Oregon Global Warming Commission

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Oregon Global Warming Commission

Forest Carbon Accounting Project Report

2018

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Introduction

In 2016, the Oregon Global Warming Commission convened a stakeholder task force with support from scientists from the U.S. Forest Service and Oregon State University's Oregon School of Forestry to advance our understanding of the carbon potential in Oregon's forests. This effort followed the Commission's 2010 "Roadmap to 2020" Report to the Legislature, which outlined recommendations for reducing Oregon's greenhouse gas emissions in other sectors. In 2010, stakeholders and Commission Members felt unable to examine forest carbon at any depth due to the lack of sufficient usable data. By 2016 the Commission had access to U.S. Forest Service Forest Inventory and Analysis (FIA) data collected from 2001-2005 and 2010-2015, and additional data generated by the Oregon State University School of Forestry. Interest had grown among legislators and stakeholders to better understand the significance and dynamics of forest carbon, and how it interacts with forest management practices and policies. With assistance and guidance from members of the Task Force and other sources, the Commission has developed a preliminary assessment of carbon stores and fluxes.[1] The results should be treated as interim, subject to additional research the Oregon Department of Forestry has been funded to undertake to answer many of these questions in greater detail.

Generally, the Commission drew the following broad preliminary observations:

1. Oregon forests hold globally significant carbon stores, in forests that, notwithstanding two centuries of harvest and other landscape changes, rival tropical rain forests for carbon density and quantity of stores.[2] Carbon contained in Oregon forests was likely substantially greater prior to Euro-American settlement over the last 200 years, settlement that included land clearing for agriculture and intensive logging as important early commercial activities.[3] While prior levels of forest carbon are unlikely to be recovered, significant increases from present levels are possible with changes in forest management, along with incentives and offset programs for forestland owners. Increasing that could be supported for forestland owners.[4] Increasing carbon stores in Oregon forests can be a valuable part of how the state contributes to global climate change mitigation, *additional* to the emissions reductions that must be found elsewhere in Oregon's economy.

[1] While this Report is not a product of the Task Force and should not be characterized as such, it has gratefully benefited from the expertise and intellectual contributions of the members of that group; and their comments on this Report have been invited.

[2] Land use strategies to mitigate climate change in carbon dense temperate forests, page 1 and Figure S1. Law, Hudiberg et al, 2018.

[3] See Davis, Ohmann et al, "Northwest Forest Plan—The First 20 Years (1994-2013: Status and Trends of Late-Successional and Old Growth Forests" USFS. The paper's maps clearly indicate very large differences in the extent and distribution of old growth and secondary growth from the 1850's to the 1920's/30's to 2012. Because the maps imply but do not directly measure carbon, it is not possible to make the unqualified claim that carbon stores were greater in presettlement times.

[4] Ibid.

2. Forest carbon stores and fluxes (withdrawing carbon from the atmosphere; emitting back to the atmosphere) vary by forest type, ecoregion and ownership. Any incentives should consider these differences and look for optimum gains in capturing and retaining forest carbon while integrating carbon capture and storage with other forest values and functions.

3. There is credible analysis of the impacts of harvesting and processing forest carbon into wood products that suggests that tracking a wood products carbon sequestration pool is important to measuring and mitigating for the loss of carbon stores that may be associated with harvest. It is less clear whether converting standing timber into wood products can be an effective strategy for maintaining or increasing overall forest carbon storage. Finding ways to better align harvest with carbon goals should be an important outcome for evolving state carbon policy and forest management practices.

4. There is ongoing discussion of how to align forest fire policies and forest health restoration treatments (generally, forest biomass thinning and prescribed fire as undertaken by the US Forest Service and others) with increased forest carbon storage. Current analysis suggests that treatments which include medium to heavy thinning result in reduced carbon stores that do not recover in any meaningful time periods. Forest managers may elect to pursue thinning and other restoration treatments to achieve other goals, but to align these activities with forest carbon goals, they should be seeking methods that involve the least loss of carbon stores and the earliest recovery of these stores.

Additional Notes:

- The material findings and recommendations in Sections I and II will frequently rely on the sometimes dense analysis presented in Section III. This burdens the Report with an unfortunate amount of redundancy for which the authors offer apologies in advance. We recommend using the index of "Questions" on page 24 of this report to search Section III for the more extended analysis that underpins specific elements of Sections I and II.

- Readers should also note that quantities of carbon may be expressed as carbon (C), and also converted to carbon dioxide equivalent (CO2e) units by multiplying an amount of carbon by the standard conversion factor of 3.667. Most scientific articles present measurements in Teragrams (Tg) of carbon or million metric tonnes (MMT) of CO2e. We have tried to make the conversion to MMTCO2e whenever doing so does not impeded the narrative, to allow easier comparisons to amounts in Oregon's historical greenhouse gas inventories and Oregon's greenhouse gas goals that are expressed as MMTCO2e. The English unit of "short tons" (2000 lbs/ton) of CO2e are also sometimes used. If not otherwise specified, when short tons are cited, the text will use the word "tons." When metric tonnes are cited, the text will use the word "tonnes."

I. Key Takeaways

The data and conclusions presented below should be taken as interim, given that tools for quantifying amounts, and for tracking flows and fluctuations that result from normal forest ecosystem functions, are incomplete and still evolving. So are harvest practices and tools for measuring and tracking carbon in wood products derived from timber harvest. While there are multiple sources of data and different analytical approaches to assessing forest carbon stocks, the data presented in this report is based on USDA Forest Service Forest Inventory and Analysis (FIA) 2001-2010 data, and is similar to the approach used for national reporting to the Intergovernmental Panel on Climate Change (IPCC) on U.S. forest carbon stocks; and where indicated on subsequent Net Ecosystem Carbon Balance (NECB) data and analysis by scientists from the Oregon State University School of Forestry.

- **Carbon in Oregon Forests**. Oregon's forests sequester very large quantities of carbon, presenting both risks (of release) and opportunities (for greater carbon withdrawal from the atmosphere and long-term forest storage). Oregon forests contain on the order of 3 billion (short) tons of carbon (or ± 10.4 to 11.6 billion tons of CO2e[5]), variously in carbon pools that include standing live trees, standing and fallen dead trees, forest floor vegetation, and soils.[6] How we manage our state's forest carbon stores and dynamics can have a significant effect on Oregon's carbon footprint and its contribution to larger, global carbon goals.

- **Net Annual Forest Carbon Removed from Atmosphere**. Since the early 1990s, Oregon's publicly- and privately-owned forests in aggregate appear to have been removing from the atmosphere and storing between 23 million (short) tons and 63 million tons of CO2e (Harmon 2018a) on average every year (total carbon removed from atmosphere via photosynthesis, less carbon respiration back to the atmosphere, less carbon lost to harvest and to disease, insect predation and wildfire combustion). If only live tree carbon is counted, the annual forest carbon gain from atmospheric exchange is about 38 million tons to 40 million tons (Harmon 2018a). Nationally, carbon stored in forests increased by 10 percent between 1990 and 2013; and

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[5] "Carbon dioxide" (CO2) is a colorless, odorless gas that exists in the earth's atmosphere at a present [2017] concentration of ± 406 ppm and acts as a "greenhouse gas" that reflects radiated heat back to earth, providing atmospheric warming. At concentrations above pre-industrial levels of ± 280 ppm, CO2's greenhouse gas properties contribute to excessive planetary warming and climate disruption. "Carbon" is an element with an atomic weight of 12; add two oxygen atoms to create a molecule of CO2 with an atomic weight of 44. When calculating a "carbon cost" per ton it's important to distinguish between the two. For purposes of analyzing forest carbon, the focus is on the flow of the carbon atom among the pools (or into a forest products pool); and then, if carbon-based plants and trees are combusted (oxidized) in or out of the forest, on the flow of the resulting carbon dioxide into the atmosphere. To convert from metric tonnes (± 2200 lbs) of "carbon" to short tons (2000 lbs) of "carbon dioxide equivalent/CO2e" multiply Tg/metric tonnes carbon by 3.67, then multiply by 1.102. Thus the total FIA all-pools Oregon forest *carbon* amount of 2582 Tg to 2865 Tg equals 10.4 billion short tons CO2e to 11.6 billion short tons Co2e.

[6] Per USFS Forest Inventory and Analysis (FIA) data (2016), and Harmon 2018, unpublished manuscript. Carbon quantities and distributions in this Report rely primarily on these two sources unless noted otherwise. Derivation and analysis is found in Section IV of this Report.

Pacific Northwest forests were among the most productive in showing gains in forest carbon capture.[7] Of carbon removed from the forest through harvest, part of the carbon lost within the forests is captured and stored for varying durations in harvested wood products such as building materials.

- **Forest Carbon Pools and Carbon Flux**. Ecosystem carbon accounting methods identify distinct "pools" of forest carbon. In this analysis we use five USFS FIA-defined pools: (1) above-ground live trees, (2) above-ground dead trees, (3) downed and woody material, (4) forest floor, and (5) soil carbon. An analysis done by the Forest Service of FIA data put soil carbon at 47 percent and live trees at 35 percent as the largest pools across all Oregon ecoregions. A second analysis done by OSU School of Forestry scientists using FIA data plus additional sources of data estimates the shares of carbon in soil and live trees at 42 percent and 41 percent respectively.[8] Soil carbon quantities are assumed to be relatively stable, while live and dead/decaying trees are the primary interface for exchanging significant amounts of carbon between the forest and the atmosphere. Forest carbon is released into the atmosphere as live trees respire, as fauna reliant upon plants for sustenance respire, and as trees and other vegetation die from the effects of disease, insects, and fire, and subsequently decompose; or are removed by harvest and subsequently decompose. At the same time, carbon is removed from the atmosphere as trees and other vegetation establish and grow. The carbon stores accumulate in different forest carbon pools reflecting interactions (flows) among the pools (e.g., some share of carbon in the live wood pool may flow into the dead wood pool after fire or insect/disease mortality). Dead wood and other plant materials release CO2 to the atmosphere, or in a more limited way into the soil carbon pool where the carbon may be stored. Carbon in harvested wood may also shift from the in-forest live tree or dead tree carbon pools into a forest products carbon "pool" stored in wood products such as houses, containers and other products.

- **Carbon Stores and Fluxes Vary Between Publicly and Privately-Owned Forests**. Almost three-quarters (73 percent) of net carbon stores are found in publicly-owned (mostly federal) Oregon forests comprising 65 percent of total forested acres; carbon stores are increasing on these lands. During the ten year period analyzed, these forests were withdrawing more carbon from the atmosphere than they were losing to in-forest decomposition, combustion and harvest. This is true in significant part because harvest from federal forests has been much reduced over the last 25 years (Krankina et al. 2012). Privately owned forests comprise 36 percent of forested acres and account for 28 percent of carbon stores. These lands are also withdrawing more atmospheric carbon than they are losing, but the margin is much smaller after netting against carbon losses to harvest.[9] Carbon densities (carbon/area) are higher for federal forestlands (0.22 to 0.246 Tg/hectare) and lower for privately-owned forestlands (0.19 to 0.204 Tg/hectare).

[7] Per EPA "Inventory of US Greenhouse Gas Emissions and Sinks", 2015, relying on USFS FIA data.

[8] Oregon Forest Biomass and Carbon Fluxes by Ecoregion 2001-2015 (unpublished paper), Law Hudiberg, Berner 2017. While Law et al begin with FIA data, various explanations are advanced for the discrepancies between the FIA and OSU figures, including factors having to do with treatment of roots, more detailed OSU plots, and other considerations. OSU also sorts the same forest carbon into seven pools: Live Trees, Standing Dead Trees, Coarse Woody Debris, Fine Woody Debris, Shrubs, Litter and Duff, and Mineral Soil.

[9] Harvest losses occur as trees are felled and branches removed in the forest, and again when logs are milled leaving residue, and again when wood products age out and are disposed of. When disposition is into a landfill, decomposition and release of carbon back to the atmosphere may take place over decades.

- **Forest Carbon Capture Efficiency Varies by Ecoregion**. Wetter, denser Coast and West Cascades eco-region forests are the most productive and so the most efficient (per acre) at capturing carbon. These stores face less frequent risk of release from fire and other natural causes. These attributes can be leveraged by carbon management strategies aimed at increasing forest carbon stores and storage residence times.

- **Wildfire as a Carbon Emissions Source**. Wildfires are widely thought to be major sources of forest carbon released to the atmosphere, as well as presenting serious public health and safety issues when occurring in proximity to human habitation. Amounts of carbon released to the atmosphere in certain extensive fires that include areas of intense, severe fire activity, can be meaningful and substantial.[10] However, on average, for the period 2001-2015, forest fires in Oregon appears to have released around 5.3 million tons CO2e annually (Law et. al, 2018) to the atmosphere, or a quantity equal to about 9 percent of all Oregon non-forest greenhouse gas emissions. This is substantially less than the net amounts of carbon annually withdrawn from the atmosphere by Oregon's forests during this same period. Wildfire management will continue to be an important part of forest practices especially where human life, health and public safety are at risk. The effects of climate change can upend many assumptions about fire in forest management overall, especially where drought and high ambient temperatures can amplify normative fire activity. That said, wildfire is an essential and unavoidable element in Oregon forest ecosystems, so eliminating or suppressing normative occurrences of fire in forests cannot be a preferred option for reducing Oregon's greenhouse gas emissions.

- **Harvest and Forest Carbon**. There are many reasons to harvest logs from forests, including economic value, usefulness in products such as housing and paper, job creation in forest communities and in product fabrication. Based on credible evidence today, forest harvest does not appear to result in net carbon conservation when compared to carbon retention in unharvested forests.

  The evidence is that significant amounts of carbon are lost at each stage in timber harvest and processing into wood products, and in decomposition at the end of useful product life. Meanwhile, trees remaining in forests are actively withdrawing carbon from the atmosphere. The forest stores and conserves carbon more effectively and for longer periods of time than do most products derived from harvested trees.[11] While individual trees will die and release their carbon, the forest can continue to renew itself, maintaining and adding to its quantities of sequestered carbon.

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[10] Between 14 and 18 million tons of carbon dioxide were released in the 2002 Biscuit fire, (Campbell et al. 2007), an amount equal to roughly a quarter of Oregon's total statewide (non-forest) sector-based GHG emissions that year.
[11] Average estimated carbon lifespan of dimension lumber wood products in buildings is 50 – 75 years, extended to 200 years for landfilled portion. The same figure for *all* harvested stem carbon, taking into account carbon lost during manufacture, use and disposition, is 43 years. Average potential carbon lifespan of trees left in Oregon forests is 87 – 200 years. (Harmon 2018e)

The Commission acknowledges that there is active disagreement and debate on the life cycle valuation of carbon stored in wood products (including substitution effects). The Commission supports active research into these questions, as well as ongoing efforts by the forest products industry to continue introducing practices that improve carbon efficiencies at harvest and product fabrication. In particular, the Commission will welcome research from the Oregon Department of Forestry and others that quantifies net carbon emissions associated with harvest consistent with the five-step methodology outlined below (pages 17-18 of this report).

II. Oregon and National Forest Carbon Trends

The fact that Oregon's forests produce a net positive carbon capture is encouraging. It is consistent with the findings of the 2014 National Climate Assessment which graphically demonstrates the history of forest carbon losses ("emissions") through most of the last three centuries, and the dramatic turnaround in forest carbon reacquisition in the last 100 years.

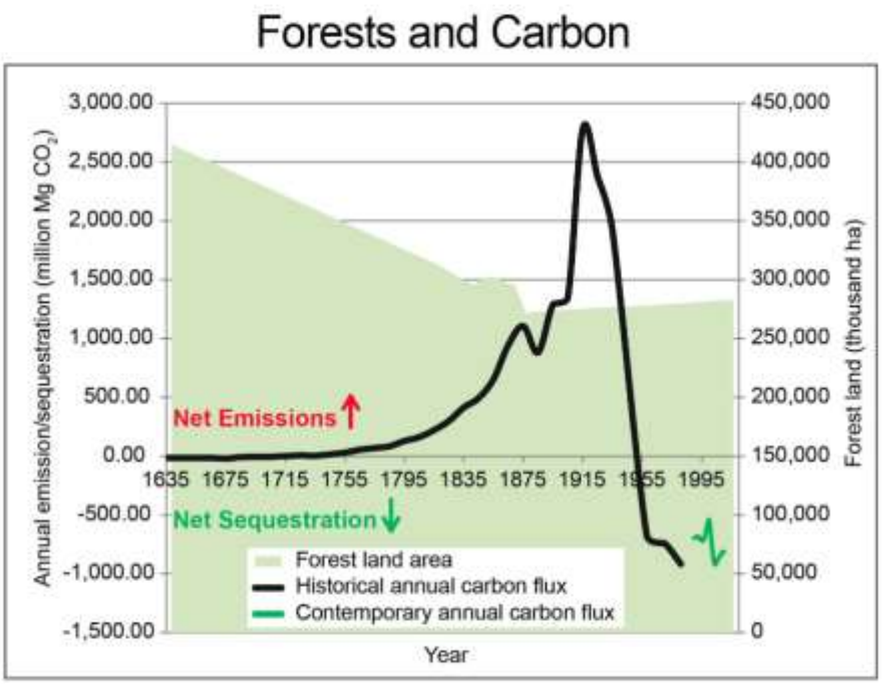


Figure 7.6 from the 2014 National Climate Assessment

The Assessment places particular importance on the 'well-watered forests of the Pacific Coast' as singularly capable of substantial carbon sequestration contributions to national and global goals for arresting and reducing atmospheric carbon.

