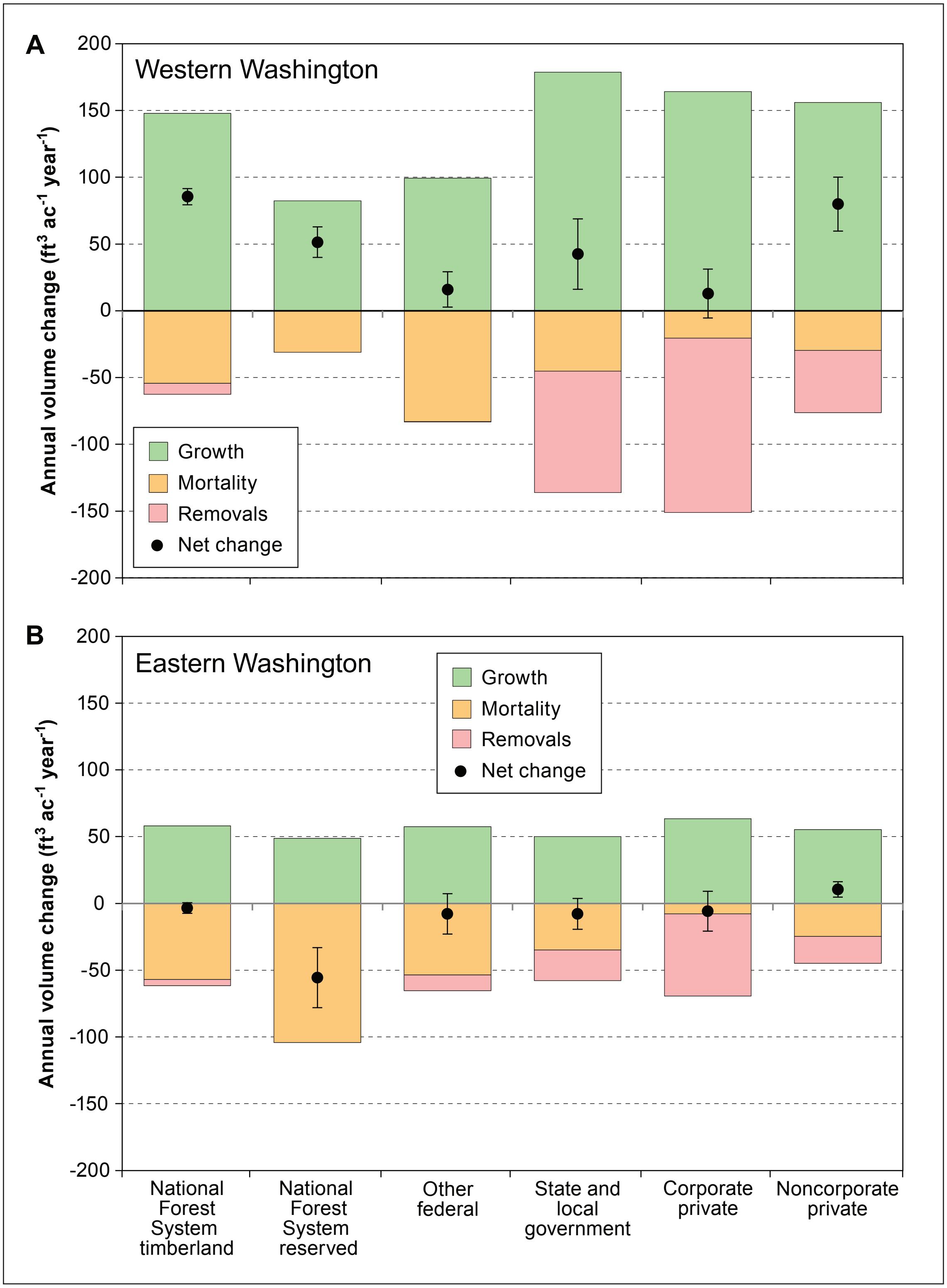

Figure 27—Average annual change in volume (cubic feet per acre per year) of growth, mortality, and removals on forest land between 2002–2006 and 2012–2016 by ownership group in (A) western Washington and (B) eastern Washington. Error bars represent standard error.

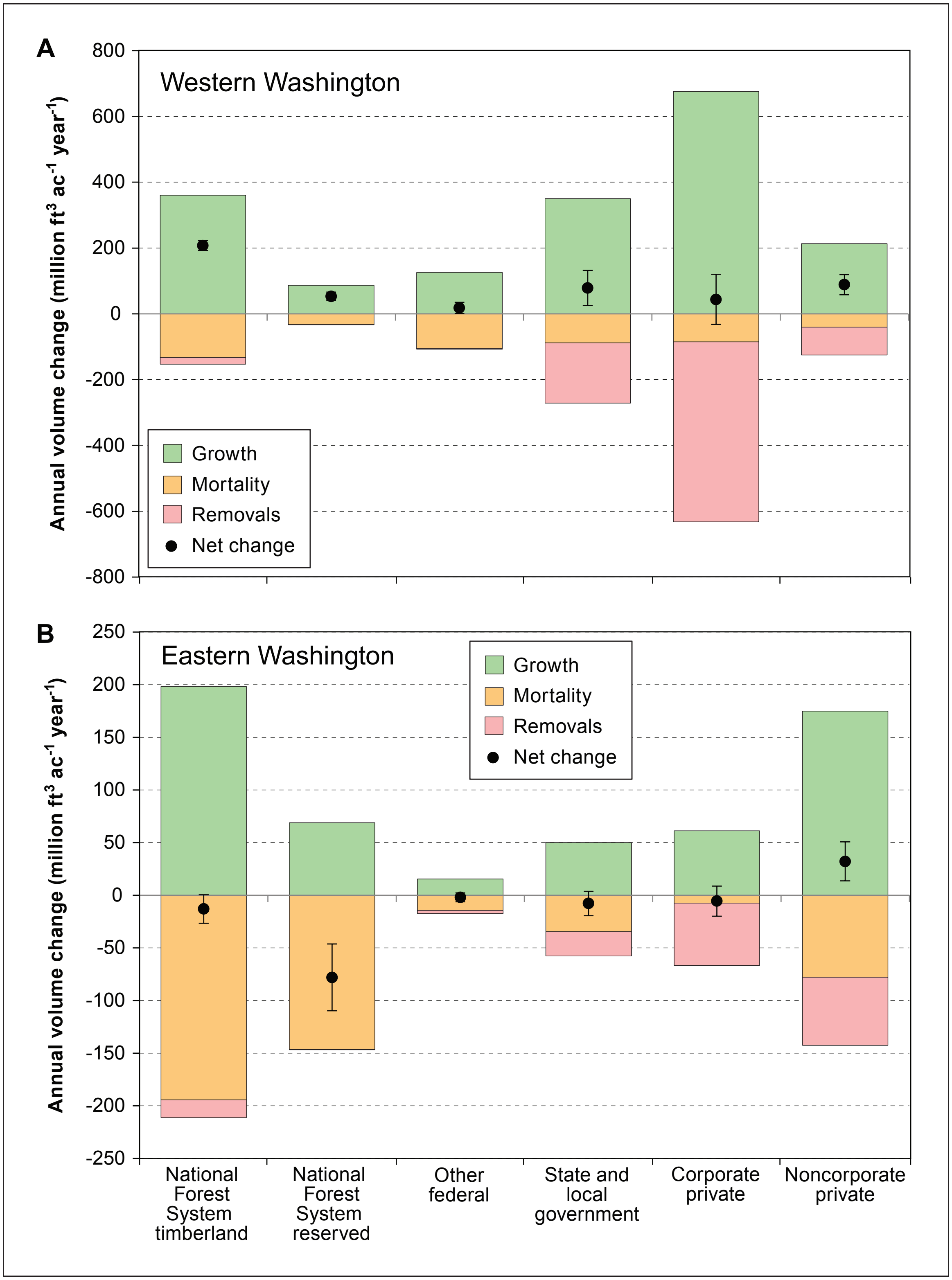

Figure 28—Average annual change in volume (cubic feet per year) of growth, mortality, and removals on forest land between 2002–2006 and 2012–2016 by ownership group in (A) western Washington and (B) eastern Washington. Error bars represent standard error.

Table 6—Average annual volume (cubic feet) growth, removals, and mortality on forest land by ownership group, Washington, 2002–2006 and 2012–2016

	Ownership group																	
	National forest												Private					
	Timberland		Reserved		Low productive		Total national forest		Other federal		State and local government		Corporate		Noncorporate		Total private		All owners	
	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE	Total	SE
	Thousand cubic feet per year																			
All Washington:																				
Growth	558,611	12,594	155,165	13,619	21,987	4,957	718,315	18,044	141,068	13,502	400,375	20,187	737,051	34,890	388,261	23,810	1,125,312	34,639	2,385,070	42,083
Mortality	326,994	15,260	179,041	32,402	22,699	6,746	511,402	35,705	119,340	15,321	123,154	13,769	93,026	12,059	118,627	13,400	211,653	17,400	965,548	44,541
Removals	37,092	7,164	739	534	—	—	37,831	7,183	5,791	3,850	206,323	48,922	605,537	69,002	148,744	30,955	754,282	74,814	1,004,227	89,443
Net change	194,525	20,637	-24,615	34,010	-713	6,229	169,082	39,686	15,938	17,397	70,898	54,720	38,487	77,195	120,890	35,867	159,377	85,299	415,295	110,201
Eastern Washington:																				
Growth	198,123	5,829	68,724	7,304	11,913	3,266	270,055	9,292	15,457	4,149	49,834	6,576	61,184	8,218	174,767	13,000	235,951	14,351	571,296	18,749
Mortality	194,283	12,026	146,521	32,051	16,507	5,633	344,929	34,132	14,382	4,789	34,664	8,618	7,542	1,779	77,913	11,901	85,455	11,960	479,429	37,472
Removals	16,907	3,377	290	227	—	—	17,197	3,384	3,174	3,081	23,032	8,698	59,268	14,862	64,723	13,306	123,991	19,655	167,394	21,971
Net change	-13,067	13,541	-78,087	31,784	-4,593	4,962	-92,071	34,529	-2,099	4,144	-7,863	11,644	-5,626	14,330	32,131	18,459	26,505	23,305	-75,527	43,409
Western Washington:																				
Growth	360,489	11,513	86,442	11,759	10,073	3,729	448,261	15,957	125,611	13,707	350,541	21,618	675,867	34,882	213,494	21,493	889,361	36,076	1,813,774	43,901
Mortality	132,711	9,476	32,520	6,381	6,192	3,712	166,473	11,397	104,958	14,922	88,490	11,593	85,484	11,976	40,714	6,667	126,198	13,299	486,120	25,573
Removals	20,185	6,320	450	483	—	—	20,635	6,338	2,616	2,330	183,291	48,588	546,270	67,954	84,021	28,070	630,291	72,986	836,832	87,633
Net change	207,592	15,296	53,472	12,193	3,881	3,766	261,153	19,389	18,037	16,924	78,760	53,475	44,113	75,868	88,758	30,779	132,872	82,025	490,822	101,256

Note: Totals may be off because of rounding; data are subject to sampling error; SE = standard error; — = less than 50 ft^3 was estimated.

