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August 1, 2018

Re: Oregon forest carbon monitoring and reporting suggestions to ODF

As a member of Oregon Governor Kate Brown's forest carbon advisory group, I am providing feedback to the Oregon Department of Forestry (ODF) to help inform its legislative mandate (HB 5201) on the development of a statewide carbon policy framework, and to assist in presenting the best available science for forest carbon accounting.

My comments are based on personal experience as a published researcher, knowledge of relevant literature on forest ecosystems and carbon especially in Oregon, and as a member of the prior governor's forest carbon task force that provided input on forest carbon accounting to the Oregon Global Warming Commission in its report to the legislature (OGWC 2018). I am also offering suggestions to improve upon the short comings of the AB 1504 forest carbon report for California (Christensen et al. 2017) which, in places, did not comport with the scientific literature, rendering sections of that report questionable for referencing to the ODF report.

As noted in my comments below, and at meetings of our advisory group, I am requesting that ODF build on the draft discussion report of the OGWC (2018) that already analyzed many of the same datasets (through 2015) as ODF will be using for monitoring. Clearly, there is no need to do much of the same analysis from scratch, however, updating the FIA datasets would be value-added and consistent with the need for ongoing monitoring.

I organized my comments into three sections below, and have attached supporting pdfs and the OGWC (2018) for referencing. Please note – this is not a comprehensive literature review but should supplement one by ODF as a report pre-requisite. I look forward to continued dialogue with ODF, the governor's office, and the advisory group on these critically important climate issues for Oregon and applaud the governor for moving forest carbon to the forefront of responsible climate mitigation. I stand ready to ensure the outcomes are science based and climatically meaningful.

Sincerely,



Dominick A. DellaSala, Ph. D
Chief Scientist

I. Key Findings of Oregon Global Warming Commission (2018) That Should be Carried Forward in the ODF Report

With no funding, and strictly on a voluntary basis, the governor's forest carbon task force along with the PNW Research Station, ODF, and leading carbon scientists at Oregon State University provided extensive datasets and analyses (for the very first time in Oregon) that were used to inform the OGWC (2018) report. FIA datasets in the OGWC report were used to partition forest carbon inventories (e.g., stocks, flows) by landownership, ecoregion, and forest type and this should be repeated and updated in the ODF report. The OGWC included key figures and graphical displays of forest carbon inventories, carbon flux (particularly from harvest and especially in relation to other emissions sectors), and wood product stores germane to the ODF report (cross referencing and updating is preferred to reinventing the wheel).

Some key findings of OGWC (2018) are repeated verbatim herein for transfer to ODF reporting, along with my supplementation of the relevant literature (bold facing is my emphasis and citations I added):

- 1) Oregon forests hold significant carbon stores. **Changes in management through incentives and offset programs that increase 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.
- 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 the best return **while integrating carbon capture and storage with other forest values and functions.**
- 3) Prevailing analysis of the impacts of harvesting and processing forest carbon into wood products suggests that tracking a wood products carbon sequestration pool is important to measuring and mitigating for the loss of carbon stores resulting from harvest, **but it is not an effective strategy for maintaining or increasing overall forest carbon storage. Finding ways to better align harvest with carbon goals, such as increasing harvest rotation periods, is likely to be more effective mitigation for harvest-related carbon losses (also see recommendations in Law et al 2018).**
- 4) There is ongoing discussion of how to align forest fire policies and active forest health restoration treatments 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 (also see Law et al. 2013).** 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.**

much smaller after netting against carbon losses to harvest¹. 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) (**also see Krankina et al. 2014**).

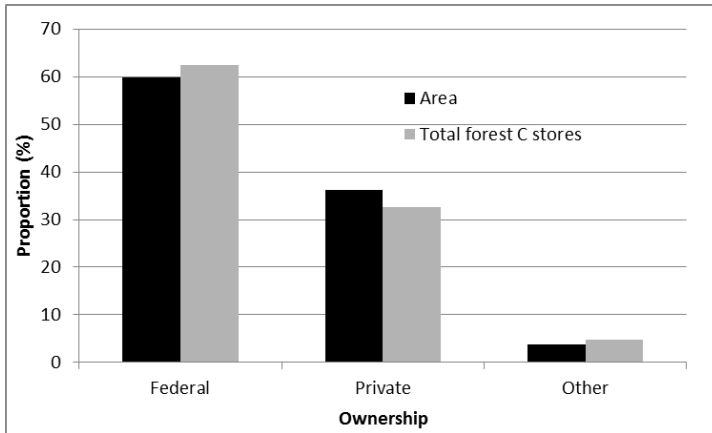


Figure 3. Proportion of total carbon stores in forests contributed by different ownerships for forested lands within those properties (Oregon Global Warming Commission 2018).