Chapter 7 of the Assessment notes the likelihood that "Climate change and disturbance rates, combined with current societal trends regarding land use and forest management, are projected to reduce forest CO2 uptake in the coming decades" (Joyce et al. 2014).

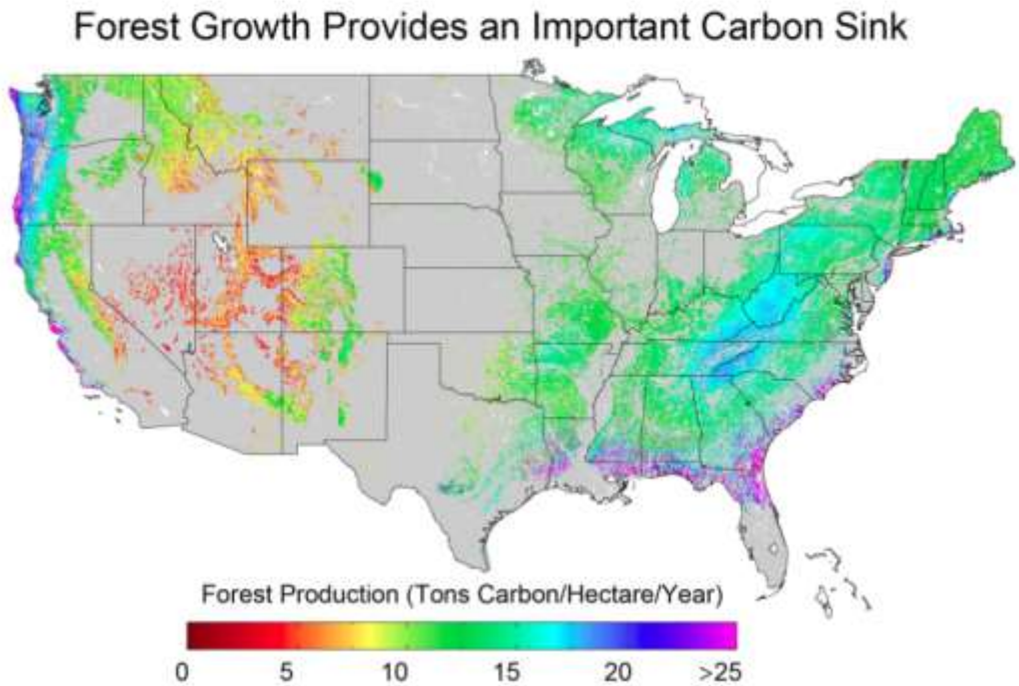


Figure 7.5 from the 2014 National Climate Assessment

If Oregon wishes to realize increased carbon uptake and sequestration in its forests as a key part of global forest carbon sequestration strategies, it will have to develop goals, and ways and means for achieving those goals. It will further have to weigh optimizing for carbon acquisition against other articulated forest sector goals including ecological restoration and fuels reduction in fire-prone forests, harvest for economic value, forest and watershed health, public health, and recreation. In some cases the tools and strategies to achieve these may align; in others they will conflict. Articulating the principles and policies to evaluate these tradeoffs is beyond the charge of this Commission. However, we can underscore the significance of forest carbon to Oregon's larger carbon objectives, and urge the State to consider how forest management practices should interact with Oregon's carbon reduction goals to achieve the fullest possible contribution to global climate outcomes.

The data we have developed to date are a place to start, but they urgently suggest additional lines of enquiry and of needed policy development. The balance of this Report provides context for, and recommends, a next round of research and analysis.

Oregon Forests Ecoregions and Ownership

The Forest Service FIA dataset allows for analysis by forest ecoregion and land ownership. The map below shows a disaggregated view of Oregon forest ecoregions, which were then combined into six larger ecoregions listed in the table to the left of the map. The table also lists the seven ownership categories and the five forest carbon pools used in the analysis presented in this report. Methods to bin data into carbon pools can vary somewhat from study to study, but they generally distinguish between the general categories of standing live trees, standing dead trees, down wood (fallen dead trees or wood pieces), forest floor vegetation, and soils and roots.

FIA Data Sorted by Six Ecoregions:

- Coast Range
- Klamath Mountains
- West Cascades
- East Cascades
- Blue Mountains
- NW Basin

Analyzed by Forestland Owner:

- U.S. Forest Service
- Bureau of Land Management
- National Park Service
- Oregon State and Local Government
- Private Industrial
- Private Non-Industrial "Family Forests"
- Other

Analyzed by Carbon Pool:

- Live Trees
- Dead Trees
- Down wood
- Forest Floor
- Soil/Roots

Ownership distribution, as categorized by the U.S. Forest Service FIA report (U.S. Forest Service, 2017), is provided in the table below:

Acres and Percentage of Oregon Forestland by FIA Ownership Categories[12]	
Public **64%**	***Private*** **Tribal: 2% | Other Private: 34%**

FIA Ownership Categories		**Acres**	**Percent**
Public	U.S. Forest Service	14,179,700	47
	U.S. Bureau of Land Management[13]	3,620,700	12
	National Park Service	165,500	1
	Other Federal	29,500	< 0.001%
	State of Oregon	1,019,300	3
	Local Governments and Other Public	186,100	1
Private	Tribal Governments[13]	475,100	2
	Private Industrial Forests	5,984,100	20
	Private Non-Industrial Forests (woodlots)	4,324,000	14
Totals		**29,984,000**	**100**

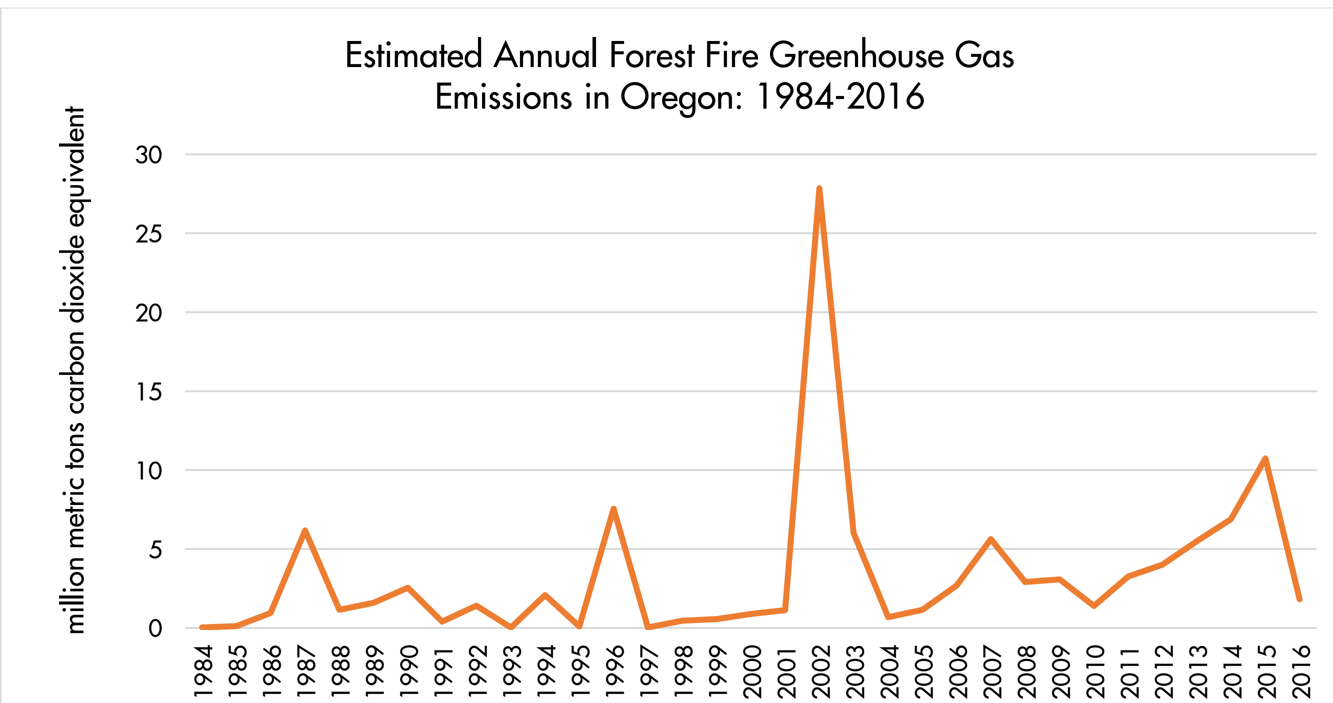
[12] U.S. Forest Service, 2017. See interactive Oregon forest ownership map at: https://oregonforests.org/content/forest-ownership-interactive-map

[13] These acreage totals do not include the effects of the passage of the Western Oregon Tribal Fairness Act (Public Law 115-103) on January 8, 2018. This law designates approximately 14,742 acres of BLM-managed lands to be held in trust on behalf of the Confederated Tribes of the Coos, Lower Umpqua, and Siuslaw Indians and approximately 17,519 acres of BLM-managed lands be held in trust on behalf of the Cow Creek Band of Umpqua Tribe of Indians.

III. Priority Forest Carbon Considerations

Forest Wildfire as Carbon Source

Forest fires are widely thought to be major sources of forest carbon release, as well as presenting serious public health and safety effects when occurring in proximity to human habitation (see summary text box below, "Climate-Relevant Wildfire Emissions"). In fact, amounts of carbon released to the atmosphere in certain very large fires can be meaningful and substantial.[14] However, on average for the period 2001-2015, forest fires in Oregon appear to release around 5.3 million metric tons CO2e annually[15] to the atmosphere, equal to about 9 percent of all Oregon non-forest greenhouse gas emissions as reported in Oregon's sector-based GHG emissions inventory for 2015 and 2016, or about one-quarter the emissions from Oregon's transportation sector for the same years (DEQ 2018).[16]



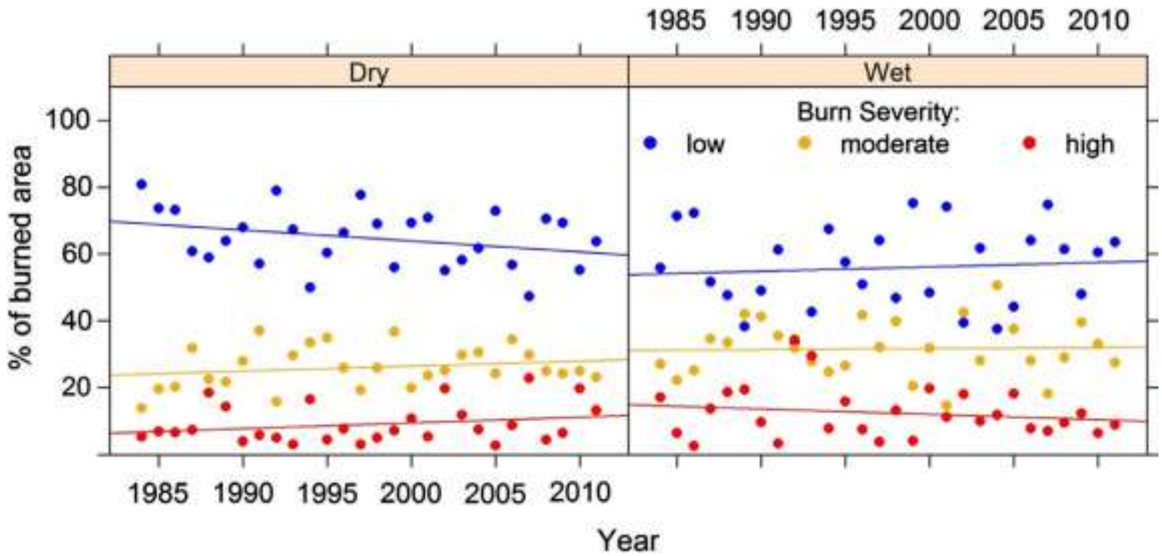
[14] Between 14 and 18 million tons of carbon dioxide were released in the 20052002 Biscuit fire, (Campbell et al. 2007), an amount equal to roughly a quarter of Oregon's overall non-forest sector-based GHG emissions in 2005. (Campbell, Donato et al, "Pyrogenic carbon emission from a large wildfire in Oregon", 20072002.

[15] Calculated with data from Table S4 in Supporting Information from Law et al. 2018. http://www.pnas.org/content/pnas/suppl/2018/03/13/1720064115.DCSupplemental/pnas.201720064SI.pdf

[16] . . . …bearing in mind that forests, unlike cars, more than offset their (fire-associated) emissions by actively capturing carbon from the atmosphere through forest growth.

This amount is more than offset by the annual net carbon gains in our forests. Fire is also an historical and necessary element in forest ecosystems, renewing forest ecosystems through multiple interactions. At low to moderate intensities, forest fires appear to release moderate amounts of greenhouse gases while performing important ecosystem rejuvenation functions. Overall and on average, most Oregon forest fires appear to release ± 5 percent of the carbon contained in a given acreage (Law and Waring 2015). Most of this comes from the small percentage of acreage subject to high intensity (vs. low to moderate intensity) burning.

Percent of Total Area Burned in the Pacific Northwest (1984-2011)[17]



The balance of carbon in the burned area remains stored in one or another of the in-forest carbon pools (although it may shift from live tree pool to dead tree pool; and over time to the soil carbon pool, or to the atmosphere).

[17] The percentage of total area burnt within each burn severity class from 1984 to 2011 for dry (left panel, less than 600 mm year_1) and wet (right panel) ecoregions in the Pacific Northwest. High severity fire accounted for an average of 9–12% of the total burn area and did not change significantly over time. Estimates are from the Monitoring Trends in Burn Severity database Eidenshink et al., 2007). Summary statistics for each burn severity class are presented in Table 2, graphs by Logan Berner. (Law and Waring 2015)

Climate-Relevant Wildfire Emissions

Wildfires emit both greenhouse gas and particulate pollutants that influence climate change. Carbon dioxide (CO2) and black carbon are two wildfire pollutants most often identified in policy discussions for their climate warming effects. CO2 is a greenhouse gas while black carbon, also sometimes simply called soot, is a tiny, solid particle emitted through incomplete combustion of fossil fuels, biofuels, or biomass. Black carbon is a component of fine particulate matter (PM2.5), a regulated air pollutant class. This text box briefly summarizes key policy-relevant characteristics of these pollutants, but more context and detail can be found in the references list and from organizations like the Climate and Clean Air Coalition: http://www.ccacoalition.org/en/science-resources.

Atmospheric Lifetime:

- CO2 is a "long-lived" climate pollutant that stays in the atmosphere for approximately 100 years. This allows CO2 to become well-mixed throughout the global atmosphere and means that its climate effects do not depend on where the CO2 is emitted.
- Black carbon is a "short-lived" climate pollutant that stays in the atmosphere for around one week. It does not become well mixed in the atmosphere, and its effects are largely regional and can vary depending on the location and time (season) of its emission.

How They Warm the Earth:

- When sunlight reaches Earth's surface, it can either be reflected back into space or absorbed by Earth. Some of the energy absorbed by the Earth is released back though the atmosphere into space as heat (infrared radiation). CO2 and other greenhouse gases prevent this outgoing heat from escaping into space, known as the greenhouse effect. This climate warming mechanism is very well understood by scientists, with the first paper attempting to quantify this effect published in 1896.
- Black carbon warms the atmosphere by directly absorbing incoming and reflected sunlight, and when deposited on snow or ice can cause surface warming and melting by darkening the bright surfaces of pristine snow and ice, which reduces their reflectivity and increases their absorption of sunlight. These are both relatively well-understood effects identified in climate science literature beginning in the late 1990s/early 2000s. A third type of effect—black carbon's interactions with clouds—has much higher scientific uncertainty and is thought to cause both warming and cooling.

Considerations for Mitigating Climate and Human Health Impacts:

- Human emissions of CO2 are the largest contributor to climate warming, followed by methane and black carbon. Reducing CO2 and other long-lived greenhouse gases is critical to limiting warming to below-dangerous levels of interference with the climate system (e.g., 2 degrees Celsius above pre-industrial levels). Reducing black carbon and other short-lived climate pollutants can help to slow the pace of warming over the next two to three decades.

- Black carbon is always emitted alongside other co-pollutants that have warming or cooling effects. For example, wildfire emissions of organic carbon and sulfate particles largely have a climate cooling effect. This creates scientific uncertainty about the net climate effect of these emissions taken together since cooling particles can offset the direct warming effect of black carbon particles. This is especially true for emission sources like wildfires and other biomass burning, which generally have high co-emissions of organic carbon (though the specific ratio of organic to black carbon will depend on factors like fuel load, fuel type, and burn severity). "Black carbon-rich" sources like diesel engines emit almost all black carbon and little organic carbon, increasing the certainty that reducing diesel emissions will reduce warming.

- Black carbon reductions can have significant local air quality, human health, and ecosystem benefits. Human exposure to PM2.5, of which black carbon is one component, has well-known and documented adverse respiratory and cardiovascular impacts. The scientific literature also indicates substantial benefits to maintaining snow and ice cover in regions like the Arctic and the Himalayas where black carbon deposits onto those surfaces.