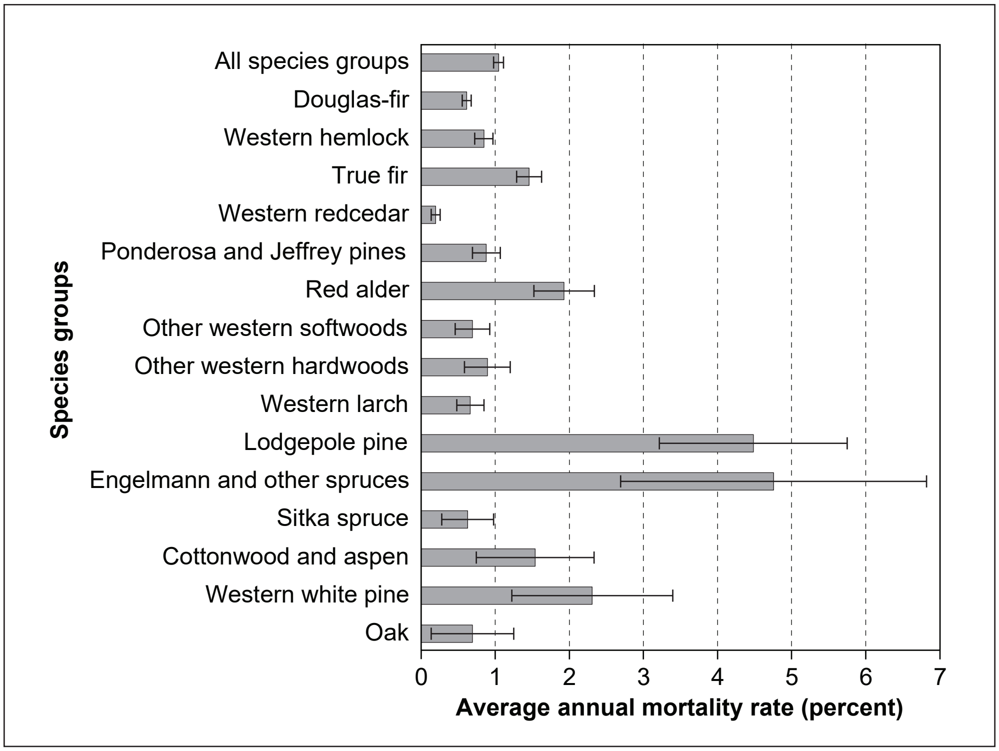

Figure 29—Average annual mortality rates (percentage of volume) for species groups on forest land, Washington, 2016. Species groups are shown ordered by total net standing volume; average annual mortality rate for all species is 1.0 percent. Error bars represent standard error.

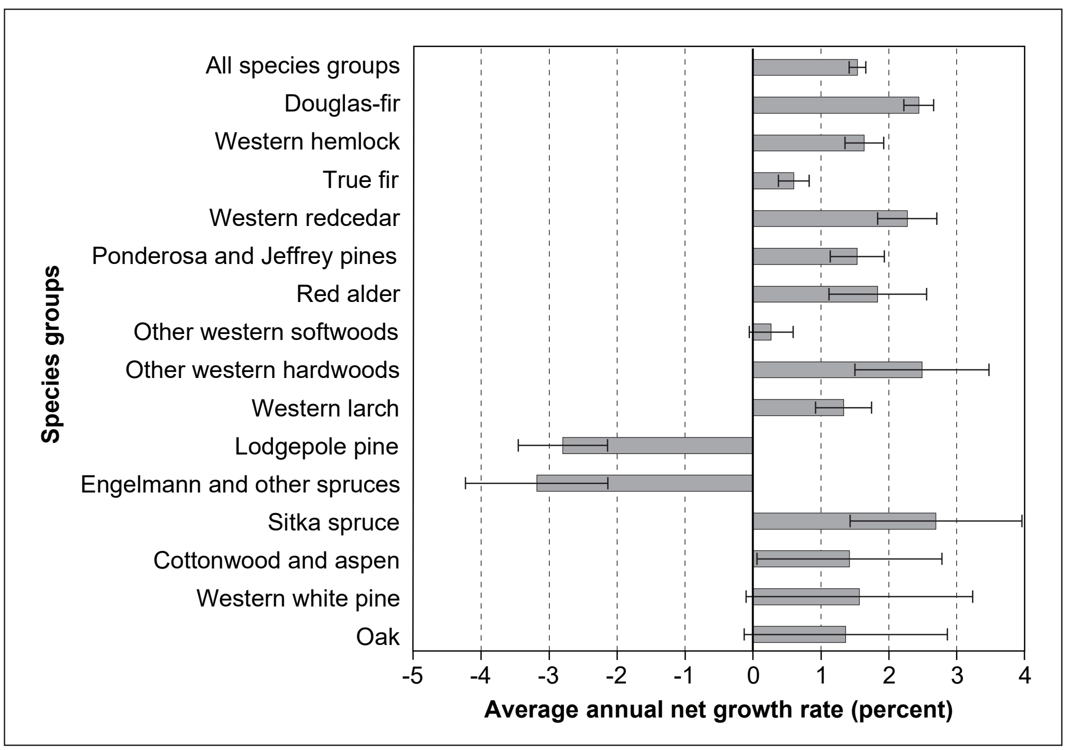

Figure 30—Average annual net growth rates (percentage of volume) by species group for all live trees on forest land, Washington, 2016. Species groups are shown ordered by total net standing volume. Error bars represent standard error.

NFS lands. Douglas-fir (43 percent) and western hemlock (30 percent) make up most of the removed volume (fig. 31).

The net growth-to-removals ratio is an indicator of sustained yield, where ratios >1 indicate that more tree volume is growing than is being harvested, but ratios <1 reveal higher harvest than net growth. The desirable net growth-to-removals ratio depends on the land management objective; in areas being managed for timber production, a ratio of ~1 may be a management goal. In Washington, the average net growth-to-removals ratio is 1.41, meaning that each year, Washington's forest lands add 1.41 times as much tree volume as is removed, after accounting for mortality losses. Douglas-fir has a net growth-to-removals ratio of 1.79 while that of western hemlock is 1.08. Western Washington has a ratio of 1.6 while that of eastern Washington is 0.5. In areas of eastern Washington with much higher tree density than the historical conditions, a management goal may be decreasing tree volume, in which case a <1 ratio could be desirable. The current ratio is driven largely by high mortality (i.e., very low net growth rather than high removals). Most forest restoration plans focus on decreasing long-term mortality by increasing both forest thinning and prescribed burning.

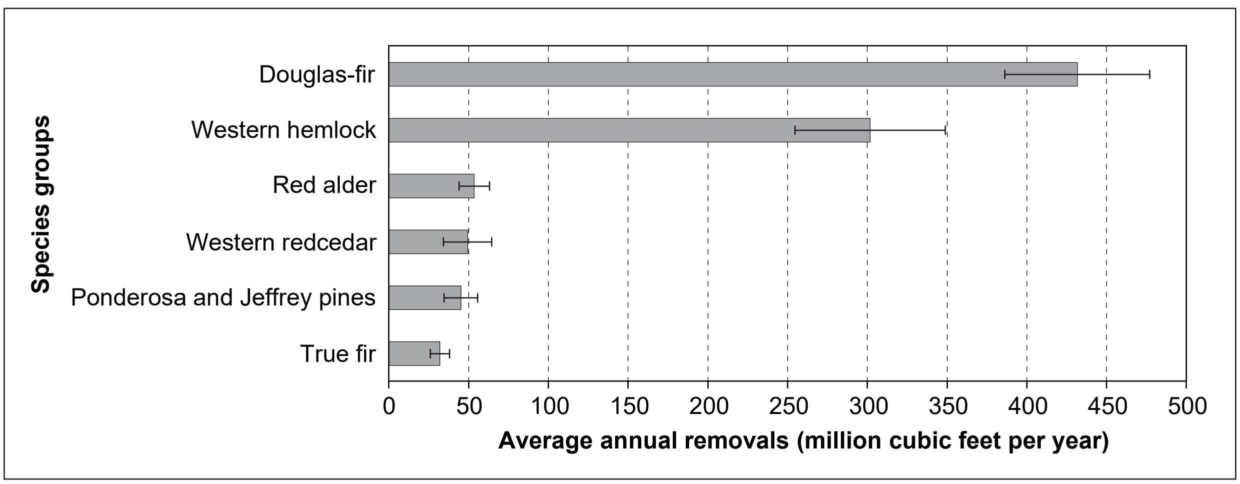

Figure 31—Average annual removals (tree harvest and forest to nonforest diversion) for selected species groups on forest land, Washington, 2016.

Wildlife Habitat

Standing dead trees (snags) and down dead wood provide key habitat components for forest wildlife in addition to their roles in carbon storage and nutrient cycling (fig. 32). Dead wood forest components are used by a variety of bird, mammal, and amphibian species for nesting, roosting, foraging, hibernating, and thermal cover (Rose et al. 2001) (fig. 33). Although local patterns and locations of dead wood structures are important in identifying potential wildlife habitat, broad-scale estimates of dead wood provided by FIA are useful in comparisons within or across forest types or disturbance histories. Recent management activity and natural disturbances can affect the amount and distribution of down dead wood in each stand, which can collectively be estimated at a landscape level. The moist west side of the state has twice as much total down dead wood as the east side, and statewide down dead wood averages 15.2 tons ac^{-1} (fig. 34). Some forest type groups contain far more down dead wood than others; western oak and ponderosa pine forest types average 3.5 and 5.7 tons ac^{-1}, respectively, while hemlock/Sitka spruce sites average 29.5 tons ac^{-1}. Expressed as volume for comparability to earlier estimates that used different decay factors for biomass, Washington forests currently average 2,018 ft^3 ac^{-1} of down wood, 16 percent less than Campbell et al.'s (2010) 2006 estimate of 2,415 ft^3 ac^{-1}.