- 6) Wildfire as a Carbon Emissions Source (also see below). 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 very large, severe fires can be meaningful and substantial². However, on average, for the period 2001-2015, forest fires in Oregon appears to have released around 6.9 million tons CO₂e annually³ to the atmosphere, or a quantity equal to **about 11% 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 (also see Meigs et al. 2009, Law and Waring 2015).** Wildfire management will continue to be an important part of forest practices especially where human life, health and public safety are at risk; and the effects of climate change can upend many assumptions about forest management overall. **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.**

¹ 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.

²Between 14 and 18 million tons of carbon dioxide were released in the 2005 Biscuit fire, an amount equal to roughly a quarter of Oregon’s overall non-forest emissions in 2005. (Campbell, Donato et al, “Pyrogenic carbon emission from a large wildfire in Oregon”, 2007

³ Law et al, PNAS January 22, 2018

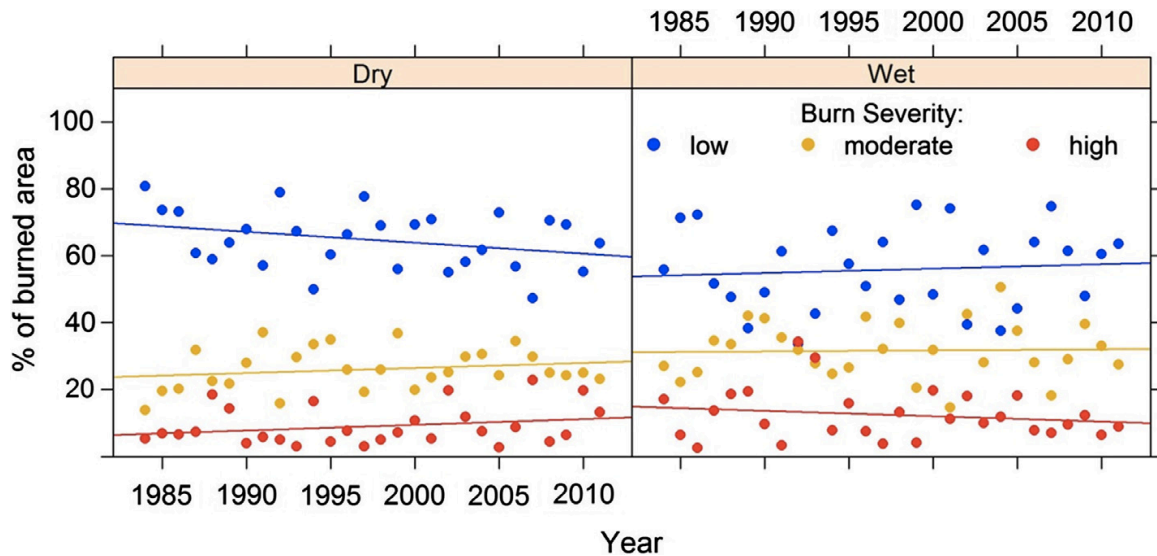


Fig. 2. The percentage of total area burnt within each burn severity class from 1984 to 2011 for dry (left panel, less than 600 mm year⁻¹) and wet (right panel) ecoregions in the Pacific Northwest. High severity fire accounted for an average of 9–12% of the total burn area **and did not change significantly over time (emphasis added)**. 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, Waring 2015) (cited in Oregon Global Warming Commission 2018).

Notably, despite statements made by land managers and decision-makers that high fire severity, and therefore emissions, are increasing, this is NOT the case as reported in regional studies (Hanson et al. 2009, Odion et al. 2014, Baker 2015, Parks et al. 2014, Waring and Law 2015). As also noted by OGWC (2018), wildfires are not currently a major source of state-level emissions, particularly when compared with emissions from timber harvest. In sum, forest emissions have been over emphasized by managers in comparison to emissions from timber harvest, especially on nonfederal lands (e.g., see Meigs et al. 2009, Krankina et al. 2012, Law et al. 2018), most often downplayed.