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Forest Harvest as a Carbon Source

There are many reasons to harvest logs from forests, including economic value, usefulness in products such as housing and paper, job creation in forest communities and in product fabrication.

Based on available evidence today, forest harvest does not result in material carbon conservation; rather it results in net carbon emissions measured against leaving forests unharvested. Notwithstanding improvements in more efficient utilization of harvested forest fiber, significant amounts of carbon are lost at each stage in timber harvest and in decomposition at the end of useful product life. Meanwhile, forests actively withdraw carbon from the atmosphere, and store and conserve it more effectively and for longer periods of time than do products derived from harvested trees.

Just as other useful economic activities, from transportation and electricity generation to food production and consumption, result in net releases of carbon into the atmosphere, so do timber harvest and wood product fabrication and use. Just as society requires that emissions from these other activities be dramatically reduced, so will emissions associated with timber harvest need to find comparable reductions. Options from reduced harvest of public lands to longer rotations[18] on private forestland, expanded riparian buffers, use of variable retention harvesting, and purchasing conservation easements could be considered. "Leakage" – e.g., more intensive logging elsewhere – would need to be accounted for, but Oregon's leadership could also encourage other regions to incorporate carbon conservation in their forest management practices.

Oregon's forests are thought of and managed in some cases as natural ecosystems, and in others as cropland. Federal wilderness areas are clearly in the first category, while privately-owned forests are predominantly in the second while still providing some ecosystem functions. State and National forests may be managed to fall more in one category or the other. West side national forests have seen limited commercial logging since adoption of the Northwest Forest Plan in the early 1990s; while the much smaller state forests have been subject to logging in accordance with their legal obligation to generate revenue for local education budgets. Forest Service operations including forest fire mitigation treatments rely in part on revenues from commercial logging (sometimes at reduced levels) for a significant share of needed agency funding. Such treatments are designed by the Forest Service to restore something closer to natural ecosystem function in forests where decades of fire suppression policies have resulted in denser forest growth than was prevalent during the pre-suppression era. Treatments often will include some measure of commercial logging, with the revenues used to defray the costs of treatments. Depending on the intensity of the treatment-associated commercial harvest, there can be a reduction in forest carbon levels that may take decades to recover.

There are generally accepted social and economic rationales for commercial logging on Oregon's public and private forest lands. These may include economic activity that supports companies and forest communities, providing local jobs, and revenue generation for public purposes. Forest managers especially in east-side dry forests are committed to forest health treatments that seek to reduce stand

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[18] Rotations might be extended to 75-80 years for industrial west-side Oregon conifer forestlands, up from current average rotations of 45 years. Rotations as short as 28 years have been reported, although this may reflect harvest of shorter-lived species such as alder. Historic tree farm rotations, e.g., in the early 20th Century, were as long as 120 years. (Law et al. 2018 and Hudiberg 2009)

densities to levels and patterns similar to what is thought to have existed prior to Euro-American settlement and the fire suppression era.

That said, extractive logging for all purposes – that is, harvesting and removing (mostly) live trees with their carbon stores – will reduce the total amount of carbon that otherwise might be expected to remain in long-term forest storage.

Harvest-related loss of forest carbon stores appears to be substantially in excess of fire-related carbon emissions; by one analysis, harvest reduced Oregon in-forest carbon stores by 34 percent between 2001 and 2015[19] (Law et al. 2018) if compared to a non-harvest base case. Live wood carbon stores have been increasing in all ecoregions and for all ownership classes since 2001. But because the greater amount of the overall harvest takes place on private forest lands, net carbon stores on private lands, with 36 percent of total forest area in Oregon account for 20 percent of the net carbon stores increase while Federal lands with 60 percent of the total area account for 79 percent of the increase in net stores.[20]

Notwithstanding the prevailing lower harvest levels on federal forests, there appear to still be significant opportunities to increase carbon stores on these lands. In contrast, the prevailing higher harvest levels on private lands may also offer greater opportunities to preserve and increase carbon stores here while continuing to harvest fiber at sustainable levels. Oregon State's School of Forestry notes that average harvest cycles in west side privately-held Oregon forests have shortened from 120 years to 45 years (and for some forests, shorter rotations still), notwithstanding that "net primary productivity peaks at 80-125 years" (Law et al. 2018). For illustrative purposes, the Community Land Model calculated that "if harvest cycles were lengthened to 80 years on private lands and harvested area was reduced 50 percent on public lands, state-level (carbon) stocks would increase by 17 percent to a total of 3,600 Tg C (or 14.56 MM short tons CO_2e) and NECB (Net Ecosystem Carbon Balance) would increase 2-3 Tg C (8.2 to 12.2 MM tons CO_2e) by 2100 (Law et al. 2018)."

Oregon can influence, but not set, forest management practices in federal forests. Key points of influence for the State include the Oregon Department of Forestry Federal Forest Restoration Program, the use of Good Neighbor Authority, and leveraging Oregon's well-respected collaborative forest restoration movement. Additionally, the State could elect different forest management practices on State-owned forests so long as it stayed within statutory limitations (or modified those as necessary). More significantly, the State could elect to use incentive and/or regulatory tools to influence management practices on the far more extensive private forestlands to increase carbon content, including reforestation, afforestation, longer harvest cycle rotations and wider riparian buffers.

Net increases in forest carbon retained and stored resulting from reduced harvest in Oregon could be limited by the potential for leakage (e.g., carbon reductions from reducing Oregon harvest offset by increased commercial harvest elsewhere to meet market demand). While there is much literature on this subject, the extent of such leakage specific to Oregon harvest levels would benefit from additional analysis. So would further Oregon-specific analysis of the net carbon effects from substituting harvested wood products for other building materials (e.g., concrete, steel, aluminum) with their own carbon footprint; and substituting combustion of mill residues for fossil fuels to generate electricity.

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[19] See below for a discussion of post-harvest carbon stored in wood products.
[20] Harmon, 2018. For more detail and discussion, see page 27-28 of this report.

The Oregon Department of Forestry has been tasked by the Legislature with giving us more such specificity.

Carbon Stored in Wood Products

As noted above, reductions in carbon stored in forests is an undisputable consequence of harvest – trees are cut and removed. From a carbon counting perspective, it is the *net* effect of the removal that is important; that is, the lower amounts of carbon remaining in the forest after harvest, offset by the increased amounts of carbon flows into a forest products carbon pool (that may consist of building framing, paneling and siding, doors and window frames, cardboard containers, paper and so on). Estimates of the size of this pool, and of flows into and out of it, are the subject of much discussion in commercial and scientific circles but counting this pool as part of a forest carbon summing up is not controversial. Calculating and quantifying it can be, with some methods only counting inputs to the pool without netting these against carbon pool losses as buildings and other wood uses age out, are demolished with residue dumped, incinerated or left to slowly decompose in a landfill, each flow in turn releasing carbon back to the atmosphere and completing the cycle. Recent calculations show that "Net wood product emissions" from 2001 to 2015 were equal to fully half of Oregon's Net Ecosystem Carbon Balance (NECB).[21]

These losses may be partially mitigated by recovering more durable wood products (e.g., dimension lumber) from the harvest and using it for construction that could endure for several decades. There may also be carbon value added from substitution effects (e.g., using wood in place of more energy- and carbon intensive materials such as concrete and steel; or displacing fossil fuel-generated energy by being combusted for heat and electric energy); and from acknowledging carbon leakage effects (e.g., foregone harvest in Oregon is offset by increased harvest in British Columbia). Finally, even wood products that are landfilled from structures are demolished can hold their carbon for decades in a properly-operated landfill. The extent of these mitigating effects must be demonstrated in each case by net life cycle carbon analysis measured against established and agreed-to baseline conditions.

Table 13a (page 95) of the recent California Forest Carbon Plan (Forest Climate Action Team 2018) notes that almost 100 percent stems reaching the mills is processed into useful products. The table also reinforces the important distinction between durable products ("finished lumber" and "veneer and other products") at 31 percent, and non-durable products (e.g., "landscaping products," "pulp," etc.) at 69 percent.

That said, an accounting of carbon in a wood products pool should include the following:

1. Count carbon loss associated with in-forest harvest where roots, stumps and branches are stripped from stems and burned or left to decompose and release their carbon back to the atmosphere (estimated at 35 percent of total contained carbon in a tree, per Harmon 2018f[22]). Duration of forest carbon deficit for the harvested forest tract should be calculated.

[21] 101.66 million tons co2e out of 199.71 million tons CO2e from 2001-2015 (Table S4, Law et al. 2018)
[22] Personal Email Communication from Dr. Mark Harmon to Angus Duncan, Chair of the Oregon Global Warming Commission, May 29, 2018

2. Count carbon emissions associated with operation of extraction, transportation and milling equipment.

3. Account for carbon associated with residue from milling stems into marketable wood products, depending on how the residue is disposed of. For example, bark and chipped residues may be burned for energy or marketed as mulch or ground covering. Combustion results in immediate carbon return to the atmosphere, while for other uses decomposition and carbon return may take place over months or years (see Table 13a referenced above).

4. Net carbon in products entering the wood products pool against substitution and/or leakage effects.

5. Net end-of-cycle wood products carbon emissions released from the wood products pool (through decomposition or combustion) against beginning-of-cycle carbon deposits into the pool. Durable wood products add carbon stores to the wood products pool where they endure for varied lengths of time. Simultaneously with carbon *entering* the pool in this way, carbon is *leaving* the pool as structures are demolished and materials disposed of. Well-designed and operated landfills may contain some part of these carbon stores for additional decades before materials decompose and return carbon to the atmosphere, while less durable forms of disposition will result in earlier such carbon returns.

Forest Restoration Treatment as a Carbon Source

There is discussion and disputation over forest management practices that are characterized as "forest health restoration treatments", i.e. reducing quantities of vegetation (live and dead trees) to reduce forest fire fuel loadings and return forest composition to something closer to densities and spacing preferred by prevailing forest practices. This may be accomplished with a combination of physical vegetation removal (thinning) and prescribed fire. "Treatments" have become policy among federal forest managers in Oregon and other western states, especially in the vicinity of human habitation (WUI, or Wild/Urban Interface) and especially as forest fires have become a public health and safety issue.

The Commission is not qualified to speak to the validity and appropriate application of these policies and practices. The Commission is clear, however, that these practices generally result in lower forest carbon stores for significant periods of time that make more difficult timely reductions in overall atmospheric carbon levels. And "timely" – that is, near term; in the next 20 to 30 years – reductions in atmospheric carbon concentrations are more valuable and necessary than such effects delayed.

Overly dense forest stands and vegetation especially in drier east side Oregon forests[23] were reduced regularly and naturally by forest fires at close intervals (for east Cascades dry Ponderosa forests, at mean intervals of 11 to 38 years [Fitzgerald, 2005]). A combination of forest fire suppression policies by 20th Century forest managers and increased human habitation penetrating forests has altered those historical forest density and fire interval patterns while increasing risks to public health and safety. Forest managers in turn have argued for thinning and prescribed fire as substitute tools for fuels management. In order to have revenues to pay for these activities, managers frequently will mix

[23] Thinning and/or prescribed fire may be appropriate in west side forests also, especially in proximity to human habitation.

commercial tree harvest with fuels reductions, which results in further reductions to in-forest carbon stores.

The 2011 OSU study (Clark et al, 2011) from which the figure on the following page is taken, looked at the carbon consequences of different levels of thinning. Carbon accumulations continue under a “no thin” policy, while light thinning requires 15 years to recover pre-thin carbon levels. The analysis continues through an intermediate “financial break-even” thin (remove all trees less than 7” DBH[24] and 20 percent of trees 7”-20” DBH) that required a 25 to 40 year carbon recovery period; and a heavy thin that fails to recover pre-thin carbon levels over a 50 year (or longer) period.

There are safety, industry and science – and cultural[25] – reasons that may support any of these different levels of thinning, often in combination with prescribed fire. At any level above “no thin” however, there are net reductions in the amounts of carbon stored in the forest and a significant delay in recovery of pre-thin carbon levels.

The figure shows simulation of carbon pools for the forest stand: No Thin (top), Light Thin (middle) and Heavy Thin (bottom). All carbon components reference the left axis. Only standing green tree volume (Volume) references the right axis.

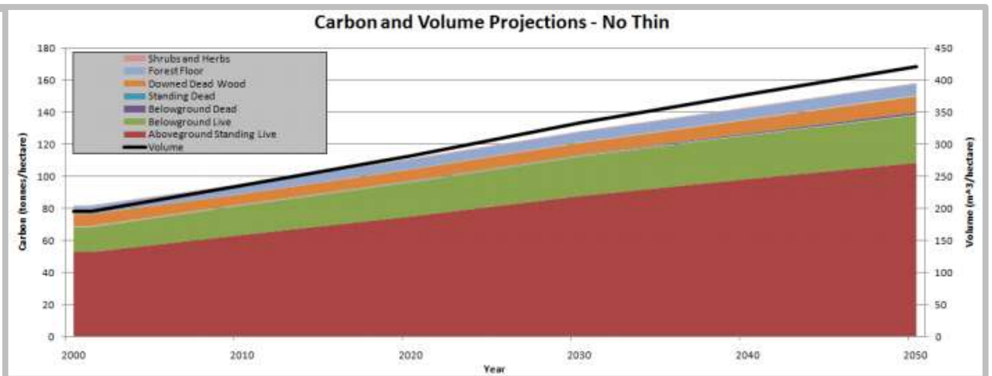
[24] “diameter at breast height”

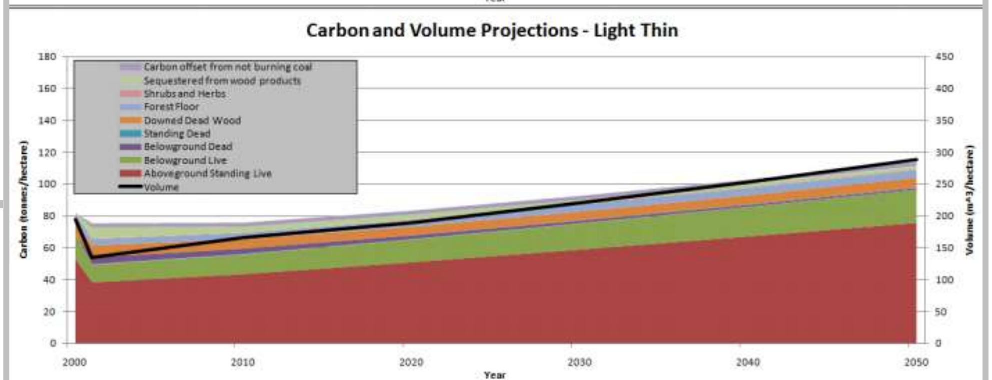
[25] The Umatilla Tribal Government, for example, seeks restoration of stand densities in the 24,000 acres of Blue Mountain forests it manages to enable native foods like huckleberries to thrive where they once did before fire suppression also suppressed the berry bushes that prospered under tribal-set fires (King 2018)

Forest Carbon Retained:

No Thin

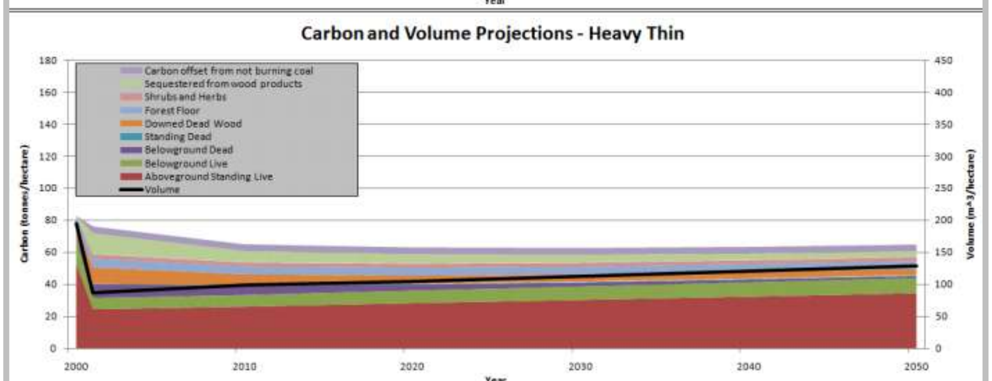
- +400 tonnes/ hectare
- No recovery time required





Light Thin

- ±300 tonnes/ hectare
- 24-40 year carbon-recovery
- 208 trees/acre remain
- Remove all trees less than 10” diameter
- Improved resistance to crown fire



Heavy Thin

- ±150 tonnes/hectare
- 50+ year carbon-recovery
- 46 trees/acre remain
- Remove all trees less than 12” diameter; 30% of trees 12-16” diameter; 10% of trees 16-20” diameter
- Leaves the stand in relatively park-like condition, with little understory and only a few of the largest trees remaining.
- Significant increase in resistance to torching and crowning.

Human Habitat Intrusion into Forests; Forestland Conversion; Reforestation; Afforestation

Human settlement continues to intrude into forests, as most states are without even the modest land use tools Oregon uses to prioritize and preserve farm and forest land.