Washington has 604 million standing dead trees, an increase of 6 percent from the estimate in Holgerson et al. (2018) that covered 2002 to 2011. Douglas-fir forest types contain 35 percent of total standing dead trees. Statewide, there are an average of 27 standing dead trees per forested acre. The amount of standing dead trees and down dead wood varies considerably by ownership, with the majority of standing dead tree biomass (133 million tons) and highest density of total standing dead trees (40 ac^{-1}) occurring on NFS lands and the lowest standing dead tree densities (15 ac^{-1}) on private lands (figs. 35 and 36).

Figure 32—Field crews measure coarse woody debris. Down dead wood provides wildlife habitat and cycles nutrients in forest ecosystems.

Figure 33—Down dead wood is an important component of forests, providing habitat for many species such as American black bears (*Ursus americanus*).

Marin Palmer

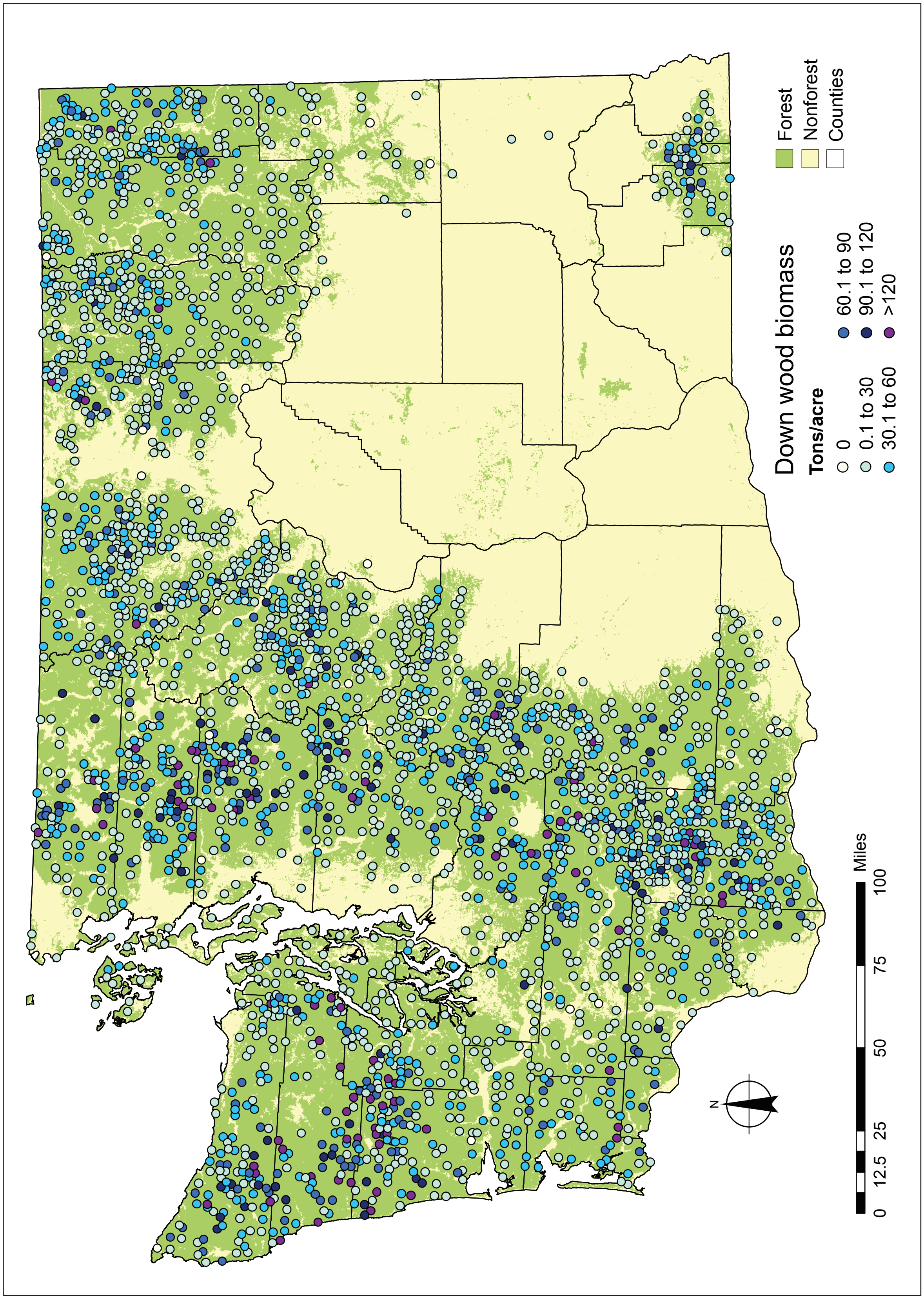

Figure 34—Plot distribution of total down wood biomass (tons per acre), Washington, 2007–2016 (forest/nonforest geographic information system layer: Blackard et al. 2008).

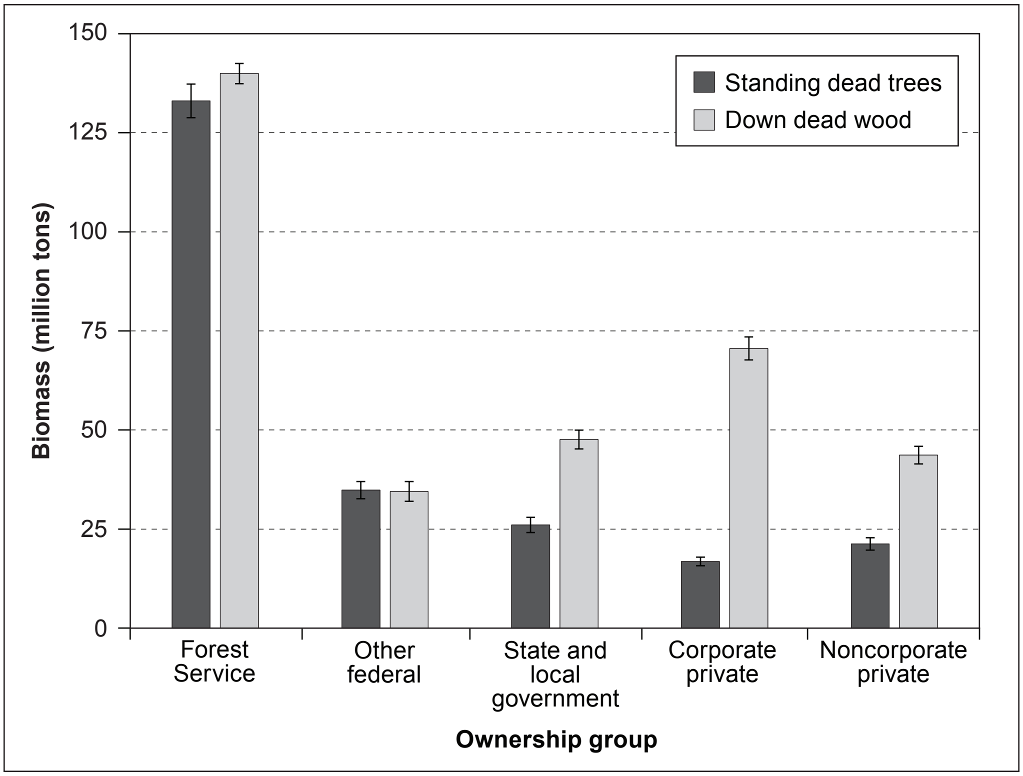

Figure 35—Total biomass (million tons) in standing dead trees (snags) and down dead wood by ownership group, Washington, 2007–2016.

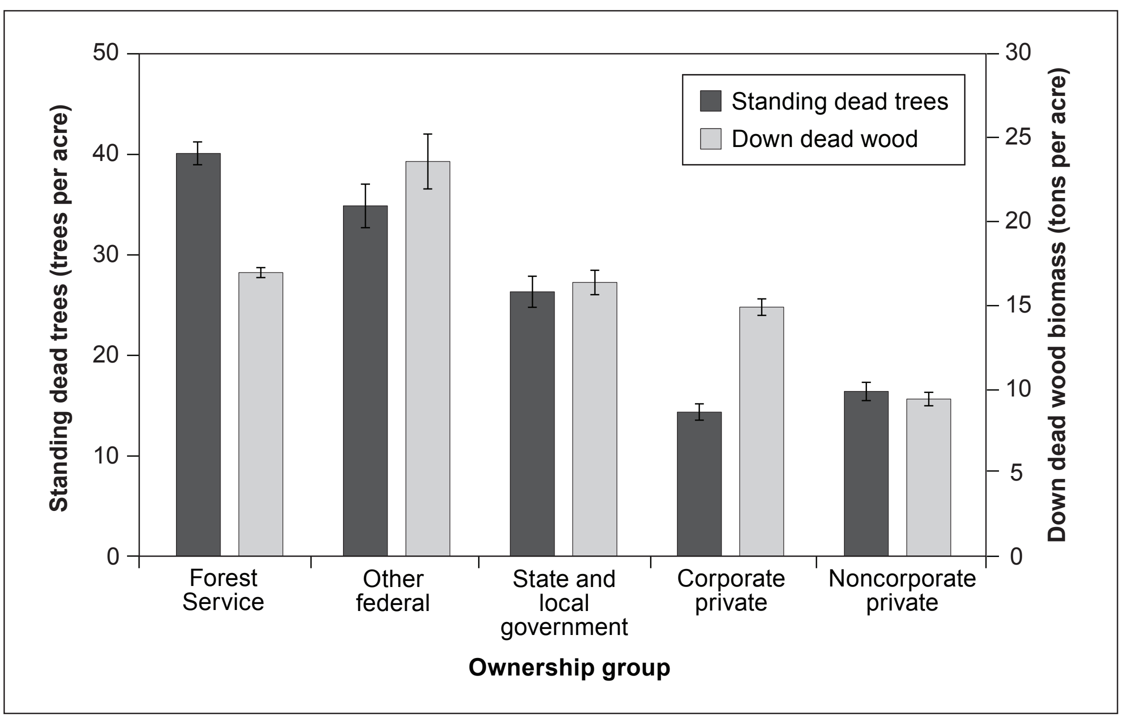

Figure 36—Average number of standing dead trees (snags) per acre and down dead wood biomass (tons) per acre by ownership group, Washington, 2007–2016.

Research Application: Urban Forests and Social Inequality in the Pacific Northwest

John Mills

Studies conducted in several U.S. cities have shown that urban neighborhoods with higher socioeconomic status (SES) tend to be greener, meaning they have a relatively larger proportion of area occupied by trees and shrubs. Trees in the urban environment provide a range of important benefits to local residents, including the removal of air pollutants, moderating air temperatures, and reducing psychological stress. Given the positive association between natural areas in the urban environment and human health, a smaller distribution of greenness in poorer neighborhoods raises significant environmental justice concerns. Studies have shown greenness to be associated with improved health outcomes even where SES indicators are considered low.