- 7) 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 available evidence today, forest harvest does not result in material net carbon conservation when compared to carbon retention in forests.** And 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 does 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; while Oregon will need to find ways to conserve and**

increase forest carbon storage. 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 trees⁴. While individual trees will die and release their carbon, the forest can continue to renew itself and maintain its quantities of sequestered carbon.

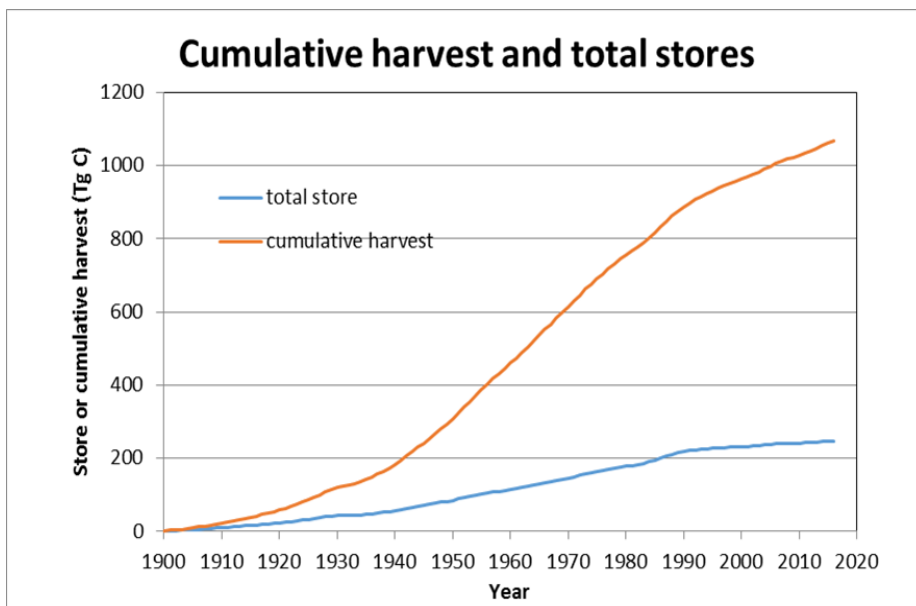


Figure 7. Cumulative harvest and store of harvested carbon in solid form of carbon 1900 to 2016 for all ownerships combined (Oregon Global Warming Commission 2018).

Wood Product Stores Need to Be Based on Best Available Science – there is much uncertainty about wood product pools that will require a regionally specific literature review by ODF to ensure best available estimates (along with degrees of uncertainty) are used in pool contributions. I have included five steps outlined on from pp. 20-21 of the OGWC (2018; also Figure 7 above) for calculating a wood products carbon pool. These steps were based on extensive consultation by Angus Duncan (report lead) with Dr. Mark Harmon, Oregon State University, as noted herein.

⁴Average 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 2018)

1. Count carbon loss associated with in-forest (in-boundary) harvest where roots, stumps and branches are stripped from stems and burned or left to decompose and release carbon to the atmosphere (~35% of total contained carbon in a tree).
2. Count carbon emissions associated with operation of extraction, transportation and milling equipment (out-of-boundary).
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 (also see Law et al. 2018).
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 carbon stores for decades before materials decompose and return carbon to the atmosphere, while less durable forms of disposition will result in earlier such carbon returns.

In sum, OGWC (2018) concluded:

“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% 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%) 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.” (also see Law et al. 2018 regarding **lifespan of buildings and over estimation of wood product stores often cited**).

II. Unsupported Statements in Christensen et al. (2017) Need to be Avoided

Christensen et al. (2017) provide useful information on forest carbon accounting using comparable FIA datasets for California. However, by my account, the report makes 19

unsupported assertions that should be avoided in the ODF report as follows:

- 1) The report sets an arbitrarily low bar of 5 MMT CO₂ e for annual sequestration levels (i.e. reference level) – this figure was ostensibly based on an unpublished report (not peer reviewed). As it stands its rather unambitious in terms of optimizing carbon in forests as current sequestration levels are nearly 8 times higher than the reference level under status quo management, thereby presenting an underwhelming picture for improvements. The ODF report should consider scientifically supported reference levels that are climatically meaningful such as increasing carbon retention timelines and sequestration levels that were most likely present before forests were intensively logged (see Mackey et al. 2013). Prior flux levels can be estimated by back-calculations from published references (e.g., Wimberly et al. 2002, also consult with Drs. Harmon and Law for back-casting methods).
- 2) Changes in land use are overly conservative – the report includes only forest carbon losses due to deforestation and is inexplicably silent on forest degradation even though degradation (i.e., selective logging, thinning, salvage, etc) is known to be a significant contributor to emissions (see discussion below).
- 3) Tree mortality is over emphasized and taken out of context– tree mortality is highest on federal lands. However, this is likely due to forests aging overtime and storing carbon long-term in dead pools. That is - much of the carbon from tree mortality simply transfers from live to dead pools, slowly decomposing as sequestration from emerging vegetation increases. Because federal lands have more old growth than nonfederal lands, this result is not surprising nor is it necessarily an ecological concern or a need for more management. The report is also silent on carbon retention times even though long-term carbon stores (live and dead pools above and below ground) are critical to climate stabilization (see Smithwich et al. 2009, Keith et al. 2009 and see below).
- 4) Most of C stocks are on public lands – this is critically important and as discussed above there is a need to include carbon retention times along with stocks and flows, which the report is otherwise silent on. Notably, the OGWC (2018) and published regional studies (Krankina et al. 2012, 2014) document the relative importance of federal lands in representing the vast majority of unlogged carbon-dense forests and long-term carbon stores (below). This important distinction needs to be recognized by ODF for its relative importance.
- 5) As noted above, the California report did not include **carbon density** estimates in relation to published accounts and C retention times per forest type, ecoregion, and landowner -- a discussion of why this is important from a climate and ecological standpoint would be value added.
- 6) If all sectors are required to reduce emissions to 1990s levels – forestry – even as a net sink – needs to reduce its emissions as well. The OGWC (2018), for example, recommended that net forestry emissions be reduced even though the state’s forests are currently operating as a carbon sink. That is –status quo management is not an acceptable reference, additionality and long-term carbon storage are what matters most climatically and ecologically.

- 7) “Promote afforestation/avoid deforestation associated with land-use change.” While this is important, there’s no mention of emissions from **forest degradation** as noted. The ODF report needs to split out carbon flux associated with deforestation vs. that associated with forest degradation in order to ensure reliable accounting (see below). Also, in situations where clearcut logging takes place, replanting forests does not compensate for emissions from logging as replanted forests can take decades to centuries to recoup the carbon emitted from logging operations depending on site conditions, timber harvest methods, and forest age classes.
- 8) The report recommends increasing C stores through “sustainable forest management practices.” What does this really mean? It’s undefined and nebulous. See Law et al. (2018) for some general recommendations to consider in the ODF report.
- 9) The report recommends considering the age of the stand and other forest management objectives. Ecologically, and from a carbon standpoint, old forests are unequivocally important in carbon stores, ecosystem services, biodiversity, and resilience to climate change (see Keith et al. 2009, Olson et al. 2012, Brandt et al. 2014, Frey et al. 2016, Strassburg et al. 2017, Griscom et al. 2017). This should be emphasized by ODF to avoid similar short comings.
- 10) The report recommends “managing forest densities and fuels where appropriate.” What does this mean and how will it affect carbon stores (i.e., C retention times will go down and C flux from management will go up, yet no mention of this in their report).
- 11) The report recommends “increasing C in HWP pools including wood used for energy.” No life cycle analysis is provided to support this assertion (but see Scharlemann and Laurance 2008, Searchinger et al. 2009, Hudiburg et al. 2014, Law et al. 2018 for significant woody biomass emissions and concerns).
- 12) The report again states “consider wood energy and material substitution effects.” No life cycle analysis or literature review is provided to support this assertion.
- 13) The report recommends “fuels management treatments on federal lands to reduce the risk of catastrophic wildfire.” This finding is unsupported as stated above regarding the relatively low emissions from wildfires vs. thinning (i.e., Figure 6 above). Wildfires also are not ecological catastrophes (see DellaSala and Hanson 2015) and the report statement reflects an inherent bias regarding the ecologically beneficial role of wildfires.
- 14) “Work with other agencies and legislative authorities to ensure development of policies, infrastructure and funding to support fuels reduction and biomass utilization.” Same comment as above – unsubstantiated assertion that contradicts findings on wildfire emissions compared to harvest emissions.
- 15) “C removed from the atmosphere by forest growth or stored in harvested wood products for the U.S. in 2015 were estimated to offset 11.8% of U.S. emissions from industry and agriculture.” This statement needs context, particularly in comparison to long-term carbon stores in forests vs. wood products (see OGWC 2018 for contrary statements about stores in forests being much longer than that in materials). The main point of a climatically meaningful framework should be to reduce emissions from ALL sectors – forestry an important emission source that can be actively reduced – so how will that be accomplished?