By one delineation methodology, since 1990 some 60 percent (8.5 million) of the new homes built in the US, have been located in the WUI, resulting in around 46 million homes now occupying the defined areas.[26] Over the period in question the average number of structures burned has increased an order of magnitude (from 405 structures in the 1970s to 4500 in 2015; while California's Tubbs Fire in October 2017, by itself destroyed some 3,000 Santa Rosa homes). Managing and controlling fires that threaten public health and safety has put intense pressure on agency forest fire management budgets,[27] pressure that is crowding out other management responsibilities.

Conversion of forest land to human habitation and other non-forest uses in Oregon slowed dramatically when the state adopted its land use laws in the 1970's and rolled out rules and planning procedures designed to protect and conserve forests and farmland. The Oregon Department of Forestry estimated current conversion of forest land to other uses at under one percent annually (Gray et al. 2016). FIA data from 2016 tables documents an annual average loss of 51,000 forest acres, or 0.2 percent of total forested acres (again, an outcome likely influenced by the shift to more conservation-minded Federal forest planning in the 1990s).

Notwithstanding, Oregon already had substantial development in and adjacent to its forests, so while its conflict issues are not worsening, they remain challenging. Managing these conflicts especially at the Wild-Urban Interface (WUI) makes maximizing forest carbon stores more challenging; the pressure to treat adjacent forests for fuels reduction is high (if somewhat mitigated by the emergence of "defensible space" rules for owners to make their homes and businesses increasingly fire resistant).

As relatively strong as are Oregon's land use regulations, the state could elect to tighten them further to altogether rule out new development within forests and reduce conversion loss to zero.[28] By limiting intrusive development (e.g., new destination resorts on forestlands), this could have the further benefit of mitigating future costs of managing fire and of human exposure to public health and safety effects.

There is a growing overall threat to public health and safety from increasing frequency and size of forest fires driving smoke and soot (black carbon) into inhabited areas. Communities adjacent to or intruding into forestlands and susceptible to greater fire and smoke exposure tend to be more at risk, but in the last several years large and relatively distant conflagrations have extended their smoke plumes dozens, even hundreds of miles. In the summer of 2017 Portland was affected first by smoke

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[26] International Code Council. The Blue Ribbon Panel Report on Wildland Urban Interface. April 4, 2008. https://inawf.memberclicks.net/assets/blueribbonreport-low.pdf. The 2008 data need updating, and likely would show these conditions have worsened.

[27] From ± $1B/year in the 1990s to ±$3B/year in the 2000s.

[28] Several other states have adopted forest preservation and enhancement goals, including a "no net loss of forestland" in Maryland. Development flexibilities can be built into such a goal, including offsets or in lieu fees that can be used to conserve or reforest equivalent acres elsewhere. Absent regulatory constraints, Maryland reportedly continues to experience net loss of forestland, leading to calls for a one-for-one replacement statute.

from fires in British Columbia, then from the Eagle Creek Fire forty miles east up the Columbia River Gorge.

Potential for Increasing Oregon's Forest Carbon Stores

Law et al, 2018, identify four strategies for accelerating the gains in carbon stores in Oregon forests: reforestation, afforestation, longer harvest rotation periods (to 80 years) on private forestlands and an additional 50 percent reduction in harvest on public (federal and state) lands.[29] Combined, these measures (at levels proposed by the authors) were calculated to increase Net Ecosystem Carbon Balance (NECB) in Oregon's forests by an additional 890 million tons CO2e by 2050.[30]

While the State has no direct authority over management policies on federal forestlands, it is in a position to influence these policies. Oregon should propose to federal forest managers a range of management and harvest strategies that could materially increase the rate of carbon capture and sequestration, and extended retention horizons, that would amplify current carbon content levels in these forests.

The State could identify private lands that would lend themselves to reforestation (e.g., in areas affected by fire and beetle kill) where forest science indicates that such treatments would be useful and not redundant of natural reseeding function. The State could also seek likely opportunities for afforestation where forests existed prior to Euro-American settlement (e.g., of Willamette Valley areas presently cultivated for grass crops; some of these areas may earlier have been cleared of trees to enable cropping). The two strategies together have the potential for increasing Oregon's Net Ecosystem Carbon Balance (NECB) by up to 67 Tg C by 2100 (270 million tons CO2e (Law et al, 2018)).

[29] "Harvest cycles in the mesic (moist) and montane forests have declined from over 120 y to 45 y despite the fact that these trees can live 500-1000 y and net primary productivity (of carbon) peaks at 80-125 y." (Law et al 2018)
[30] Ibid., Figure 3, page 3 (teragrams carbon/year converted to million short tons CO2e).

IV. What Can We Say About the Present State of Carbon Stores and Flows in Oregon Forests; In Principal Reliance Upon United States Forest Service Forest Inventory and Analysis (FIA) Data

We present this section of the Report in a Question and Answer format, by way of seeking clarity and specificity for what are inherently complex and interactive data sets. Carbon stores in forests are not static but dynamic. Flows among forest carbon pools, flows between the forest and the atmosphere, and flows by way of harvest into a wood products carbon pool may take place over decades or even centuries, or they may occur rapidly and dramatically. Measuring forest carbon has to recognize these dynamics.

We must also acknowledge up front that while data on forest carbon amounts and flows are far advanced from our first review (in the Commission's 2010 "Roadmap to 2020" Report), they still leave too much unknown or imperfectly understood. Thus quantities are generally expressed as ranges, reflecting the uncertainties remaining in the data. A section at the end of this Q&A proposes a list of uncertainties that a next iteration of analysis should address.

This document summarizes findings from an analysis of FIA data augmented with additional data and analysis developed by Oregon State University School of Forestry scientists (Harmon 2018 a-d; Law et al[31]). These more detailed reports include descriptions of methods and fuller sets of results, and will be posted on the Commission's website. The information and findings herein should be considered a preliminary analysis of carbon stores and flows, their amounts and trends, and their significance in describing forest carbon policy options.

In Harmon (2018a) FIA estimates provided by USFS scientists Drs. Fried and Gray were adjusted to incorporate data Dr. Harmon felt would be useful, including missing pools (e.g., tree roots), lack of decomposition losses (e.g., standing dead trees), or double counting (e.g., soil stores). These modified data were then used to estimate the store and change in stores of pools for Oregon's forests and for major ownership groups. Harmon (2018b) undertook a similar analysis, but at the ecoregion level. In Harmon (2018c) information about the rate of change and the estimated lifetime of carbon in pools was used to estimate the future potential store of carbon as well as sensitivity to change in the processes underlying changes in carbon stores. In Harmon (2018d) a model of wood product manufacturing, use, and disposal was coupled with historical information about the durability of these stores to estimate the fraction of current harvests that result in a net gain in solid wood products

[31] Professors Harmon and Law are both associated with the School of Forestry, Oregon State University, and were contributors to the Commission's Forest Carbon Accounting Task Force. Doctors Jeremy Fried and Andrew Gray, to whom we are indebted for the FIA data on which these findings rely (but not the findings themselves), are with the USUSDA Forest Service.

stores. This variable was then used with the FIA derived estimates of harvest to estimate the quantities and variability over time in wood product stores at the state-level.

The questions and answers that follow, taken together, describe and quantify storage and flows of carbon from pool to pool through Oregon's major forest ecosystems (including a post-harvest wood products carbon pool). It focuses on factual findings rather than policy implications, which are raised elsewhere in the Report. In the many places where uncertainty exists in these factors, that uncertainty is identified. Where values are uncertain, the estimates are states as ranges.

Questions and answers are arranged below as follows:

A. State of Carbon Stores in Oregon Forests

- What is the present total store of carbon in Oregon's forests?
- How much has this total store of forest carbon changed over time?
- What is the distribution of total carbon and carbon density (store per unit area) among ecoregions?
- What is the distribution of total carbon and carbon density (store per unit area) among owners?
- What is the distribution of total carbon and carbon density (store per unit area) among owners?
- How does the distribution of total carbon for each ownership vary among ecoregions and among the major forest carbon pools?
- What is the distribution of total carbon among in-forest carbon pools?
- How is the distribution of total carbon and carbon density (store per unit area) among in-forest carbon pools influenced by ownership?
- How does the distribution of total carbon among in-forest carbon pools vary by ecoregion?
- How much carbon that has harvested from Oregon's forests has accumulated in the form of wood products?
- How have the stores of wood product stores varied over time for the different ownerships?
- What is the current total store of carbon in Oregon's forest sector (forest and wood products)?

B. State of Flux of Carbon in Oregon Forests

- What is the estimate of annual gross and net amounts of carbon flowing into Oregon's forests (all pools) from the atmosphere?
- How has this flow varied over recent years and why?
- How do flows vary by ecoregions?
- How do these vary by ownership?
- How might the net carbon flux between the Oregon's forests and the atmosphere change in the future?
- What has been the net flux of the entire forest sector (forests and wood products)?
- Has this changed in recent years? And how might this change in the future?
- What can we usefully say about the potential effects of climate change on forest composition and carbon flux functions in Oregon's forests?

C. Data Uncertainties and Research Needs

A. State of Carbon Stores in Oregon Forests

What is the present total store of carbon in Oregon's forests?

These amounts are based on the FIA data that were provided by the US Forest Service and after the various adjustments for unreported pools and corrections were made. The total store of carbon in Oregon's forests is estimated to range between 2582 and 2865 Tg[32] C (2847 to 3159 million short tons of C). This is stored over a total of 12,167,082 ha (30,065,488 acres) of forest land. The range in estimates is related to uncertainties in both correction and adjustment factors and does not include uncertainties related to sampling or the empirical models used to estimate carbon stores from the data FIA collects. This range in estimates is 6 percent to 15 percent lower than the 3036 TgC estimated by Law et al (2018), a difference that appears to be primarily caused by differences in live tree stores estimates.

How much has this total store of forest carbon changed over time?

The FIA data provided only gives information for the 2001-2015 period. Forthis period it appears that total stores of carbon have increased for Oregon's forests as a whole, for all ecoregions, and all ownerships. Based on the estimated range of annual net increase in total forest ecosystem carbon stores (5.8 Tg to 15.8 Tg C/yr)) Oregon's forests have gained approximately 81 to 221 Tg of carbon over this 14 year period; or an average annual gain of 23 to 64 short tons CO2e. That reflects a 3 percent to 8 percent gain in total stores over the 14 years. In contrast, and based on previous modeling studies, it is likely that the total carbon stores associated with Oregon's forests *declined* between 1900 and 1990 due primarily to harvest of carbon-dense old growth forest (Krankina et al. 2012). It also likely that state-wide total carbon stores have been increasing on federal forestlands since the inception of the 1992 Northwest Forest Plan, due to significant reductions in harvest of federal forests. While some datasets (Krankina et al. 2012; Law et al. 2018) support this conclusion, this FIA-based analysis does not. New techniques (e.g., LIDAR) promise more detailed and definitive measurements in the near future.

What is the distribution of total carbon and carbon density (store per unit area) among ecoregions?

The West Cascades, Coastal, and Klamath ecoregions are contributing more to the state-wide total carbon stores than their area would suggest (Figure 1); that is, their contained carbon density per acre is higher than in other eco-regions. This is especially true for the first two ecoregions given their wetter, milder climate that leads to higher timber and carbon productivity in these denser western forests.[33] The Blue Mountain, east Cascades, and Other (a mixture of areas with low forest cover

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[32] One Teragram (Tg) is equal to one million metric tonnes; or to 1.102 million short tons. Values in this report may be expressed in Teragrams (Tg), in millions of metric tonnes (one tonne = 2200 lbs), or in millions of short tons (one ton = 2000 lbs.). Quantities of carbon may be expressed as carbon (C), and also converted to carbon dioxide equivalents (CO2e) by multiplying an amount of Carbon by the conversion factor 3.667. Most scientific articles use Tg or million metric tonnes (MM tonnes). We have tried to make the conversion to MM tons CO2e whenever doing so does not impeded the narrative, to allow easier comparisons to amounts in Oregon's historical GHG inventories that are expressed as MMCO2MMCO2e.

[33] ". . . Law et al. 2018, page 3663: "…Oregon . . .… coastal and montane forests have high biomass and carbon sequestration potential. They represent coastal forests from northern California to southeast Alaska, where trees live 800 years or more and biomass can exceed that of tropical forests." Law et al, "Land Use Strategies . . ." January 22, 2018. Average According to Dr. Mark Harmon, the average life span of carbon in an Oregon forest is "87 - 200 years" per direct (personal communication from Dr. Mark Harmon, May 2018).

throughout the state) ecoregions contribute less to total carbon stores than their area would suggest. On a per unit area basis (i.e., carbon density) there is a 2-fold difference in stores between the ecoregion with the highest (West Cascades) and that with the lowest (Blue Mountains) values (Figure 2). Both the West Cascades and Coastal total stores are approximately 40 percent higher than the state-wide average, whereas the Blue Mountain and East Cascades ecoregions are 35 percent lower than the state-wide average.

Figure 1. Proportional distribution of area and total carbon stores by forested area within each ecoregion.

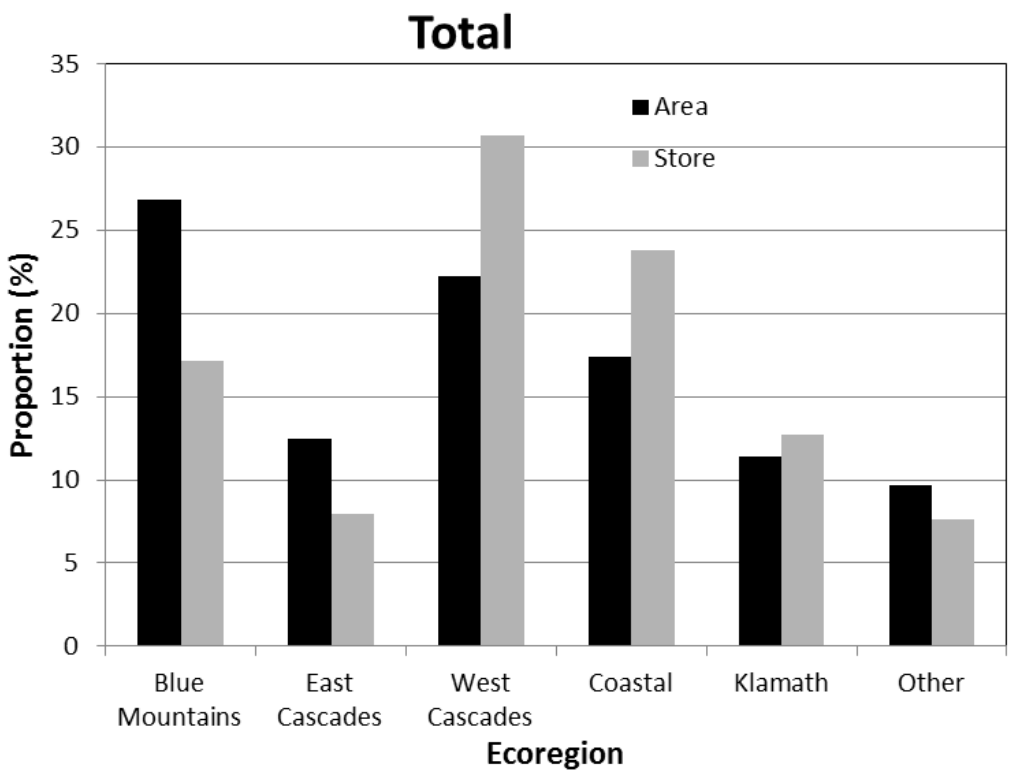
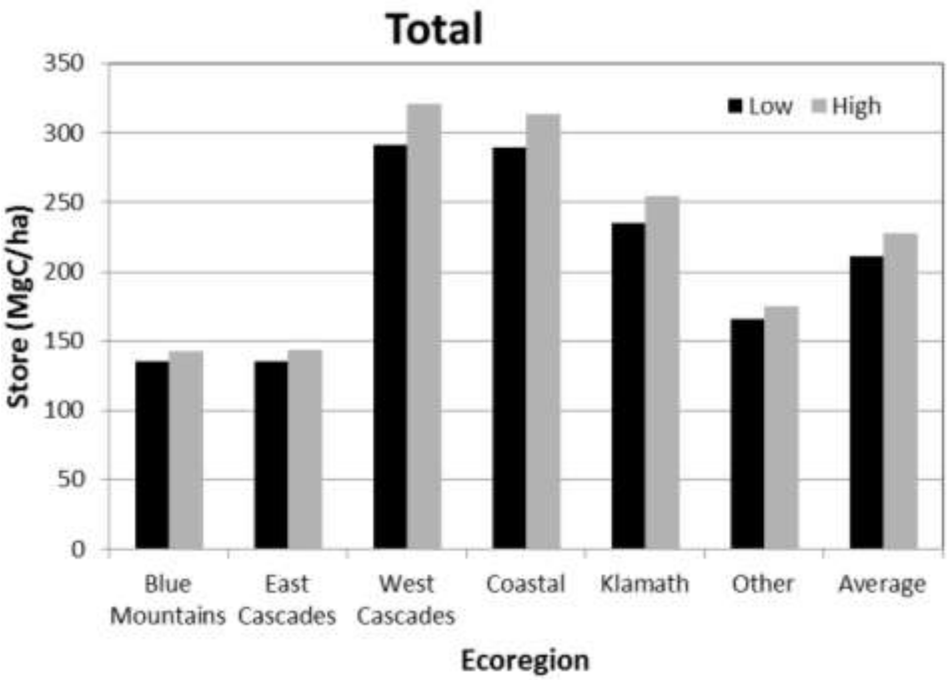


Figure 2. Density of total forest carbon stores by ecoregion. The "low" and "high" estimates reflect the range of certainty associated with adjustments and correction factors used.[34]



What is the distribution of total carbon and carbon density (store per unit area) among owners?