In 2011 and 2012, the Pacific Northwest Research Station Forest Inventory and Analysis (PNW-FIA) program initiated a pilot study to extend data collection to include the urban areas of the Pacific Coast states. The study included 213 FIA plots in urbanized areas, as defined by the U.S. Department of Commerce Bureau of the Census, located west of the Cascade Range in northwest Oregon and western Washington (fig. 37). The data allowed for the exploration of the relationship between neighborhood SES, land use, tree cover, tree size, and species diversity across multiple cities in the Pacific Northwest.

Our objective was to link the measured attributes of greenness to the demographic data from the census block group where that greenness was measured (Mills et al. 2016). A pool of candidate SES variables were selected for which past research found a correlation with environmental variables. These include the number of households in a block group, population density, percentage of non-Hispanic White residents, percentage of owner-occupied housing, median household income, and median home values. We assumed that higher levels of owner-occupied housing would reflect greater neighborhood stability and higher home values, and that higher median household income would indicate greater neighborhood wealth. Also considered was a city's length of membership in the Tree City USA program as a surrogate for recognizing the benefits of urban trees by having a city budget and a plan for promoting urban trees via an urban forestry program.

We chose percentage of canopy cover as a dependent variable because cover has been shown to be important in other studies. It was found that subplots had more canopy cover where block groups had higher household incomes. We did not find a significant relationship between canopy cover and race. Perhaps the sample was too dispersed to establish a correlation with race as other studies found, too few or no plots in the few neighborhoods where the majority population is non-White.

A third question asked if higher tree counts might be associated with neighborhoods with higher socioeconomic status. The number of trees on a subplot was positively related to home values after accounting for land use. Because block group median home value is based on owner-occupied housing, this might be thought of as a surrogate for the rate of home ownership as well as relative wealth associated with the neighborhood.

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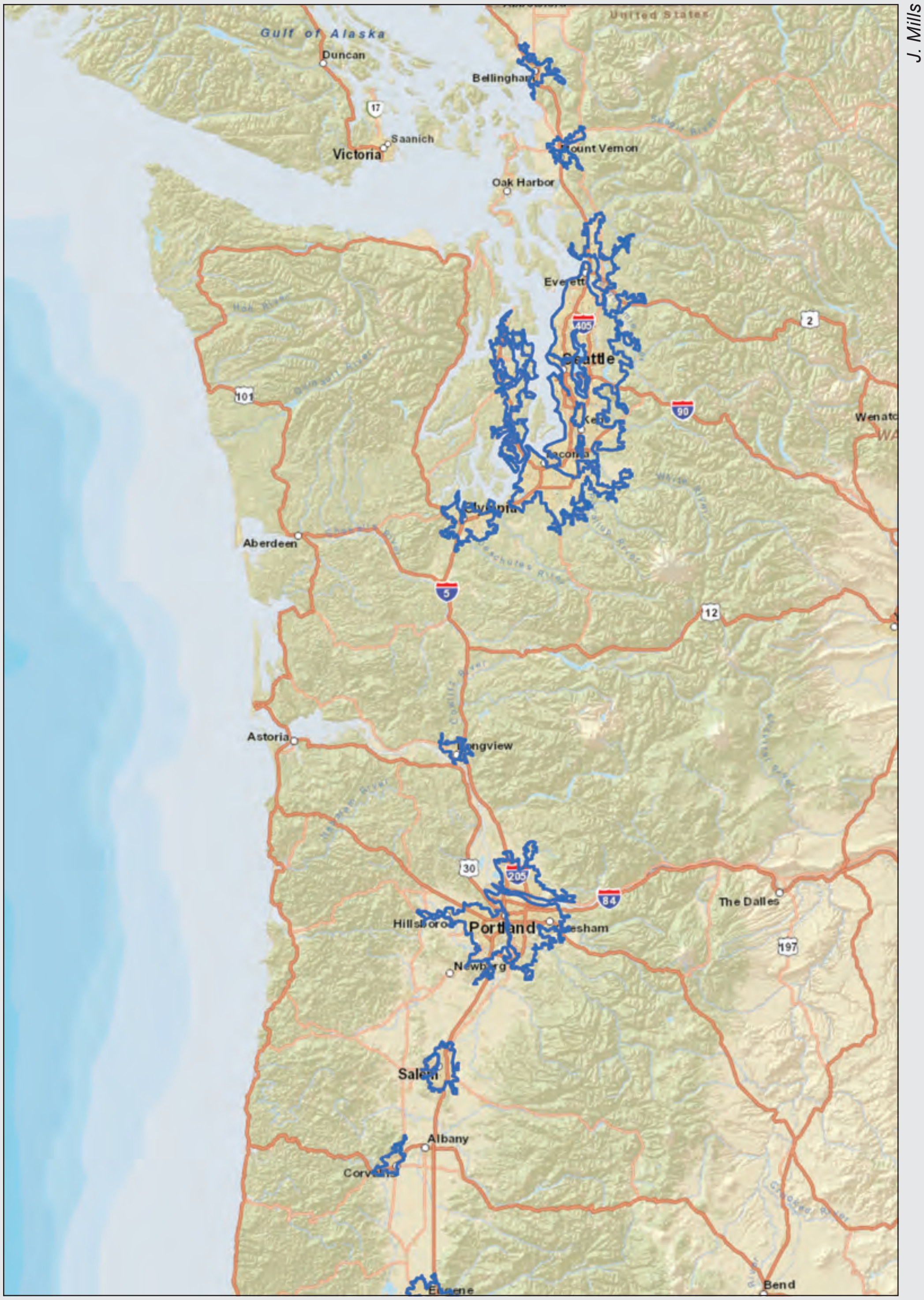

Figure 37—Study area: urbanized areas of western Washington and Oregon (outlined in blue).

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Whereas tree canopy cover and the count of trees are a measure of the urban forest, the number of tree species on a subplot can be an indicator of longer term resiliency. Many tree diseases and pests thrive on a narrow range of species, so neighborhoods with a greater diversity of tree species will likely fare better in the future, in terms of ecosystem services, than those supporting monocultures. This can be an environmental justice issue if there is less tree diversity where SES is lower. The model did indicate a positive relationship between species count and median house value. This supports the view that resiliency of the urban forest will be more likely in neighborhoods with a higher SES.

Many communities use Tree City USA standards to enhance urban forest management through improved ordinances to plan for trees, innovative tree planting programs, and increased emphasis on tree care. Though not a traditional measure of SES, our analysis suggests that over time, in terms of the occurrence of tree canopy, these efforts are usually providing benefits. After adjusting for land use, the odds of the existence of tree canopy cover increases by two times on a subplot for each additional decade that a city has participated in the Tree City USA program.

In the Pacific Northwest, there is a positive correlation between the SES of urban residents and the abundance of the urban forest. This finding agrees with other studies that have found lower neighborhood SES is associated with fewer neighborhood trees. If a city plans to increase total canopy cover to avoid environmental injustice, planners will want to tailor tree planting programs so they will be more likely to succeed in underserved neighborhoods. Increasing canopy cover in these areas has the potential to provide a larger marginal ecosystem services benefit as compared to planting in neighborhoods that tend to have more, and better maintained, environmental amenities.

This study was the first to use urban FIA data for a broad-scale analysis, but it was limited by density of the plot grid in the urban environment. Starting in 2014, FIA adopted a new national strategy for selected urban cities. The plot has been redesigned; rather than four subplots, there is one 48-ft radius circle. The single-subplot sample area is the same (1/6 ac) as the four subplot design, but the design typically intersects fewer properties and is easier to install. The sampling intensity was also increased so that 200 plots could be installed in a city's core area. Like the forest plots, the urban plots are assigned a panel number and scheduled for future remeasurement. This approach is being implemented in roughly 30 large cities east of the Rocky Mountains. Meanwhile, PNW-FIA has partnered with San Diego, California, and Portland, Oregon, to begin this inventory system west of the Rocky Mountains. FIA hopes to continue this urban effort on a city-by-city basis as it evolves into a broader forest-monitoring mission.

Literature cited—

Mills, J.R.; Cunningham, P.; Donovan, G.H. 2016. Urban forests and social inequality in the Pacific Northwest. Urban Forestry & Urban Greening. 16: 188–196.

Understory Vegetation and Nontimber Forest Products

The PNW-FIA collects information on the predominant understory species in each life form (shrubs, forbs, and graminoids) and structural classifications for each life form on every forested plot. Structural classifications provide information on the vertical layers (height) that each life form occurs in, which can be used to model fuel loading. Understory plant composition often indicates underlying ecological conditions within microsites, and broad species trends are useful at a landscape level. Wildlife may use specific understory plant species or communities, and both woody and nonwoody plants contribute to the carbon storage of a site. Abundance of tree seedlings is important in determining potential forest succession.

Average understory vegetation cover across all forested lands in Washington is around 56 percent, but is highly variable depending on each stand's species composition, age, and disturbance history (fig. 38). In general, riparian-associated forest types such as alder/maple and elm/ash/cottonwood tend to have the densest understory cover, while dry-site forest types such as lodgepole pine have more sparse understories. Young stands with recent disturbance tend to have the highest cover of graminoids, while shrub cover peaks in stands aged 40 to 79 years. The oldest stands have the lowest total understory plant cover (fig. 39).

An analysis of presence of selected nonnative plants was conducted using the available vegetation data, in which only plants with at least 3 percent cover on field plots were recorded. Nonnative plants were recorded by field crews on approximately 15 percent of field plots, and nonnative plants are estimated to cover less than 2 percent of all forest land area. Cheatgrass and Himalayan blackberry are the two most prevalent forest invaders in Washington, each estimated to cover more than 110,000 ac of forest land (fig. 40). Cheatgrass is most common in east-side forests near rangeland areas, and Himalayan blackberry is found throughout the west side. Several other annual grasses as well as Scotch broom are common nonnatives on Washington forest land. Nonnative, invasive plants on forest lands can affect forest composition and health, alter wildlife habitat, and affect ecosystem processes (Rapp 2005).

In the Pacific Northwest, evergreen boughs, floral greens, and edible mushrooms are valuable nontimber forest products (NTFPs) with substantial cultural significance and economic value (Alexander et al. 2011). NTFPs include plants, fungi, and animal products that are harvested for both commercial and individual uses. The most abundant NTFP shrubs, in terms of acres of forest land with a cover of each species, are salal, vine maple, and salmonberry (fig. 41).

Jessica Deans

Figure 38—Forest understory vegetation cover differs broadly by ecoregion and forest type and at smaller spatial scales with microhabitats within each stand. This stand near Lake Quinault in Olympic National Park demonstrates dense understory where increased light levels penetrate through canopy gaps.

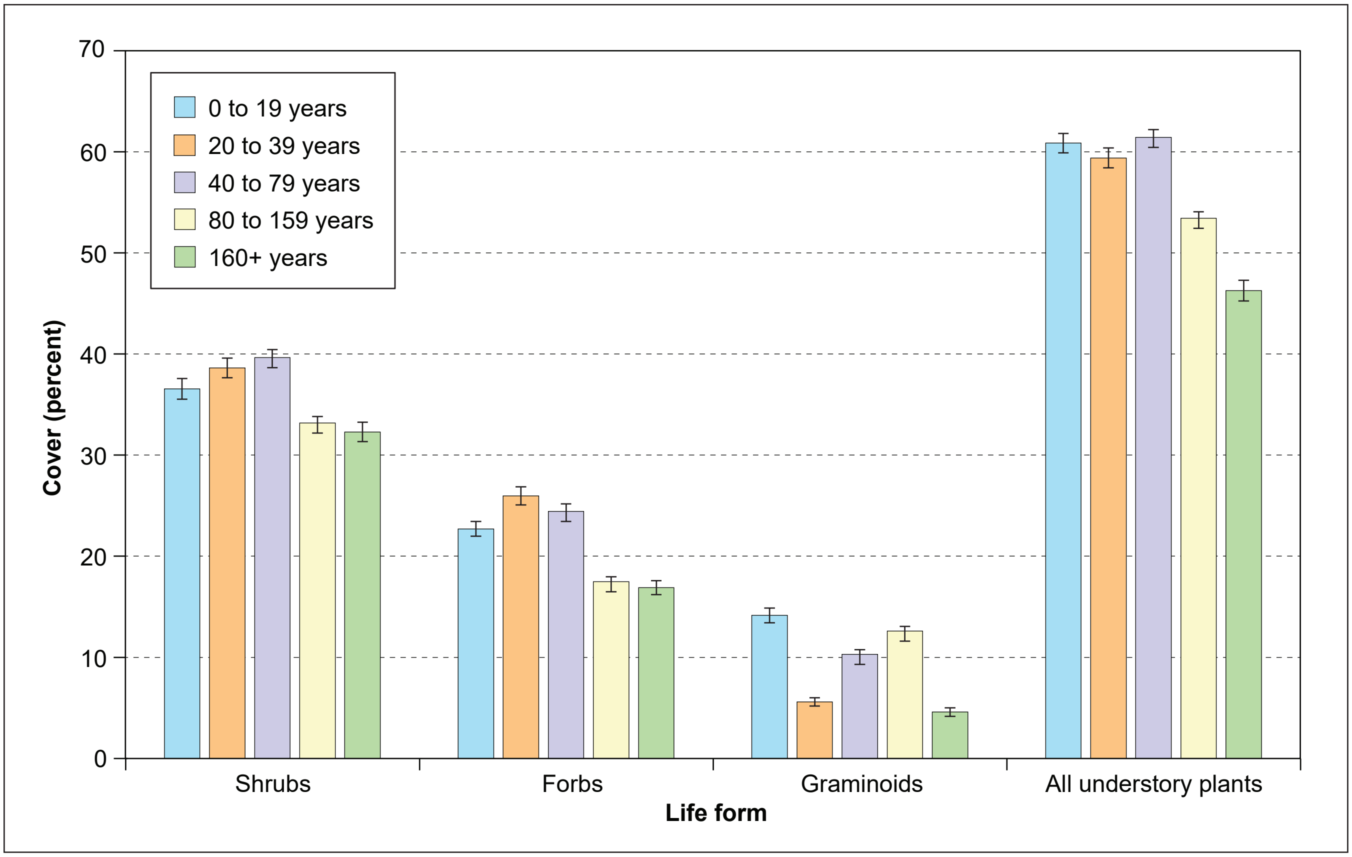

Figure 39—Cover of understory vegetation life forms by forest age class (years) on forest land, Washington, 2007–2016.

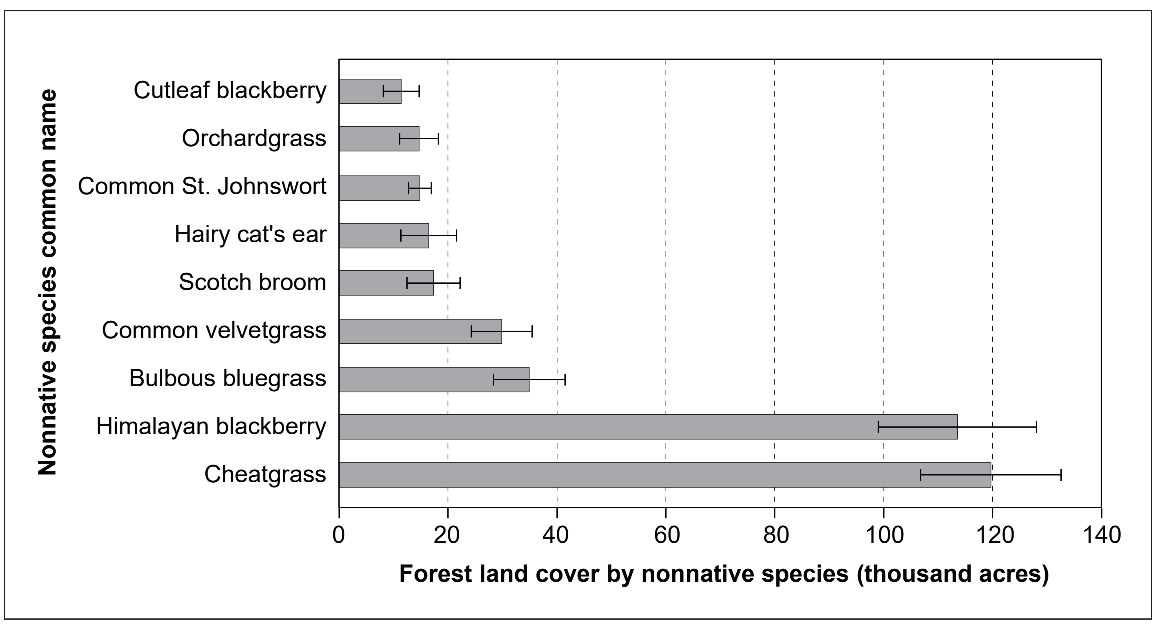

Figure 40—Nonnative invasive species with the highest acreage of cover on forest land in Washington, 2007–2016. Nonnative species estimated to comprise at least 10,000 ac of cover are shown.

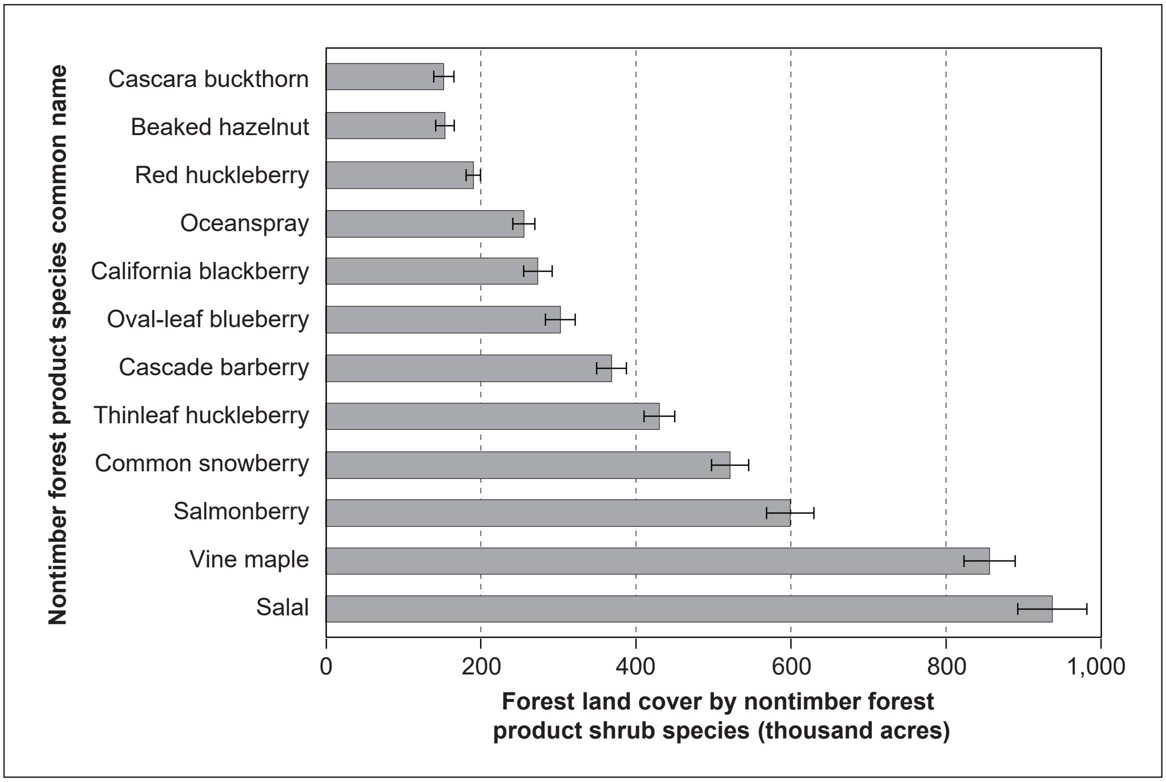

Figure 41—Total shrub cover (acres) on forest land by selected species used in nontimber forest products. Shrub species with at least 150,000 ac of cover are shown.

Forest Recreation

Washington's forest lands provide tremendous recreation value, and user demand at recreation sites continues to increase with the state's growing population. Most forest recreation activities occur on the 57 percent of Washington forest lands that are publicly owned. Forest recreation on federal lands takes a multitude of forms, and the values that individuals receive from recreation are difficult to quantify. White et al. (2016) examined the top recreation activities occurring on federal lands, noting that the top activities on NFS lands include viewing scenery/natural features, hiking/walking, relaxing/hanging out, and viewing wildlife. National Forest System visitor recreation fee revenues for the Pacific Northwest Region (covering Oregon and Washington) have steadily increased during the 10-year period of this report, reaching $9,740,790 in 2016 (compiled from the region's Recreation Fee Program Accomplishment Highlights reports, https://www.fs.usda.gov/detail/r6/passes-permits/recreation/?cid=fsbdev2_026999). A 2012 analysis estimated that recreation visits to federal lands nationwide contributed $51 billion to the U.S. economy and supported 880,000 jobs (English et al. 2014). Rural communities surrounding these recreation destinations benefit from recreation-related spending. Recreation activities expected to increase most in the next 15 years include developed skiing, visiting interpretive sites, day hiking, birding, and equestrian activities (White et al. 2016). Washington's 3.8 million ac of reserved forest lands provide many recreation opportunities, and recreation occurs on many of the 12.7 million ac of publicly owned forests.