The proportion of total forest carbon was higher for federal ownerships than area would suggest, lower for private ownerships and Other[35] owners (Figure 3). This pattern was consistent across all ecoregions.

[34] Figures and text will sometimes reference "forest carbon stores" to include the contents of all in-forest carbon pools per US Forest Service Forest Inventory and Analysis (FIA) data. At other times it may reference "live tree carbon" to indicate that pool only, or when that pool is used as a rough proxy for all in-forest carbon stores when calculating ratios. Live tree carbon data are the most reliable available, but when used as a proxy the values should be taken as indicative and not definitive. Carbon density refers to the amount of carbon stored per unit of area (hectare or acre)

[35] "Private" owners include industrial timberland and smaller, often family-owned, woodlots. "Other" owners include State of Oregon and tribal forest lands.

Figure 3. Proportion of total carbon stores in forests contributed by different ownerships for forested lands within those properties.

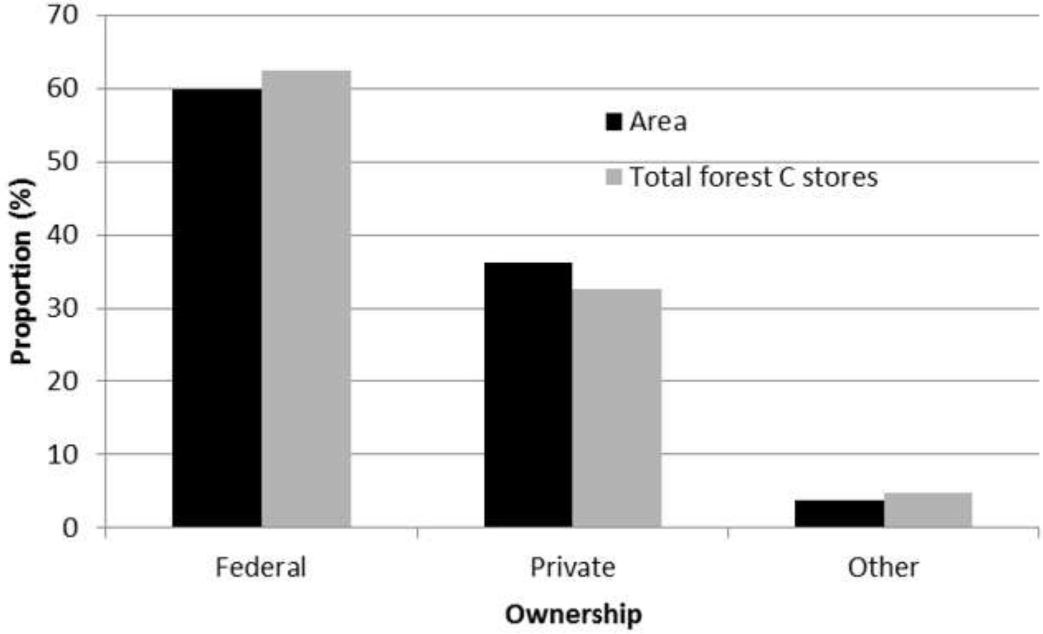
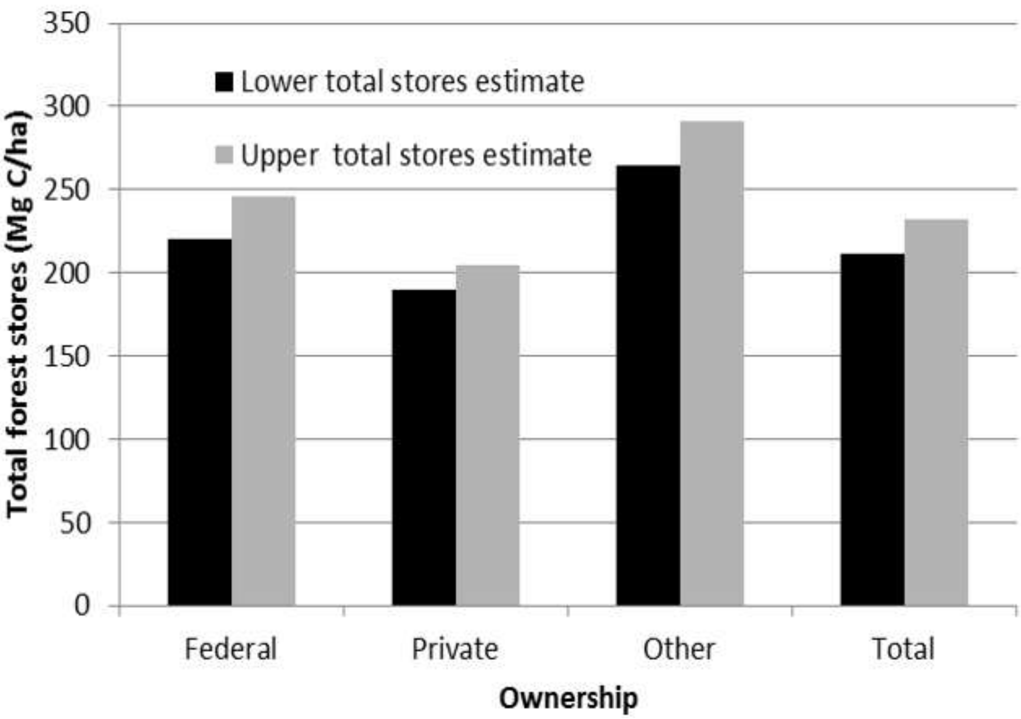


Figure 4. Carbon density in all forms in Oregon's forests by ownership.[36]



[36] Table 4 reflects *carbon density/intensity* of forests by owner. While the "Other" ownership category (see Footnote 31 above) compares well on carbon density, it comprises less than 5 percent of total Oregon forested acres.

Total forest carbon density varied among ownerships, with the highest for Other owners compared to federal or private owners (264 to 291 Mg C/ha, respectively) (Figure 4). The lowest was for private lands (190 to 204 Mg C/ha) and federal ownerships were intermediate in terms of carbon density (220 to 246 Mg C/ha). These estimates do not include carbon associated with stumps or their dead roots, and so may be slightly higher than reported here by about 0.5 percent (Harmon 2018a).

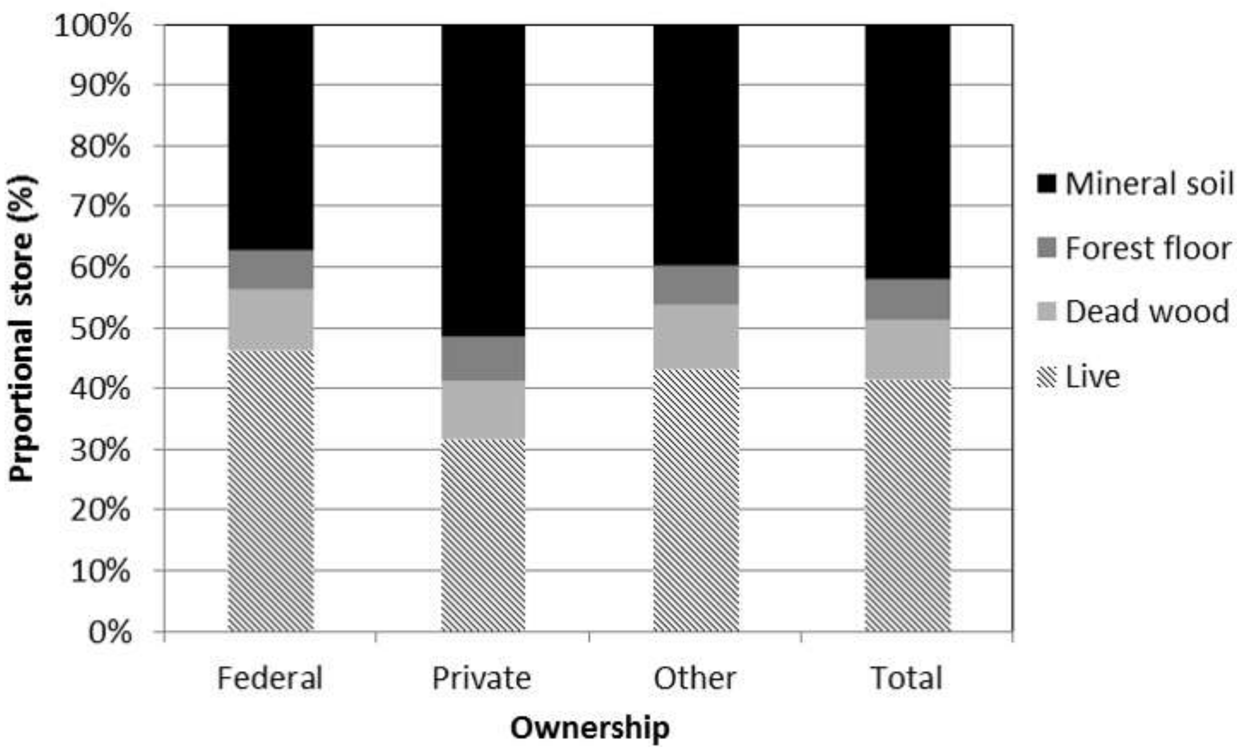
How does the distribution of total carbon for each ownership vary among ecoregions and among the major forest carbon pools?

Federal forests consistently have higher total carbon stores than private forests. This suggests that a chosen management approach has a fairly consistent impact of total forest carbon stores; specifically higher rates of harvest reduce carbon stores in forests while lower rates of harvest retain more carbon in forests. This effect is mitigated to some degree by the net difference between inflow and outflow of carbon in a post-harvest wood products carbon pool, as discussed below.

What is the distribution of total carbon among in-forest carbon pools?

The majority of carbon is stored in the mineral soil and live tree pools (42 percent and 41 percent respectively) (Figure 5). Dead wood and forest floor stores comprised the remaining 17 percent.

Figure 5. Proportional stores of carbon in Oregon's forests by major pool and ownership. Total indicates the distribution among pools for the state as a whole.



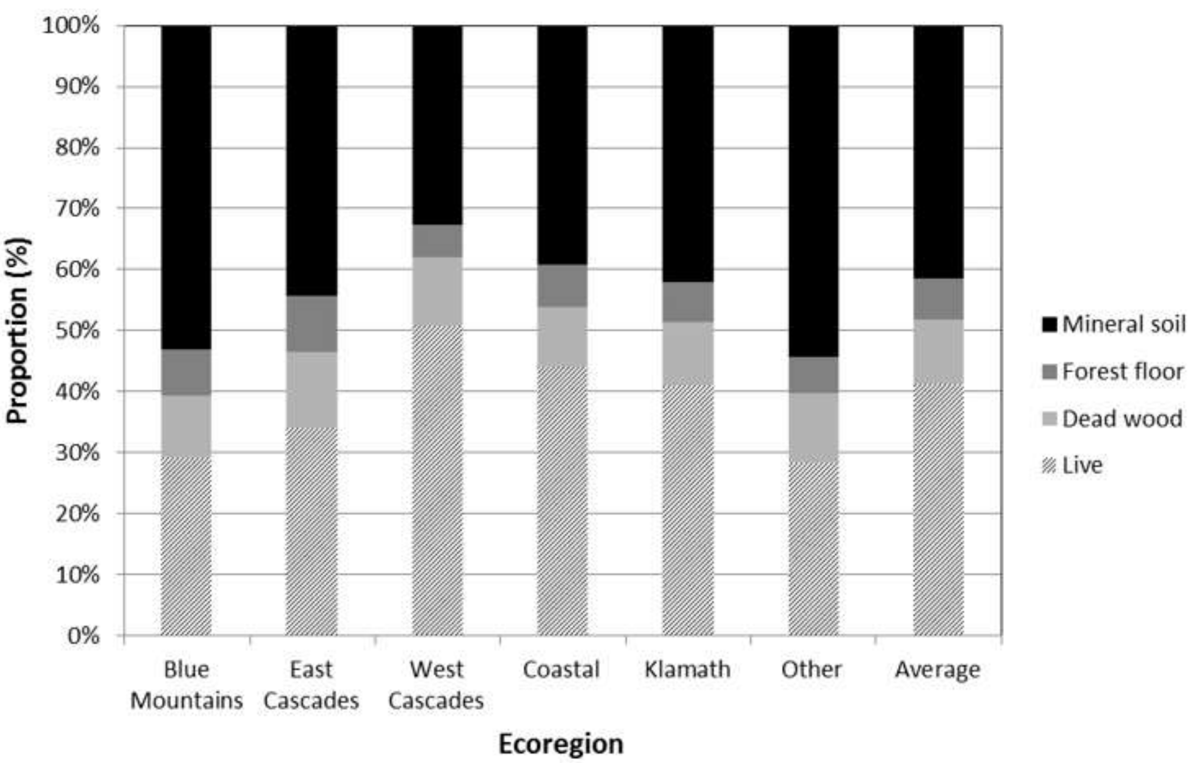
How is the distribution of total carbon and carbon density (store per unit area) among in-forest carbon pools influenced by ownership?

There is a higher proportion of mineral soil carbon stores on private ownerships than federal ones (Figures 5 and 6). Conversely, there is a higher proportion of live carbon stores on federal ownerships than private ones. This is a function of the higher level of harvest on private ownerships. The proportion of stores in the dead wood and forest floor pools is similar across ownership types. This distribution may reflect the historical prior selection of more productive forests and soils (e.g., lower elevation Coast and West Cascade areas) being captured by private forest owners while higher elevation, less productive lands became federal forests.

How does the distribution of total carbon among in-forest carbon pools vary by ecoregion?

In general, mineral soil carbon is proportionately higher in drier ecoregions (e.g., Blue Mountains) and live carbon is proportionately higher in wetter ecoregions (e.g., West Cascades and Coastal). However, as described above, management is also important given that harvest-related mortality and carbon removal from the forests can reduce overall stores within those forests.

Figure 6. Distribution of total carbon stores for each major pool by ecoregion. The far right-hand column is the statewide "average" of ecoregions.



How much carbon that has harvested from Oregon's forests has accumulated in the form of wood products?

Wood products represent another forest carbon "pool." As with other pools, carbon flows into the wood products pool as harvest converts trees into products. The amount of carbon entering the wood products pool is less than that removed from the live wood pool because branches, stumps and roots are left behind to enter the in-forest dead wood pool, or to decompose and return carbon to the atmosphere. The harvested carbon is further reduced as trees are processed into products with mill residues left for disposal. Different products will have different product – and carbon storage – lifespans (e.g., paper -- short duration; structural lumber – longer duration) in the wood products pool. As carbon in new products is flowing into the wood products pool, the carbon in old, disposed of and decomposing products is returned to the atmosphere. The amount of carbon stored in this pool (as in all the pools) is the net of carbon flowing in minus the carbon flowing out; and the storage duration varies with the product and/or form of disposal. For structural lumber in a building this duration may extend as much as 230 to 345 years but the average is much shorter: 50 – 75 years (Harmon 2018e). However, well-buried landfilled debris from demolished structures can take 200 to 900 years to decay and release carbon to the atmosphere (Harmon 2018e). For comparison, carbon in west side coastal and montane forests may be stored for up to 800 years (Law et al.. 2018); the average for all live trees is 28 – 20028 – 200 years (Harmon 2018e, which states that the wide range reflects "variation in short versus long-lived tree species" and that live trees in federal forests generally have a longer average carbon lifespan (109 years) when compared to the average on private forestlands (28 years)).