Forest Health

Several key forest health concerns exist in Washington, among them forest insect and disease outbreaks and wildfire. Eastern Washington forests were historically dependent on frequent low-severity fires, but more than a century of grazing, removal of large fire-tolerant trees, and a policy of fire exclusion has created current forest conditions that differ markedly from the original composition (Perry et al. 2011, Stine et al. 2014). When the first forest survey of eastern Washington was completed in 1936, 40 percent of net sawtimber volume (at least 12 inches d.b.h. on all forest land) was in ponderosa pine and 27 percent in Douglas-fir; just 9 percent of volume was in true firs (Cowlin and Moravets 1938). Estimates from 2016 that used the most similar definitions possible demonstrate that species distribution has shifted considerably away from ponderosa pines and into Douglas-fir and true firs (fig. 42). Total net volume (Scribner board feet, 12+ inches d.b.h.) is harder to compare because of the uncertain merchantability standards used in the 1936 survey. Assuming that the 1936 survey used the same cull/defect rates, net volume on eastern Washington forest land has more than doubled in the past 80 years. It is likely that more gross volume was excluded in the 1936 survey than in 2016 because of improved harvest utilization and forest products technology, so the true volume increase over this time is probably closer to 50 percent. Overall, it is clear that current forest conditions on the east side include denser forests of smaller diameter trees (more volume per acre) as well as a less fire-tolerant species mix (increased Douglas-firs and true firs and fewer ponderosa pines).

FIA data are used to track forest health in a number of ways. Trends in forest composition and structure are important baselines for comparison of the historical variability of forest resources in the state. In addition, specific FIA variables such as damaging agents (tracking damages to live trees), mortality agents (listing cause of death of recently dead trees), stand level disturbances, and evidence of fire can provide clues to how and why forests are changing across the landscape.

Current forest composition exposes eastern Washington forests to additional risk of both insect and disease and wildfire mortality. Aerial survey results for 2017 estimated 3.4 million recently killed trees and increases in several beetle species that may be associated with 2015 wildfires in eastern Washington (WDNR 2018b).

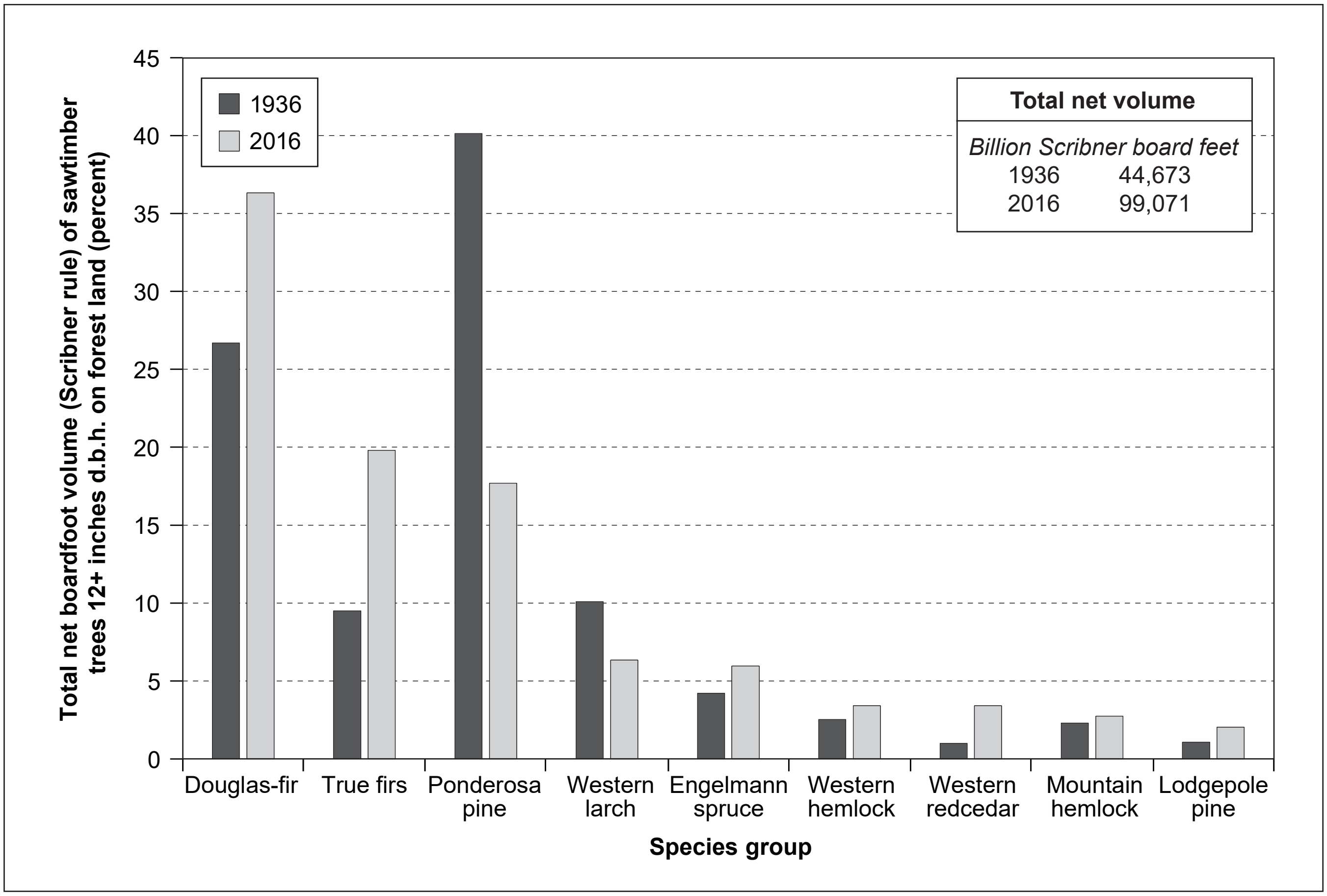

Figure 42—Distribution of major species on eastern Washington forest land, 1936 and 2016. Estimates show the percentage of total net live volume, in Scribner board feet, in live trees at least 12 inches diameter at breast height (d.b.h.). Estimates for 1936 are from Cowlin and Moravets (1938). Merchantability standards differed between 1936 and present, so comparisons are approximate.

Damaging Agents

Although the health of each tree is a combination of many physical and environmental factors, physical signs of stress or damage can often be attributed to a primary agent. Damage can occur owing to a number of factors including animals, insects and disease, mistletoe infestation, weather, or physical defects. Most of the damages assessed by FIA are natural agents that play a role in forest succession. Detecting trends in damages to live trees at the stand level can aid in assessments of a forest's future composition and resiliency.

FIA field crews assess each measured live tree for damaging agents. In the Pacific Northwest states, regional damage codes, including location and severity, were implemented at the start of the annual inventory. This damage coding system was replaced by a nationally consistent protocol in 2013. Details for both protocols are included in O'Connell et al. 2017, and the two systems are compatible when summarizing to general categories.

Eastern Washington 20-Year Forest Health Strategic Plan

Marin Palmer

In 2017, the Washington Department of Natural Resources released the *20-Year Forest Health Strategic Plan: Eastern Washington*, available at https://www.dnr.wa.gov/ForestHealthPlan. This plan was developed in collaboration with more than 33 organizations and agencies, and it outlines five broad goals for addressing eastern Washington's urgent forest restoration needs. Nearly 30 percent of eastern Washington's forests need treatment to become more resilient to insects, diseases, and wildfire. Goal 1 of the plan is "Conduct 1.25 million acres of scientifically sound, landscape-scale, cross-boundary management and restoration treatments in priority watersheds to increase forest and watershed resilience by 2037" (WDNR 2018c).

The plan acknowledges that this effort will not succeed overnight, but establishes the collaboration structure necessary to increase the pace and scale of restoration in the state. HUC-5 level watersheds were each given a priority level for restoration need, with highest priority given to areas with high disturbance probability and low fire or drought resilience. This scientific assessment was based on a multitude of factors, including fire risk, wildland-urban interface areas, drinking water, aquatic resources, wildlife habitat, timber volumes, and factors associated with climate change. The *20-Year Forest Health Strategic Plan* has promise to meaningfully reduce wildfire and forest health risks at a landscape scale and reverse the current trend of declining forest health.

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Almost one-fourth of all live trees in Washington (2.27 billion) are affected by damage or defect. These affected trees represent 37 percent of Washington's total live tree volume. The most common damage agent, affecting 13 percent of all live trees, was physical injury and defects (fig. 43). This category includes fire damage; human activities, including damage caused by harvest activity; and deformities such as broken tops, crooks, or open wounds. Two percent of all live trees were affected by dwarf mistletoe.

Physical injury and defects affected between 9 and 15 percent of live trees for each of the four most numerous conifer species in the state (Douglas-fir, western hemlock, Pacific silver fir, and western redcedar). Western white pine and whitebark pine had the highest damage rates at 44 percent each. Cankers, often indicative of white pine blister rust infection, affected 17 percent of all live western white pine trees. Western white pines were most often damaged by physical injury and defects (36 percent of live trees) or weather (16 percent).