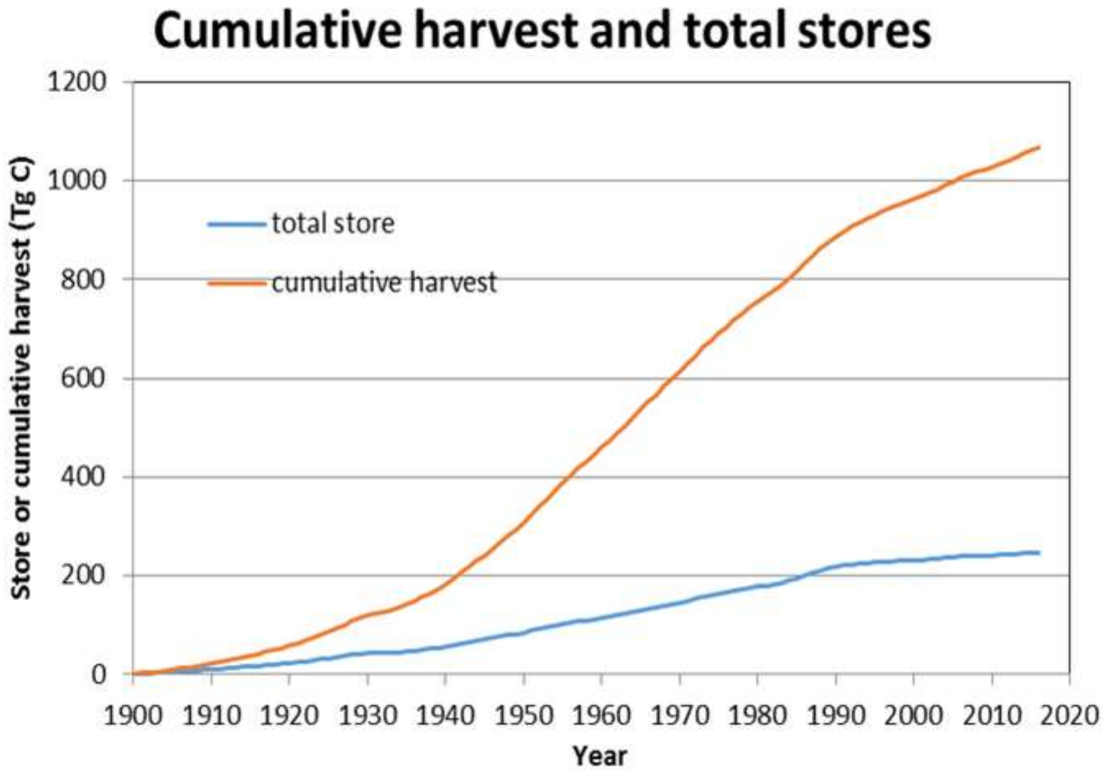
This question is further complicated and can only be answered in a relative sense because Oregon's harvests have traditionally been reported in board feet and there is uncertainty about the conversion to cubic units. However, using historical data on harvest levels, the path of manufacturing, product uses and lifespans, as well a fate after disposal, approximately 1067 Tg C have been harvested and 247 Tg C of solid product-related carbon has accumulated between 1900 and 2016 (Figure 7) (Harmon 2018d). This means that 23 percent of the carbon harvested from forests over this time period is currently stored in solid wood products that are either being used or have been disposed. The majority of these stores (68 percent) produced from stem wood and in the form of products in use have an average lifespan is 43 years; however, the fastest growing store is disposed products principally in landfills. As harvest and mills become more efficient, the amount of stem wood captured in product can be expected to increase. It is less clear whether buildings and other wood products will have longer or shorter lifespans.

For the 2001 to 2015 period the process model used to predict the net growth of solid wood products suggests that the proportion of the harvested carbon that is resulting in an increase in wood product stores for the state as a whole is 13.9 percent (Harmon 2018d). This means that the rest of the harvest is either lost to the atmosphere during manufacturing or is replacing products in use or disposal that are losing carbon to the atmosphere by decomposition and combustion.

Based on the amount of harvest estimated from FIA data for the 2001 to 2015 period, approximately 15.8 Tg C[37] of wood products have accumulated over this same period (Harmon 2018a). This is 7 to 19 percent of the value accumulating in the forest itself over the same period. This analysis does not capture emissions associated with harvest and transport operations, or the significant multi-decadal delay in rebuilding in-forest carbon store after harvest (see wood products carbon accounting steps, page 18 of this report).

[37] The average annual increase in wood products was 1.13 Tg C/y. Multiply by 14 years to get 15.8 Tg C. The 1.13 Tg C figure is derived by beginning with harvest cuttings per year (9.56 Tg C/y), less 15 percent to account for branches not harvested, times 0.14 (rounded up). The product of that calculation is 1.13 Tg C/y.

Figure 7. Cumulative harvest and store of harvested carbon in solid form of carbon 1900 to 2016 for all ownerships combined.

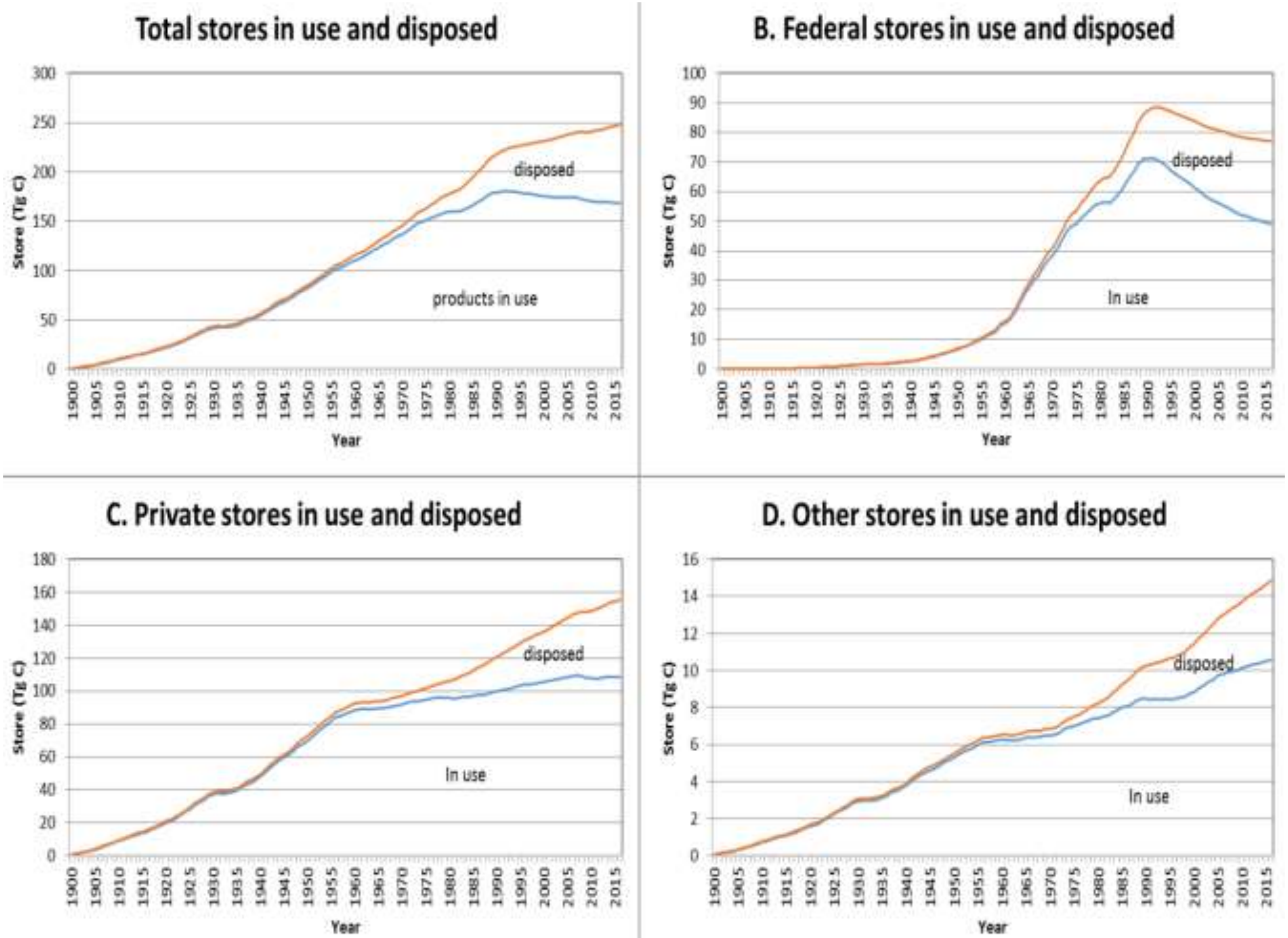


How have the stores of wood product stores varied over time for the different ownerships?

A decline in harvest in Oregon's federally-owned forests since the early 1990's has led to consistent declines in product carbon stores deriving from these forests, over this period (Figure 8). This trend in federal forests has resulted in a declining overall rate of carbon accumulation in this pool (offset by a much larger net carbon accumulation within the same federal forests) and a reduction in net carbon contained in the wood products pool from all Oregon forests (Figure 8A). The accumulation rate for all ownerships since 1990 is approximately half the pre-1990 rate. The declining trend in solid wood product stores from federal ownerships (specifically national forests) was also found by the baseline assessment of harvested wood products conducted by the USDA Forest Service, Pacific Northwest Region (USDA Forest Service 2015).

There is considerable variation among ownerships when net changes in wood products are expressed as a fraction of harvest resulting in a net accumulation of wood products. For federal ownerships net change in products stores on federal lands is negative, declining at a rate equivalent to 69.5 percent of the harvest (offset by carbon stores within federal forests gaining significantly). The net change in product stores on private and other ownerships is positive and is equivalent to 21.6 percent and 31.9 percent of the harvest, respectively (while carbon stores within private forests are gaining slightly).

Figure 8. Store of carbon in solid wood products in use or disposed 1900 to 2016.



What is the current total store of carbon in Oregon's forest sector (forest and wood products)?

The estimates of wood product stores presented above do not address the issue of uncertainty in converting board feet to cubic feet. Based on the correspondence of the FIA-based harvest estimates and those reported by from the Oregon Department of Forestry, the uncertainty in solid wood products in use and disposal would be approximately 20 percent so the range in wood product stores might be between 247 and 315 TgC. This would put total stores of carbon for Oregon's entire forest sector (in-forest and wood products) as large as from 2829 to 3180 TgC.[38] This estimate assumes that the uncertainties associated with these two sources (i.e., the forest and wood products) are positively correlated, and this may or may not be the case. It also leaves aside issues raised above of difference in carbon retention (in forests; in wood products) and the delay in rebuilding forest carbon stores after harvest. So it is an approximate sum at a point in time and not a true picture of forest carbon distributions, losses and gains over time.

[38] While most estimates of total carbon stored in Oregon forests round to ± 3 billion metric tonnes, specific quantities and ranges can vary. For example, Law 2018 gives an estimate of 3036 TgC (3.036 billion tonnes, or about 12 billion tons CO2e).

B. State of Flux of Carbon in Oregon Forests

What is the estimate of annual gross and net amounts of carbon flowing into Oregon's forests (all pools) from the atmosphere?

The average annual gross amount of atmospheric carbon flowing into Oregon's forests via photosynthesis during the period 2001-2015 was estimated to be 114 to 150 Tg C/y (141 to 165 million tons C/y; or 517 to 606 million tons CO2e) (Figure 9). Of this approximately 50 percent was lost within a year to plant respiration, 28 percent was allocated to short-lived plant parts (leaves and fine roots), and 22 percent was allocated into longer-lived woody tissues. Gross growth was estimated to be 27.8 to 29.0 Tg C/y (30.6 to 32.0 million tons C/y) for above- and belowground live woody parts.

Figure 9. Quantities, expressed as ranges, in estimates of carbon fluxes associated with Oregon forests.

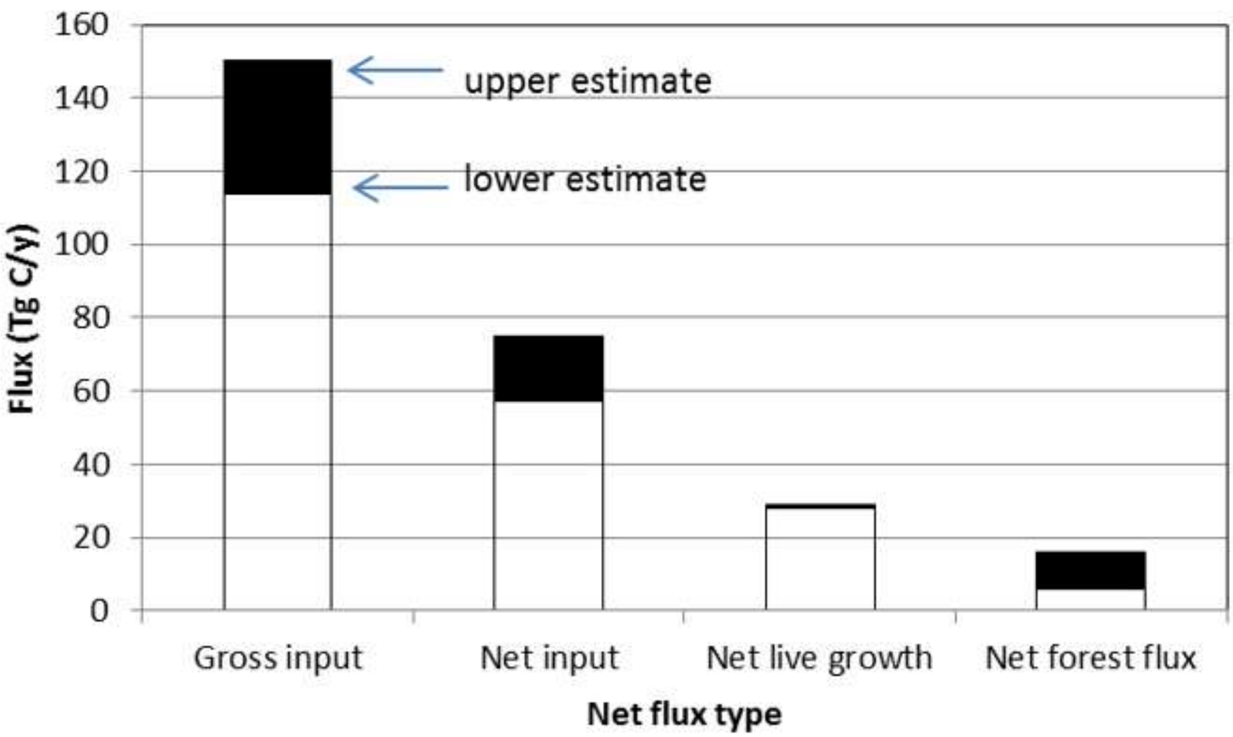


Figure 9 presents estimates of carbon net fluxes associated with Oregon forests over the 2001-2015 period (quantities expressed as ranges).

The net exchange between the forest and atmosphere, the key balance or net flux of concern, is shown on this figure as the net forest flux (also termed NECB, or Net Ecosystem Carbon Balance). Conceptually, to estimate this term we begin with the **gross input** which is equivalent to the total amount of carbon entering the forest system via photosynthesis (also termed gross primary production or GPP).

Approximately half of the gross carbon input is lost as plants respire (also termed autotrophic respiration) during their growth, maintenance, and nutrient uptake. This leaves the other half as the

net input (also termed net primary production (NPP)[39] or when just the aboveground stem wood is considered it is termed gross growth).

Net live growth (also termed net growth) represents the net flux when losses from mortality related to natural causes and harvest are deducted from net input, *but does not represent the net exchange with the atmosphere*.

To estimate the **net forest flux** the losses associated with harvest, respiration from decomposers and other heterotrophs such as animals, and combustion in fires are deducted from the net input term.

The maximum **net forest flux** (or Net Ecosystem Carbon Balance/NECB) value of 15.8 TgC/y (63.9 million short tons CO2e) in Figure 9 is slightly less than the 18.15 TgC/y (73.4 million short tons CO2e) estimate by Law et al. (2018). **Net forest flux** (NECB) shown here includes the net changes in *all* forest pools above- and belowground.

Additional analysis would be required to calculate the net forest flux by ecoregion or owner.

Notwithstanding limitations associated with the equations for estimating tree biomass, the best data on net change of pools is for live carbon. If all pools other than the live ones are remaining constant, then the net rate of exchange with the atmosphere would be between 9.4 and 9.8 Tg C/y (equivalent to 38.0 to 39.6 tons/y CO2e) meaning that Oregon's forests as a whole are removing these net amounts of carbon from the atmosphere and storing them in forest carbon pools.

However, it is unlikely that the other pools, particularly the dead wood pools, meet the assumption of no change. A sensitivity analysis varying possible changes in dead wood, forest floor, and mineral soil pools suggested that the net change with the atmosphere could range between 5.8 to 15.8 Tg C/y (equivalent to 21.3 to 57.9 Tg/y of CO2e; or 23.5 million to 63.8 million short tons CO2e)) (Harmon 2018a). This is lower than the mean of 18.15 Tg C/y estimated by Law et al. (2018); however, the uncertainty in their estimate is approximately 9 TgC/y which indicates considerable overlap with this estimate made directly from the FIA data provided by the USDA Forest Service. The wide range between low and high estimates is largely due to insufficient data from pools other than the live tree pool. Additional analysis of these other pools will result in narrowing the range.

How has this flow varied over recent years and why?

The FIA data were used in the analysis to approximate changes over the last decade. This limits our ability to analyze changes within this period on an annual basis, and it does not contain information about earlier decades. However, other analyses based on FIA data and simulation models suggest it is likely that the trend of net removal from the atmosphere has been present since 1992 when major changes in management of federal lands occurred. Prior to this period the level of the high harvest across all timberland ownerships would suggest that Oregon's forests were a net source to the atmosphere. The most likely explanation of changes in Oregon's forest to being a carbon sink

[39] NPP = Net Primary Production of carbon by forest flora including heterotrophic respiration (Rh), or carbon returned to the atmosphere by organisms – including above-ground dwelling animals, and soil-dwelling flora and fauna, that through their biological functions process and emit to the atmosphere forest carbon captured by trees and plants. NEP = Net Ecosystem Production, or NPP less heterotrophic respiration.

(acquiring net atmospheric carbon) versus a source (releasing forest carbon to the atmosphere) is harvest level in federal forests.

How do flows vary by ecoregions?

Gross flows and total forest net flows were not examined at the ecoregion level in Harmon 2018 a-d, from which the following analysis is taken. However, relative ecoregion differences are likely well represented by differences expressed in the net change in live carbon stores per hectare per year. The east Cascades and Coastal ecoregions are contributing more to the net change in live stores than area would suggest (Figure 10). In contrast, the Blue Mountains, West Cascades and Other ecoregions contribute less, and the Klamath ecoregion contributes about what would be expected from area. While the per unit area change in net live stores is highest in the west Cascade and Coastal ecoregions, it is positive for all ecoregions (Figure 11). This indicates that, at least for live carbon, there is a statewide increase of live carbon in all ecoregions. However, there is considerable variation in the per unit area net change in live stores across ecoregions, with a four-fold difference between the highest values (Coastal) and the lowest (East Cascades). For each of the ecoregions, federal ownerships are contributing more than would be expected from area alone and private ownerships less. All ownership-ecoregions have a positive net change in live carbon, except for other ownerships in the west Cascades.

Figure 10. Proportion of net change in live carbon stores <u>in forested areas within</u> different ecoregions <u>and contributed by each ecoregion</u>. Total low and high include roots and represent low versus high correction factors to account for roots.

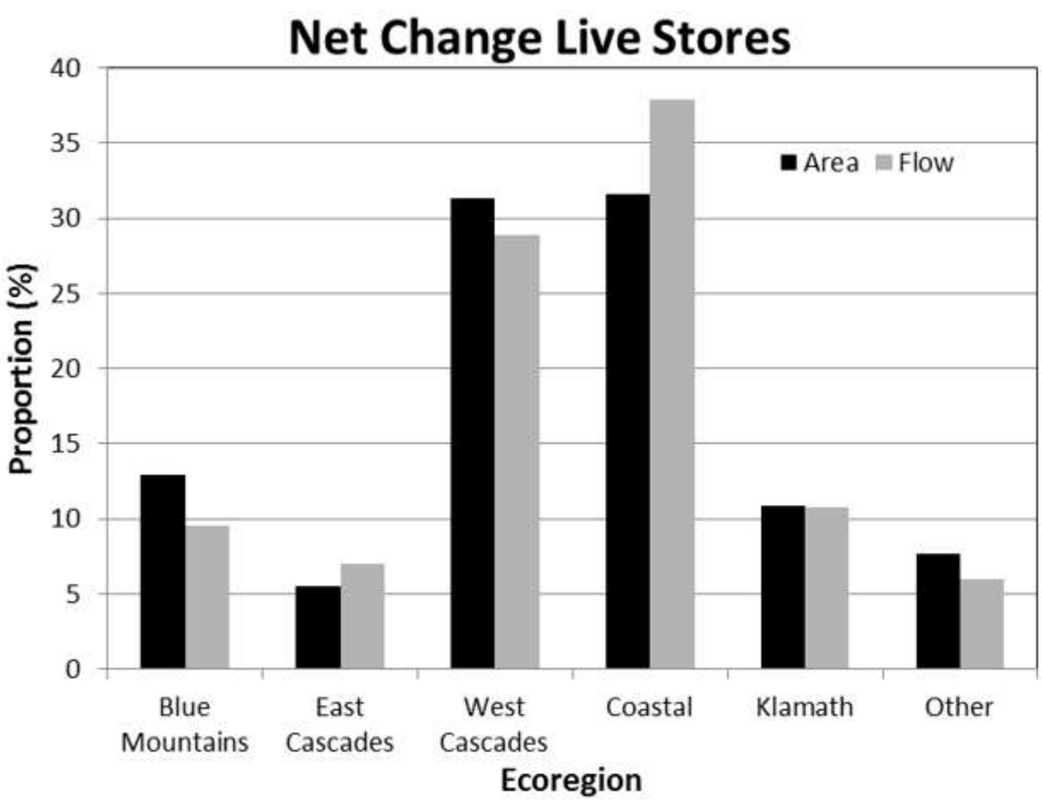
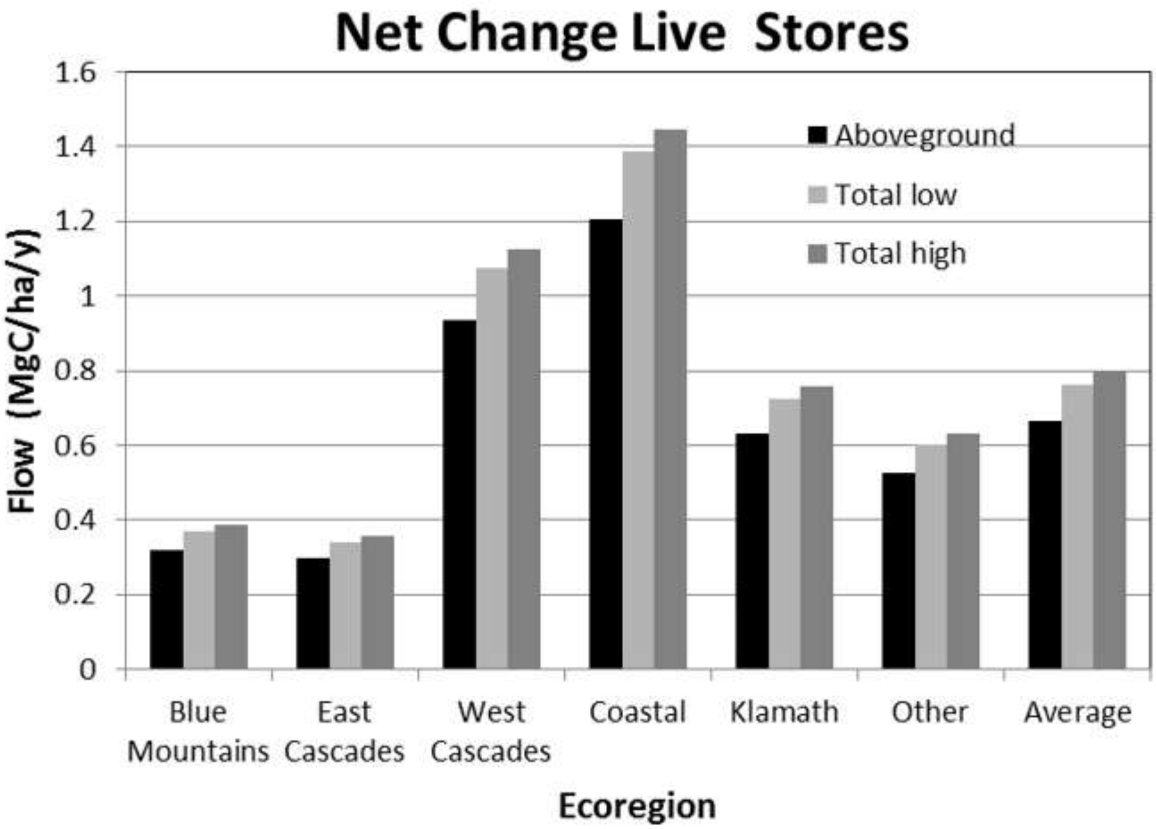


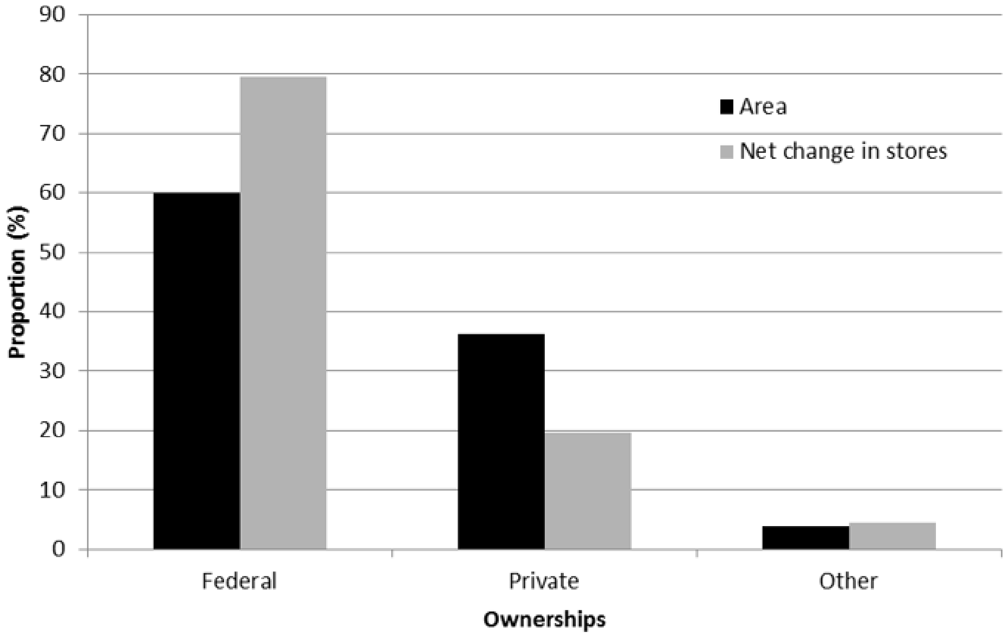
Figure 11. Average per area net change in live stores by ecoregion, expressed as a flow (MgC/ha/yr). The "average" ecoregion represents the state-wide average. Total low and high include roots and represent low versus high correction factors to account for roots.



How do these Live Carbon Stores vary by ownership?

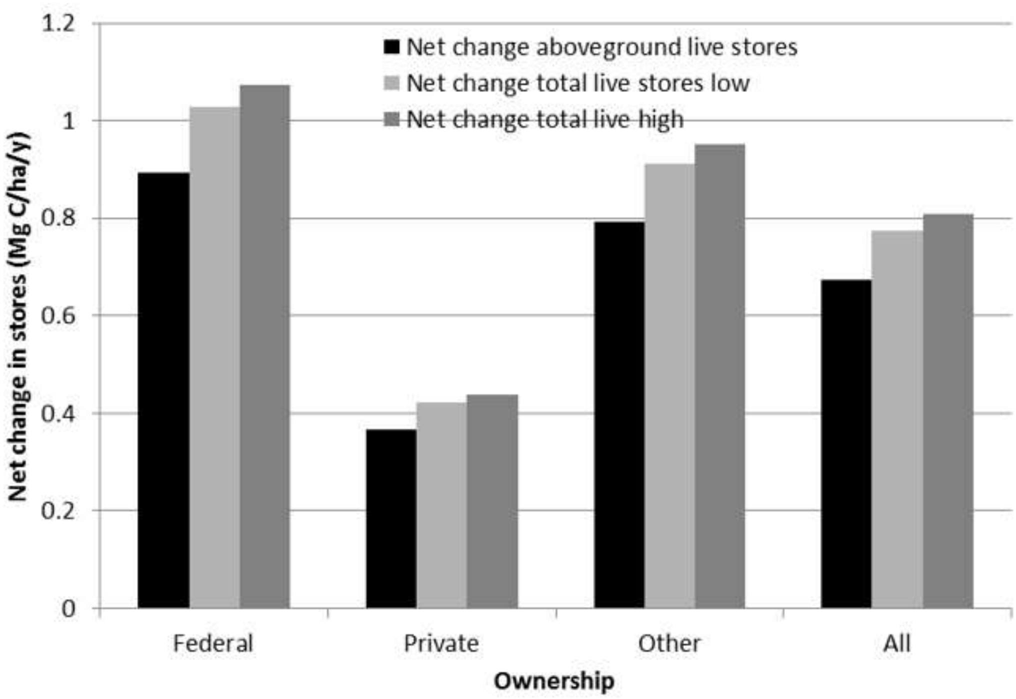
Gross flows and total forest net flows were not examined at the level of ownerships. However, relative ownership differences are likely well represented by differences expressed in the net change in live carbon stores per hectare per year. Federal ownerships are contributing more to the positive net change in live stores than area would suggest. Federal lands comprise 60 percent of the area, but 79 percent of the overall net change in live stores (Figure 12). In contrast, private lands comprise 36 percent of the area, but 20 percent of the net change in live stores. For other land ownerships, the proportions of area and net sink are similar.

Figure 12. Proportion of area and net change in aboveground live stores by ownership of Oregon's forests.



Considered on a per area basis the rate of net change in live tree aboveground stores was highest on federal lands (0.89 Mg C/ha/y) and lowest on private lands (0.37 Mg C/ha/y) (Figure 13). Interestingly, the net rate of stores change on other ownerships was nearly as high (0.79 Mg C/ha/y) as for those of federal lands.

Figure 13. Net change in live stores for different Oregon forest ownerships. Total low and high include roots and represent low versus high correction factors to account for roots.



How might the net carbon flux between the Oregon's forests and the atmosphere change in the future?

Without detailed process-based modeling for a range of likely scenarios this question is impossible to answer. From the FIA-based analysis one can make an estimate of the degree of change in either the carbon entering the system (input) or the amount of time carbon spends in the system (output) that is needed to cause Oregon's forest to become a source to the atmosphere. This suggests that either input or output functions for Oregon's forests could be reduced by up to 27 percent without forcing the system to be a source to the atmosphere (Harmon 2018c). However, this varies considerably among ownerships: under current management practices, federal ownerships could "tolerate" a 35 percent change, whereas private ownerships could tolerate a 6 percent change. Current research (Law et al. 2018) suggests that changes in such practices – in particular, "reforestation, afforestation, lengthened harvest cycles on private lands and restricting harvest on public lands (could) increase NECB (Net Ecosystem Carbon Balance) 56 percent by 2100, with the latter two actions contributing the most." That would increase NECB by some 890 million metric tonnes CO2e by 2050, or an average of around 25 million metric tonnes CO2e/year captured and stored in Oregon's forests, over and above the present net forest carbon gains. This increase, added to existing forest carbon gains, is the equivalent of about 80 percent of Oregon's present annual emissions from all sources, combined, including forest sector emissions from decomposing wood products.[40] Other factors, including unanticipated climate change factors, could increase or reduce these gains. But the figures suggest the significant potential contribution by forests in Oregon and elsewhere could be making toward global goals to reduce greenhouse gas concentrations in the earth's atmosphere.

What is the net flux of the wood products derived from harvest of Oregon's forest relative to the atmosphere?

The change in products stores estimated from a process-based model of solid wood products was equivalent to 14 percent of the stem harvest removals or 1.13 Tg C/y. It should be noted that this estimate does not reflect likely uncertainty related to the board foot to cubic conversion. Uncertainties for this net change in wood products stores would also be associated with that introduced by biomass models and estimates of the fraction of cut trees that were removed from the forest.

What has been the net flux of the entire forest sector (forests and wood products)?

When the net accumulation from solid wood products (i.e., paper, wood in buildings, etc.) is included, a sensitivity analysis varying possible changes in dead wood, forest floor and mineral soil pools suggests that the net change with the atmosphere, or the total net uptake of Oregon's forest sector, could range between 6.9 and 16.9 Tg C/y (equivalent to 25.3 to 62.0 Tg carbon dioxide/y). The upper end of this range corresponds to forest Net Ecosystem Carbon Balance (NECB) of 68.98 MM tons CO2e/year estimated by Law et al, (2018)

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[40] Current non-forest (e.g., energy) emissions are about 60 million tons CO2. Current emissions from decomposing forest products materials add another 28 million tons, for a total emissions level of about 88 million tons CO2/CO2e. Law estimates a present net rate (NECB) of carbon uptake by Oregon forests of about 69 million tons. Adding another 25 million tons/year (890 million tons CO2e over 35 years) would increase forest uptake to 94 million tons/year, exceeding the 88 million tons of energy + forest product emissions at least through 2050 (Law et al. 2018).

Has this changed in recent years? And how might this change in the future?

As indicated above, the FIA-based analysis of the data on hand cannot, on its own, answer this question. , It is likely that at least for the next decade that Oregon's forest sector, under prevailing management practices, will remain a carbon sink from the atmosphere and add to forest sector carbon stores. Changes in management practices described above could increase these additions. Further research to narrow uncertainties will hopefully enable policymakers to frame more effective remedies, and arguments for their adoption.

What can we usefully say about the potential effects of climate change on forest composition and carbon flux functions in Oregon's forests?

The FIA-based analysis of carbon data does not report species or provide information about how forest composition might be changing from any cause. In addition, the FIA-based data provides insufficient information about how climate change might influence carbon flux functions. All that can be derived is the degree to which these functions can change without causing Oregon's forest sector to become a source of carbon to the atmosphere. Another question to punt forward to a next research iteration.

See also Appendix D: *Summary of Oregon Forest Ecosystem Expected Effects of Climate Change, Oregon Climate Change Research Institute.*

C. Data Uncertainties and Research Needs

1. **Adjustments to FIA Data**: For stores the main uncertainties are related to the adjustments that need to be made to FIA-based estimates. These include adjustments to account for carbon pools that were not reported (e.g., live and dead coarse roots) as well as those needed to account for volume and density losses for the standing dead trees. There were also uncertainties associated with the estimates for mineral soil carbon stores related to the inclusion of pools that were not strictly mineral soil related (e.g., forest floor). These uncertainties can be significantly reduced (probably by at least a factor of two).

2. **Biomass[41] Estimating Equations**: For live stores there is also uncertainty associated with the biomass estimating equations used to convert FIA field measurements to carbon. This uncertainty is difficult to completely eliminate, but a more regional-based set of biomass models would probably be more accurate than the national level equations used in the current analysis.