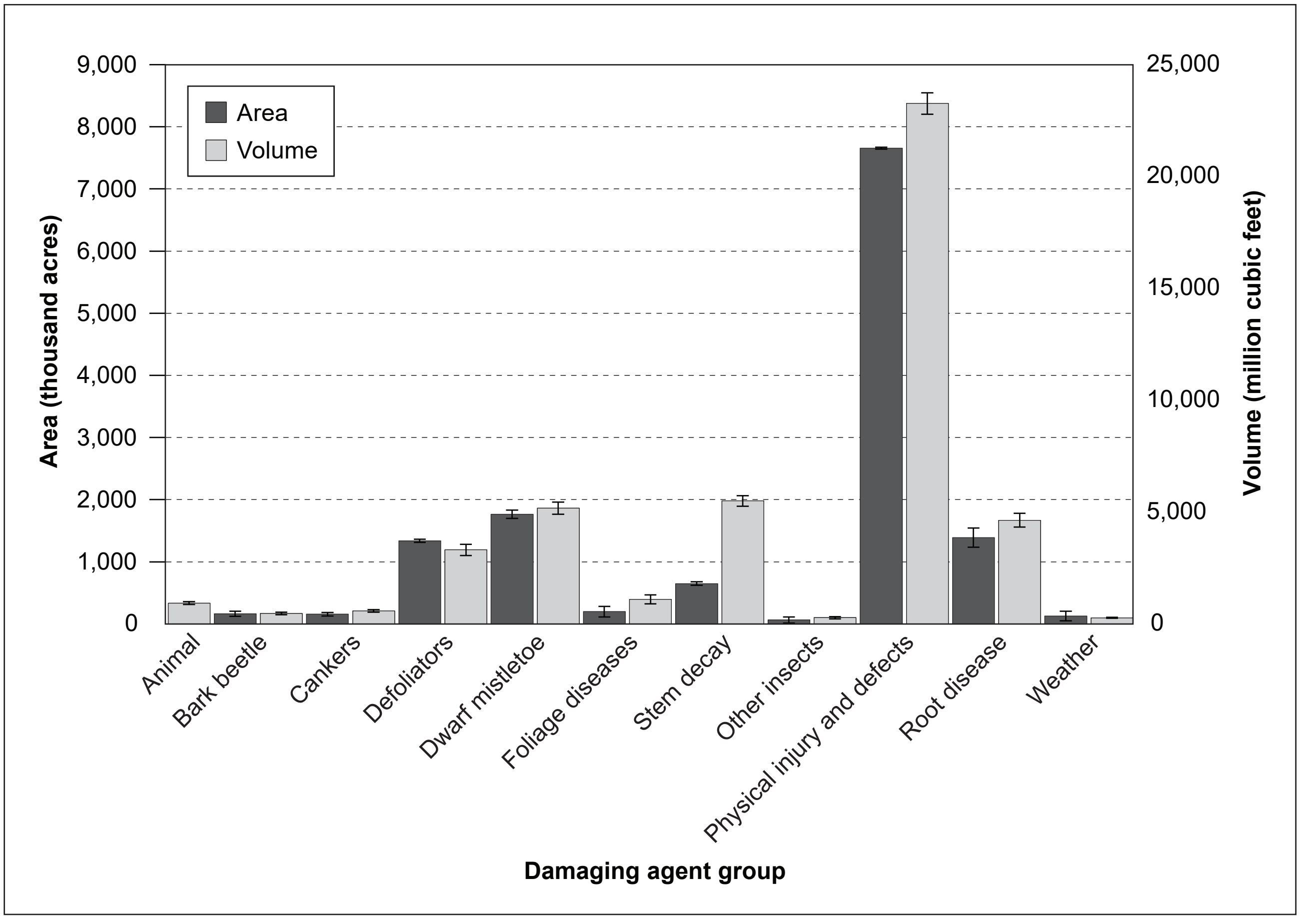

Figure 43—Area and volume of live trees affected by one or more damage agents on forest land, Washington, 2007–2016; volume is gross volume of live trees >5 inches diameter at breast height (d.b.h.); area includes stands with >25 percent of the basal area with damage.

Research Application: Inventory Data Shed Light on Fire Effects on Washington's Forested Lands

Jason Barker

Improving the assessment of wildfire hazard and associated risk of mortality is central to planning forest management in Washington. Pacific Northwest Research Station Forest Inventory and Analysis researchers started the Fire Effects and Recovery Study (FERS) to gather postfire data on fire-affected FIA plots in California, Oregon, and Washington. Data gathered include fire effects on tree crowns, boles, and the forest floor. A major factor in determining the postfire morality is damage done to the photosynthetic capacity of trees through burning or scorching. Foliage consumed in the fire is referred to as burned, while foliage killed by convective heat transfer is termed scorched. Forty-one FIA plots in Washington had additional FERS variables collected between 2012 and 2015, selected for their location within a recent fire perimeter.

Twenty of the FERS plots were located in the area burned by the Table Mountain Complex, which started September 8, 2012, and burned 42,312 ac near Cle Elum. The fire-affected plots had first-year postfire mortality, expressed as a percentage of basal area, ranging from a low of 24 percent in ponderosa pine forest type to 100 percent in Douglas-fir (table 7). Stands with higher basal area had higher mortality, with the exception of the grand fir forest type. The lone Douglas-fir stand saw complete mortality as most of the tree crowns were burned in the wildfire. Within Engelmann spruce forest types, an average of more than 40 percent of each tree crown burned with comparable levels of crown scorched (fig. 44) The high mortality (above 75 percent of basal area) in the Engelmann spruce and subalpine-fir forest types was associated with roughly 40 percent mean burned and scorched crowns.

Directly linking mortality of individual trees with crown damage is a major research challenge. Trees with substantial damage to their crowns,

Table 7—Prefire basal area (BA) and postfire percentage of mortality for FIA plots directly affected by the 2012 Table Mountain wildfire

	Prefire mean BA		Mortality		Number of stands
Forest type	Mean	SE	Mean	SE	
	Square feet per acre		*Percent*		
Douglas-fir	264	—	100	—	1
Engelmann spruce/subalpine fir	234	92	84	11	4
Grand fir	191	47	46	44	3
Lodgepole pine	144	77	35	49	3
Ponderosa pine	62	10	24	27	2
Subalpine fir	174	50	78	18	7

SE = standard error; — = not applicable.

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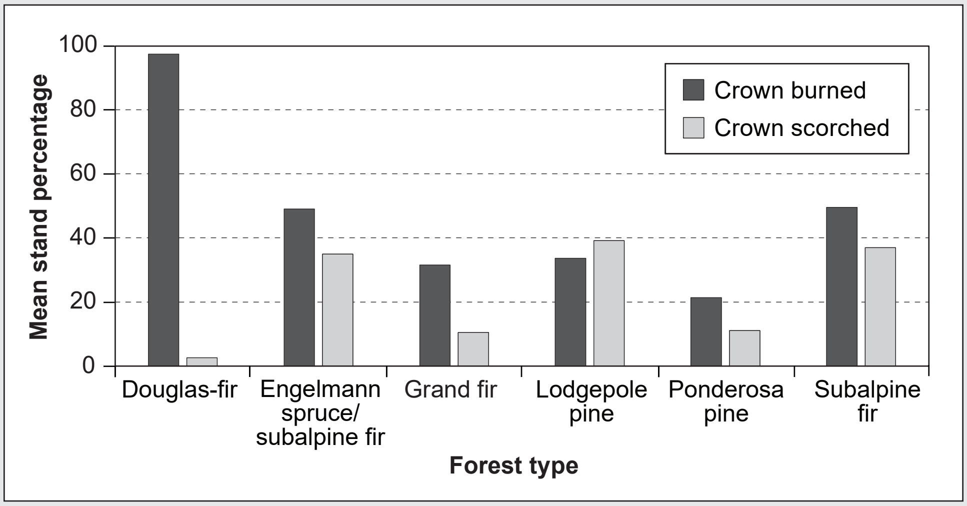

Figure 44—Mean stand percentage of crown burned and scorched in Fire Effects and Recovery Study wildfires by forest type.

through burning, scorching, or a combination of the two, are likely not to survive 3 years postfire. What constitutes substantial damages differs by species. For example, research into ponderosa pine suggests that conifers with more than 80 percent scorched or more than 40 percent burned crowns are likely to die within 3 years postfire (Fowler and Sieg 2004). Trees with low crown damage can nonetheless experience mortality because of damage to their roots.

Ongoing research is linking fire-effects data collected with the regular pre- and postfire inventory sampling to look at relationships between postfire mortality at the stand and tree levels. This research is being used to improve models used to predict postfire mortality and plan fuels reduction treatments, such as the widely used Forest Vegetation Simulator.

Literature cited—

Fowler, J.F.; Sieg, C.H. 2004. Postfire mortality of ponderosa pine and Douglas-fir: a review of methods to predict tree death. Gen. Tech. Rep. RMRS-GTR-132. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 25 p.

Wildfire

Wildfire plays an important role in both forest and nonforest ecosystems in the Northwest and is a driver of forest succession. Eastern Washington's forest composition today has been shaped by a history of relatively frequent low-intensity fires, followed by aggressive and effective fire suppression efforts for the past 100 to 150 years (Stine et al. 2014). Wildfire management and forest restoration remain contentious issues. Consensus exists around the dependence of many of Washington's forest ecosystems on fire to maintain forest health. However, uncontrolled wildfires can result in loss of timber value and changes in wildlife habitat, threaten structures and lives, and pose risks to human health from smoke. Management plans must necessarily be unique depending on the historical and recent disturbance patterns of each forest stand or watershed, which differ depending on moisture regimes and forest composition.

The Northwest Interagency Coordination Center (NWCC) tracks wildland fire on an annual basis for Oregon and Washington, compiling statistics for large fires (at least 100 ac on timberlands or 300 ac in grasslands/rangelands). In Washington, between 2007 and 2016, an average of 264,860 ac burned in large fires annually (NWCC 2017); this estimate covers all wildlands including grass/shrub areas. In 2015, Washington had several very large fires including the Okanogan Complex; with more than a million acres burned, the 2015 total was more than seven times the prior 10-year average (fig. 44).

FIA collects fire occurrence data and fire year on all forested field plots when fire causes mortality or damage to at least 25 percent of all trees in a stand or 50 percent of a single species count or when at least 25 percent of the soil surface or understory vegetation has been affected (fig. 45). These data can give an indication of the area of forest land burned by all fires regardless of their size. The annual average using FIA 2007–2015 field plot estimates was 153,917 forested ac burned statewide, with forested acreage burned in 2015 astoundingly fivefold higher (fig. 46). This estimate covers evidence of fire on forest land only, in contrast to the NWCC estimate above, which covers large fires on all wildlands, including grass/shrub lands.

The number of burned acres oversimplifies fire dynamics in ecosystems because fire severity is not uniform even within a single burn; to gauge effects on forest stands, individual tree measurements add valuable information on pre- and postfire carbon dynamics and stand regeneration. A comprehensive analysis of all Oregon and Washington NFS land area affected by fire indicated that less than half that area burned at high severity (Whittier and Gray 2016). In addition, the amount of carbon per acre lost from stands within 5 to 10 years of fire is on average comparable to the amount lost from current thinning practices (Gray and Whittier 2014).

G. Burkhart

Figure 45—Field crew collecting data on a Forest Inventory and Analysis plot recently affected by fire, eastern Washington.

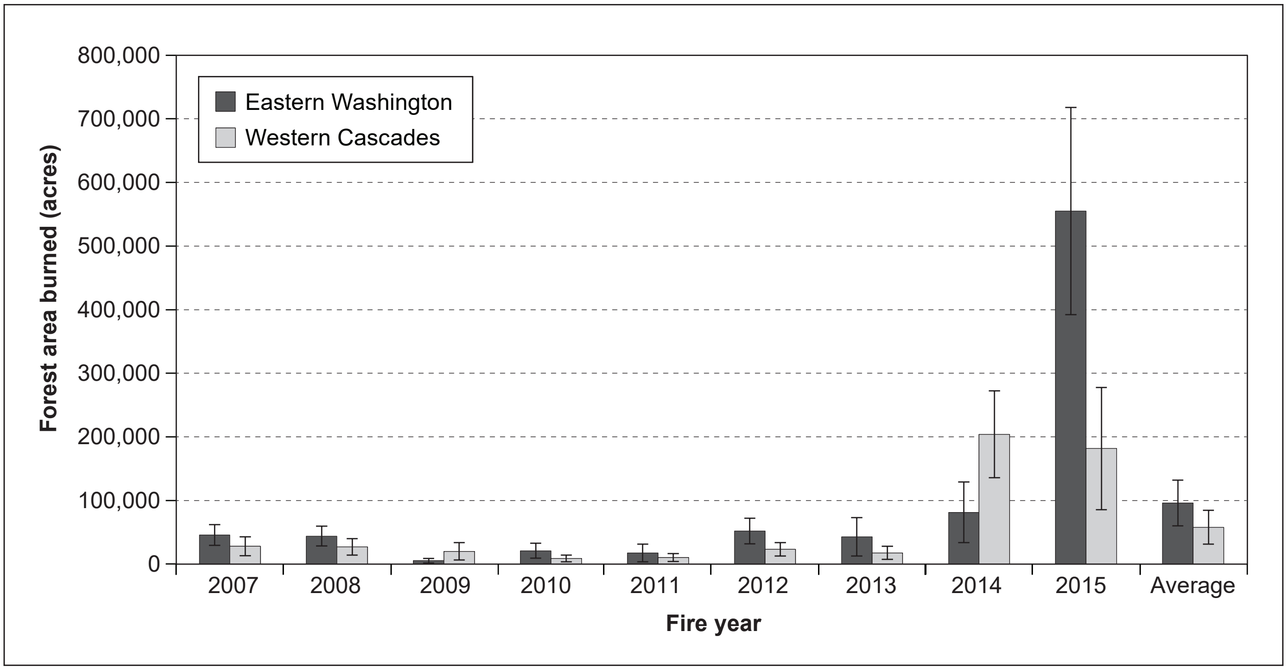

Figure 46—Area of forest land with evidence of fire, by region, Washington, 2007–2015.

The PNW-FIA implemented an additional postfire study starting in 2015 on recently burned plots to capture fire effects and gauge regeneration across the Pacific Northwest. The FIA grid provides prefire and postfire comparisons for a variety of fire intensities. Postfire measurements include individual live tree, dead tree, down wood, and groundcover and fuels variables. A study using these protocols on FIA plots in California determined that the conceptual carbon trajectories frequently used, which assume rapid flux of carbon out of woody pools, may not be appropriate for many postfire stands. Eskelson et al. (2016) found no evidence of net change in total wood carbon (wood in standing trees >5 inches d.b.h. and down wood >3 inches in diameter) over the period 1 to 6 years postfire, regardless of fire severity class. Further analysis of postfire dynamics using this extensive network will provide new insights on the effects of fires on carbon stocks and regeneration.

Research Application: Climatic Constraints Among Washington's Forest Plants and Lichens

Robert J. Smith and Sarah Jovan

Agencies, industry partners, conservationists, and the public are increasingly interested in how shifting weather trends may constrain forest vegetation. Declining performance and turnover in species composition are becoming especially evident among epiphytic lichens, whose habit of growing harmlessly upon woody plants exposes them directly to the atmosphere. Given knowledge of climatic constraints, which species and sites are most vulnerable to change if Washington's forests become warmer or drier?

Vulnerability assessments can anticipate forest health declines by giving an expectation of locally losing species where their climatic limits become violated. For each of 443 epiphytic macrolichen species, we combined herbarium data with presences/absences in 6,474 Forest Inventory and Analysis plots nationwide to estimate a realized niche describing summer temperature tolerances (Smith et al. 2017). Vulnerable populations were those near each species' climatic limits in the 95th percentile "tail" of the niche.

Widespread species with many vulnerable populations in Washington included *Alectoria sarmentosa* (witch's hair lichen) (fig. 47), *Hypogymnia wilfiana/metaphysodes* (deflated tube lichen) and *Nephromopsis orbata* (variable wrinkle lichen), among others. Because these populations represent a combination of high exposure and high expected sensitivity to climate changes, they could be suitable candidates for climate monitoring in the state.

The vulnerability approach readily extends from single species to sites with many co-occurring species. Three novel niche-based indices revealed that Washington's most vulnerable sites were clustered near the forested margins of the Columbia River basin in the north-central and northeastern interior of the state. Intensified monitoring in these high-vulnerability areas could help efficiently detect changes in forest diversity by directing effort to where changes are most expected.

A common assumption is that warming air temperatures should most affect "cold-adapted" communities in northern or montane locations—in contrast, we found that vulnerability was concentrated in low-elevation and southerly sites where species were close to exceeding their thermal limits, despite being "warm-adapted." For example, Washington's most vulnerable lichen communities were at interior sites in the dry *Pinus ponderosa*–*Pseudotsuga menziesii* zone characterized by low to moderate elevations and hot summer temperatures.

Ongoing work will provide Web-accessible, accurate, regionally specific forecasts of future impacts based on relative vulnerability among trees, shrubs, herbs, and lichens. This will help distinguish

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Figure 47—Mature conifers draped with an abundance of *Alectoria sarmentosa* (witch's hair lichen) near Cascade Pass in northern Washington.

which groups of vegetation will be most sensitive and exposed to future shifts in climate regimes. Characterizing climatic limits to species distributions will help to identify which forest species and sites are most at risk of declining, and can help provide early warning of long-term forest changes.

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Online Tables

A suite of 125 summary data tables that accompany this report are available online at https://www.fs.fed.us/pnw/pubs/pnw_gtr976-supplement.pdf. and are listed below for reference.

Number of Plots

Table 1—Number of Forest Inventory and Analysis plots measured by sample status, land class, and ownership group, Washington, 2007–2016

Area

Table 2—Area of sampled land and water by land status and ownership group, Washington, 2007–2016

Table 3—Area of forest land by county and land status, Washington, 2007–2016

Table 4—Area of forest land by county and ownership group, Washington, 2007–2016

Table 5—Area of forest land by ownership and land status, Washington, 2007–2016

Table 6—Area of forest land by forest type group and land status, Washington, 2007–2016

Table 7—Area of forest land by forest type group and site productivity class, Washington, 2007–2016

Table 8—Area of forest land by forest type group, ownership group, and land status, Washington, 2007–2016

Table 9—Area of forest land by forest type group and stand size class, Washington, 2007–2016

Number of Trees

Tree Volume

Biomass

Carbon

Down Wood

Combined Dead Trees and Dead Wood (Standing Dead Trees and Down Wood)

National Forest System (NFS)

Tree Damage

Understory Vegetation

Timber Products Output and Removals:

Annual Growth, Removals, and Mortality

Evidence of Fire

Common and Scientific Plant Names

Life form	Common name	Scientific name
Trees:	Alder	*Alnus* spp.
	Ash	*Fraxinus* spp.
	Aspen, quaking aspen	*Populus tremuloides* Michx.
	Birch	*Betula* spp.
	Cottonwood	*Populus* spp.
	Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
	Elm	*Ulmus* spp.
	Engelmann spruce	*Picea engelmannii* Parry ex Engelm.
	Hemlock	*Tsuga* spp.
	Jeffrey pine	*Pinus jeffreyi* Balf.
	Lodgepole pine	*Pinus contorta* Douglas ex Loudon
	Maple	*Acer* spp.
	Mountain hemlock	*Tsuga mertensiana* (Bong.) Carrière
	Oak	*Quercus* spp.
	Ponderosa pine	*Pinus ponderosa* Lawson & C. Lawson
	Red alder	*Alnus rubra* Bong.
	Sitka spruce	*Picea sitchensis* (Bong.) Carrière
	Spruce	*Picea* spp.
	True fir species	*Abies* spp.
	Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
	Western juniper	*Juniperus occidentalis* Hook.
	Western larch	*Larix occidentalis* Nutt.
	Western redcedar	*Thuja plicata* Donn ex D. Don
	Western white pine	*Pinus monticola* Douglas
	Whitebark pine	*Pinus albicaulis* Englem.
Shrubs:	Beaked hazelnut	*Corylus cornuta* Marshall
	California blackberry, trailing blackberry	*Rubus ursinus* Cham. and Schltdl.
	Cascade barberry, dwarf Oregon grape	*Mahonia nervosa* (Pursh) Nutt.
	Cascara buckthorn	*Frangula purshiana* (DC.) A. Gray
	Common snowberry	*Symphoricarpos albus* (L.) S.F. Blake
	Cutleaf blackberry	*Rubus laciniatus* Willd.
	Dwarf mistletoe	*Arceuthobium* spp. M. Bieb.
	Himalayan blackberry	*Rubus discolor* Focke
	Oceanspray	*Holodiscus discolor* (Pursh) Maxim.
	Oval-leaf blueberry	*Vaccinium ovalifolium* Sm.
	Red huckleberry	*Vaccinium parvifolium* Sm.
	Salal	*Gaultheria shallon* Pursh
	Salmonberry	*Rubus spectabilis* Pursh
	Scotch broom	*Cytisus scoparius* (L.) Link

Life form	Common name	Scientific name
	Thinleaf huckleberry	*Vaccinium membranaceum* Douglas ex Torr.
	Vine maple	*Acer circinatum* Pursh
Forbs:	Common St. Johnswort	*Hypericum perforatum* L.
	Hairy cat's ear	*Hypochaeris radicata* L.
Graminoids:	Bulbous bluegrass	*Poa bulbosa* L.
	Cheatgrass	*Bromus tectorum* L.
	Common velvetgrass	*Holcus lanatus* L.
	Orchardgrass	*Dactylis* L.

Acknowledgments

Countless field staff worked diligently to collect our field data, traversing all portions of the state. This report would not be possible without our data collection, quality assurance, and information management specialists who contribute their time and talent to capture the FIA dataset and make it available to the public.

Metric Equivalents

When you know:	Multiply by:	To find:
Inches (in)	2.54	Centimeters
Feet (ft)	0.3048	Meters
Acres (ac)	0.405	Hectares
Board feet	0.0024	Cubic meters
Cubic feet (ft^3)	0.0283	Cubic meters
Cubic feet per acre (ft^3/ac)	0.0670	Cubic meters per hectare
Tons per acre	2.2417	Megagrams per hectare

U.S. Equivalents

When you know:	Multiply by:	To find:
Kilograms (kg)	2.2046	Pounds
Megagrams (Mg)	1.1023	Tons
Megagrams per hectare	0.4461	Tons per acre

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