3. **Accuracy in Measuring Carbon Flux of Forest Pools In Addition to Live Tree Carbon**: For fluxes associated with the forest, the primary source of uncertainty is related to the lack of change in stores data for pools other than live carbon. In other words, the current estimates are only relatively certain for the live aboveground carbon because re-measurement data were available

[41] We distinguish between the broad definition of forest biomass as the total plant material comprising a forest; and biomass as a shorthand label for plant or other biologically-derived material collected, processed and used as a fuel source for generating thermal or electric energy, or both. In this paper "biomass" refers to the first instance; and "biomass fuel" the second.

for half of the FIA forest inventory plots. However, re-measurement data exist that can be used to estimate the net changes in dead wood and the forest floor. This would likely decrease the uncertainty in net change in total forest stores by a factor of two. This would leave changes in mineral soil stores as the only one that cannot be reduced with re-measurement data.

4. **Refine Estimating Methods for Mineral Soil Carbon**: Potential changes in mineral soil carbon stores are highly uncertain, but likely to occur. It is therefore unrealistic to assume that because the uncertainty is high the change is zero. A more realistic estimate of the change that is possible in this pool could be made by focusing on the situations and locations where this change is most likely. For example, if changes in mineral soil stores are likely to occur on a limited area, then the state-wide uncertainty in how this pool changes would be far less than if they occur state-wide. Since uncertainty in mineral soil changes account for about half the uncertainty in the total, this research could potentially narrow the total uncertainty considerably.

5. **Board-foot to Cubic Foot Conversion Factor**: While there are many uncertainties associated with wood products stores, a significant one is related to the board foot to cubic foot conversion factor. This not only causes a gap between these estimates and the FIA-based harvest estimates (which are cubic based), but also makes it difficult to estimate the absolute amount of accumulated products. A better reconstruction of past cubic harvest estimates, together with a policy of requiring current timber harvest to be reported by volume as well as board feet would mitigate this uncertainty.

6. **Reconcile FIA Modeling with Process Modeling Methodologies**: This report has largely focused on FIA data and subsequent analyses. However, there are other ways to estimate carbon stores and fluxes such as process-based models. It would be important to do comparisons between FIA-based and process models for the most recent decades. This would not only help resolve differences, but also would strengthen efforts to use process-based models to either reconstruct the past or project the future changes in stores and fluxes.

7. **Translating the vulnerability assessment and productivity modeling into losses or gains in forest carbon**: Latta et al (2010) developed a model to estimate the impacts of climate change on the potential productivity of PNW forests and found that for the west and east sides of the Cascade Mountains, respectively, potential mean annual incremental increases from 2 percent to 23 percent, depending on the climate scenario used. Translating the vulnerability assessment and productivity modeling into losses or gains in forest carbon is a more challenging problem that will require additional research.

8. **State Forest Carbon Storage**: This analysis grouped Oregon's 1,205,000 acres of state and local government managed forests in the "Other" category. In order to evaluate the potential for increasing these forests to store additional carbon, they would need to be evaluated separately? Any changes in policies would need to consider interactions with other historic and/or mandated goals for management of these forests?

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Appendix A: Forest Carbon Accounting Terms

Aboveground live carbon | the amount of carbon stored in stem wood and bark, branches, and leaves.

Belowground live carbon | the amount of carbon stored in coarse and fine roots.

Dead and downed wood | this includes dead wood and attached bark greater than 6 mm diameter.

Forest floor | includes decomposing leaves, wood less than 6 mm diameter, and buried wood. This might be considered the organic soil horizon.

Gross growth | equivalent to the net primary productivity (NPP) of woody parts. This is computed from the net change in stores plus any losses associated with natural or harvest-related mortality.

Harvest-related mortality | a flow indicating the amount of tree carbon being killed by cutting activities related to harvest. This does not equal the amount of harvest removals unless all the cut material is removed.

Mean retention time | the average amount of time in years that carbon resides in a pool. It can also be considered the average lifespan in a pool. This is not the same as the maximum time carbon can reside in a pool.

Mineral soil | this is the organic carbon (as opposed to mineral forms of carbon such as calcium carbonate) in the portion of the soil that is primarily mineral in nature. Typically the concentration of organic carbon in the mineral soil is less than 10 percent. Values for different depths are reported, in this case the depth was 1 m, which means that the organic carbon in deeper layers was neglected.

Natural mortality | a flow indicating the amount of tree carbon being killed by processes other than harvest including wind, fire, insects, disease, competition).

Net primary production (NPP) | equivalent to gross production for wood related NPP. Essentially the carbon available to offset losses via mortality (natural or harvest related) and to increase live stores.

Standing dead wood | includes stems, branches, and roots associated with trees that are standing. The original values did not account for losses associated with volume or density loss during decomposition. It therefore is an overestimate.

Teragram (Tg) | this is 10^{12} grams or a million metric tonnes.

Appendix B: Ways to Measure Forest Sector Carbon, Track Flows and Account Disposition

There are multiple, interrelated, and complementary ways in which carbon in the forest sector can be examined and described. While it may be tempting to focus on one key carbon metric, more understanding is reached when the entire suite of metrics is examined. By analogy one can certainly paint using one color, but using the full pallet is often more effective than monochrome.

Perhaps most fundamental is how much carbon is stored (i.e, the size of a pool) expressed either as a carbon density per unit area (e.g., tons per acre) or as a store for a region (e.g., tons in west-side forests, tons in the state of Oregon). The advantage of stores expressed as a carbon density is that it allows one to more directly compare regions of different size to each other. For example, by using carbon density we can separate differences in regional stores due to differences in areal extent versus whether something different going on within those areas. These terms are interrelated: the regional store is the carbon density multiplied by the area of a region.

While are stores are important, the change of stores from one time to the next that indicates whether carbon in a pool is increasing, decreasing, or remaining the same over time. The change in stores can be calculated by comparing estimated stores at two times or by comparing the flows coming in versus out over the same time period. Both methods yield the same result; the method used depends on the pool being considered because sometimes it is better to inventory stores and determine the net change (e.g., live wood) and sometimes it is better to estimate flows to determine the net balance (e.g., wood products). If the store is increasing over time, then the conservation of mass law implies this additional carbon must be coming from somewhere else. Likewise, if the store is decreasing over time, then the store must be going somewhere else system. However, one must bear mind that the change in stores ultimately reflects the net difference between the carbon flowing into and out of a pool or store. Therefore is possible to have no change in the stores over time, but to still have carbon flowing into and out of a pool; it just turns out that in this case the flows in and out are of equal size. One must also bear in mind that just because there is a net flow in or out of a store does not mean that this carbon is coming from or going into the atmosphere as that depends on the particular flow involved.

To understand the mechanisms causing stores to change it is important to examine the flows associated with key processes occurring within the forest carbon system. Flows (sometimes referred to as fluxes) can be expressed similarly to stores on a per unit area or total area basis, but also include time (typically per year but it could be for a period of time such as 5 years). Examining flows not only allows one to understand why the change is occurring, but also whether these processes are directly interacting with the atmosphere versus involve internal transfers within the forest sector. Carbon is removed from the atmosphere via photosynthesis, hence photosynthesis is the only real carbon uptake mechanism. Carbon is only lost to the atmosphere via respiration and combustion, hence these are the only real release mechanisms to the atmosphere. All other flows move carbon from one part of the system to another and do not directly lead to removal of atmospheric carbon or releases to the atmosphere.

In addition to knowing the stores and flows controlling carbon, valuable insights are provided by estimating how long carbon, on average, stays within a pool. This can be thought of as the turnover time (τ) or the mean retention time (MRT) or the average lifespan of carbon within a store or pool. This metric is a ratio: the store divided by the flows removing carbon from that store. Conceptually this represents the number of "times" the flow can be removed from the pool and for forestsforest is usually expressed as the number of years. The reciprocal of the turnover time is the proportion leaking out of the store each year. While estimates of turnover time are best made when a store is not changing over time, approximate estimates also provide two key insights: the potential size of a store (the longer carbon stays within a pool, the more it can store) and the time required to change a pool (the longer the carbon stays within a pool, the longer the store takes to change if the flows into a pool are changed). Comparison of turnover times can also indicate whether changes in management or disturbance regimes will lead to potential changes in carbon stores as well as the approximate size of change of these stores as one moves from one regime to another.

[Provided by Dr. Mark Harmon, Oregon State University School of Forestry (retired), May 15, 2018]

Appendix C: Acknowledgements

The OGWC convened its Forest Carbon Task Force to advise and inform this report and future policy recommendations. While members of the Task Force were not asked to approve the findings herein, their contribution to the Commission's understanding of the data and issues has been invaluable. Members included:

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Lesley Jantarasami (Oregon Department of Energy)

Jessica Shipley (Oregon Department of Energy)

Dr. Andrew Yost (Oregon Department of Forestry)

Appendix D: Summary paragraphs on forest ecosystem impacts from climate change: from the OCCRI Third Oregon Climate Assessment, January 2017.

Oregon Climate Change Research Institute

Chapter 5: Forest Ecosystems

Summary

Future warming and changes in precipitation may considerably alter the spatial distribution of suitable climate for many important tree species and vegetation types in Oregon by the end of the 21st century. Changing climatic suitability and forest disturbances from wildfires, insects, diseases, and drought will drive changes to the forest landscape in the future. Conifer forests west of the Cascade Range may shift to mixed forests and subalpine forests would likely contract. Human-caused increases in greenhouse gases are partially responsible for recent increases in wildfire activity. Mountain pine beetle, western spruce budworm, and Swiss needle cast remain major disturbance agents in Oregon's forests and are expected to expand under climate change. More frequent drought conditions projected for the future will likely increase forest susceptibility to other disturbance agents such as wildfires and insect outbreaks. Adaptive forest management will be critical going forward in order to reduce wildfire hazards, to promote forests that are resilient to insects and diseases, and to maintain a suitable habitat for Oregon's wildlife.

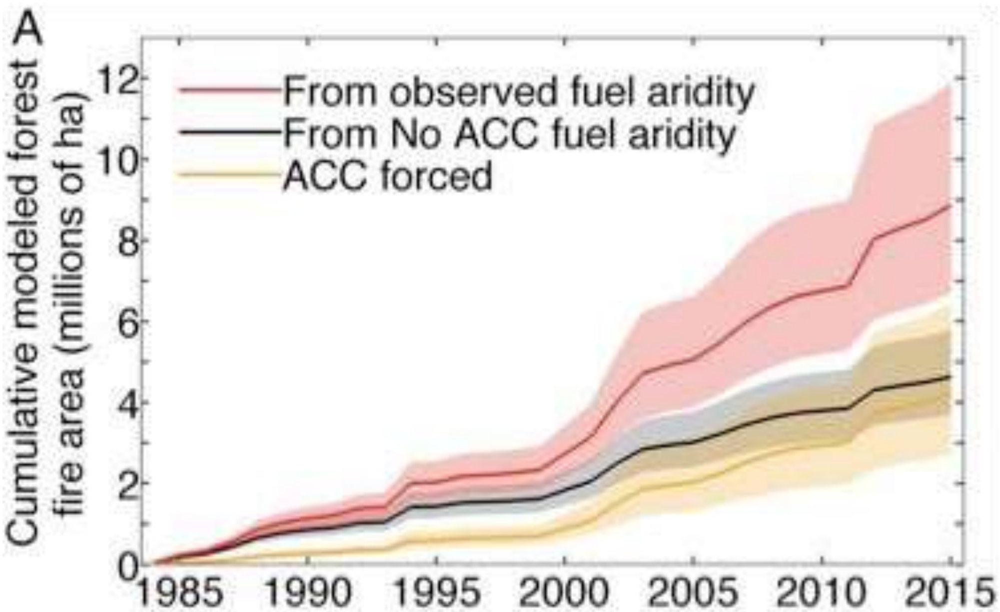
Introduction

Future warming and changes in precipitation may considerably alter the spatial distribution of suitable climate for many important tree species and vegetation types in Oregon by the end of the 21st century (Littell *et al.*, 2013). Furthermore, the cumulative effects of changes due to wildfire, insect infestation, tree diseases, and the interactions between them, will likely dominate changes in forest landscapes over the coming decades (Littell *et al.*, 2013). Forest management practices will continue to affect the forest economy and the resilience to climate change of forests and the wildlife they support.

Wildfire

Over the last several decades, warmer and drier conditions during the summer months have contributed to an increase in fuel aridity and enabled more frequent large fires, an increase in the total area burned, and a longer fire season across the western United States, particularly in forested ecosystems (Dennison *et al.*, 2014; Jolly *et al.*, 2015; Westerling, 2016; Williams and Abatzoglou, 2016). The lengthening of the fire season is largely due to declining mountain snowpack and earlier spring snowmelt (Westerling, 2016). In the Pacific Northwest, the fire season length increased over each of the last four decades, from 23 days in the 1970s, to 43 days in the 1980s, 84 days in the 1990s, and 116 days in the 2000s (Westerling, 2016). Recent wildfire activity in forested ecosystems is partially attributed to human-caused climate change: during the period 1984–2015, about half of the observed increase in fuel aridity and 4.2 million hectares (or more than 16,000 square miles) of burned area in the western United States were due to human- caused climate change (Abatzoglou and Williams, 2016) (fig. 5.1).

Figure 5.1: Attribution of western US forest fire area to anthropogenic climate change (ACC). Cumulative forest fire area estimated from the (red) observed fuel aridity record and (black) the fuel aridity record after exclusion of ACC (No ACC). The (orange) difference in the forest fire area forced by anthropogenic increases in fuel aridity. (Figure source: Abatzoglou and Williams, 2016)



The extent of the area burned in forests of the Pacific Northwest is highly correlated with the summer water balance deficit, or fuel aridity (Littell *et al.*, 2016). Summer water balance deficit is defined as the difference between potential evapotranspiration (how much moisture evaporation from vegetation is possible given the conditions of the atmosphere) and actual evapotranspiration (how much moisture actually evaporates from the vegetation). Larger differences indicate drier vegetation. In the future, the summer water balance deficit is projected to increase across most of Oregon, with the most pronounced increases in southern Oregon, the eastern Cascade Range, and parts of the Blue Mountains (Littell *et al.*, 2016). In non-forested areas of the Pacific Northwest, a strong predictive indicator of potential burn area is high antecedent winter precipitation (conducive to large fuel accumulation) coupled with low summer precipitation (Littell *et al.*, 2016).

Under future climate change, wildfire frequency and area burned are expected to continue increasing in the Pacific Northwest (Barbero *et al.*, 2015; Sheehan *et al.*, 2015) (fig. 5.2). Model simulations for areas west of the Cascade Range, including the Klamath Mountains, project that the fire return interval, or average number of years between fires, may decrease by about half, from about 80 years in the 20th century to 47 years in the 21st century (Sheehan *et al.*, 2015). The same model projects an increase of almost 140 percent in the annual area burned in the 21st century compared to the 20th century, assuming effective fire suppression management and a high emissions pathway (RCP 8.5) (Sheehan *et al.*, 2015). In the eastern mountains of the Pacific Northwest, an area that includes the northern Rocky Mountains and the Blue Mountains, the mean fire return interval is projected to decrease on average by 81 percent, while the annual percent area burned is projected to increase by 36 percent, assuming that effective fire suppression can be maintained under the high emissions pathway (RCP 8.5) (Sheehan *et al.*, 2015). In the Northwestern Plains and Plateaus region, which includes parts of the Columbia Basin and Great Basin, fire frequency and annual percent area burned are projected to decrease under fire suppression but increase under non–fire suppression management scenarios (Sheehan *et al.*, 2015). Furthermore, the probability of climatic conditions conducive to very large wildfires is projected to increase by the end of the century in the western United States (Barbero *et al.*, 2015; Stavros *et al.*, 2014).

Forest management in the face of climate change

“Land managers planning for a future without climate change may be assuming a future that is unlikely to exist” (Halofsky *et al.*, 2014). Forest vulnerabilities to climate change are similar across biogeographically diverse regions of the Pacific Northwest, as are many of the current adaptation options (Halofsky and Peterson, 2016). Increasing temperatures and changes in precipitation and the hydrologic cycle are expected to lead to temperature and drought stress for many tree species, making forests more susceptible to wildfire and insect attacks and leading to widespread climate-induced forest die-offs, shifts in ecosystem structure and function, a concomitant loss of habitat for plants and animals, and the loss of large carbon stores. Recent science-management partnerships have generated an extensive list of adaptation strategies and tactics, primarily focusing on increasing resilience to disturbance and reducing existing stressors; the list is being used to inform sustainable resource management in large part by adjusting existing management strategies (Halofsky and Peterson, 2016) that already have broad support and accomplish multiple goals (Kemp *et al.*, 2015).

Management principles to foster resilience to disturbance while conserving ecosystem services include: 1) managing dynamically and experimentally through a sustained commitment to adaptive management, 2) managing for ecological processes and functional characteristics instead of specific structures and species compositions, 3) considering trade-offs and conflicts that include ecological and socioeconomic sensitivities, 4) prioritizing choices that are likely to work within a range of possible futures and in crucial areas that are most exposed to changing disturbance regimes, 5) managing for realistic outcomes by focusing on a broader set of ecosystem services, and 6) treating disturbance as a management opportunity for applying adaptation strategies (Seidl *et al.*, 2016).