- 16) “Another concern with increasing carbon stores in forests is the notion of permanence; areas that are fire-prone are at higher risk that live trees will be killed and C lost to fire and decay, especially in forest types where denser (higher C) forests are likely to burn at higher severity.” While this statement may be true, it is out of context and needs to be based on literature showing carbon removed from the forest by logging typically exceeds that emitted in most forest fires, even severe ones (as noted above). Additionally, most of the C in a fire is not lost to the atmosphere – by comparison, only the living biomass (foliage, duff layer) is combusted in severe fires (a relatively small proportion of large fire complexes) with most of the remaining carbon unaffected or transferring from live to dead pools.
- 17) “The use of harvested wood and wood products may reduce overall C emissions through their use as biomass energy in situations where the use of wood as biomass for fuel results in fewer C emissions from the use of fossil fuels. Another effect of using wood products could be through substitution of wood instead of steel or concrete, which result in more C and other greenhouse gas emissions to produce.” Again – this statement is falsified by the published literature and lacks carbon life cycle analysis (see Scharlemann and Laurance 2008, Searchinger et al. 2009, Hudiburg et al. 2014, Law et al. 2018).
- 18) “Only on reserved forest lands managed by the USDA Forest Service are carbon losses from mortality in the live tree pool estimated to exceed gains from live tree growth.” Notably, this is likely due to forests maturing, which is ecologically desirable. As noted, most carbon from tree mortality is transferred from live to dead pools and not emitted all at once.
- 19) “Additionally, as the forests age in unharvested stands, growth rates slow. Older forests tend to store more carbon, but they might not accumulate new carbon as quickly as younger, fast-growing stands. Consequently, the stocks and flux represented in this report may not be sustainable in the future without forest management.” This statement is largely conjecture and unsupported (see Keith et al. 2009, Smithwick et al. 2009).

Key Literature and Data Analysis Suggestions

I have attached several pdfs of published studies on forest ecosystems, wildfires, and carbon in the Pacific Northwest of direct relevance to the ODF report. In addition, I am requesting that you consider the following in the ODF report:

- Include a comprehensive literature review of forest carbon stocks, fluxes, emissions from logging, wildfire, and other natural disturbances along with statements regarding degrees of confidence (uncertainty) in key findings based on the FIA analysis (see attached Memo from Dr. Mark Harmon on datasets and methods).
- Compare annual emissions from logging with other sectors (CO₂ e). ODF should use the social cost of carbon to evaluate long-term potential impacts to human health and socio-

economic systems from emissions⁵.

- Provide breakdown of forest carbon stores by ecoregion, forest type, and landowner.
- Provide spatially explicit identification of high carbon stores (see Krankina et al. 2014 for published carbon density thresholds) overlaid on land use (GAP land use codes 1-4 – protected to intensively managed – see Krankina et al. 2014). It should be noted, and emphasized in the ODF report, that at least in the tropics about 1% of the oldest trees store more than 50% of the carbon in Amazonia (Fauset et al. 2013) and old forests globally are critical to climate stabilization (see Keith et al. 2009).
- Provide a graphic displaying carbon retention times by ownership (at a minimum), forest type, and ecoregion (see figure below) and discuss the value of long retention times.
- Overlay tree mortality with forest age classes to determine if mortality is associated with forest maturation.
- Include a comprehensive review of carbon stores and flux prior to industrial logging (e.g., see Wimberley et al. 2002) as a reference or discussion point for comparison to current emissions and any other reference levels chosen.
- Provide a literature review of wood product stores using five steps noted above.
- Include a comparison of carbon stores/flux using FIA datasets vs. the NECB dataset in Law et al. 2018.
- Correlate (or cite) high carbon density areas with other ecosystem services and biodiversity (see Brandt et al. 2014, Strassburg et al. 2017).
- Discuss emissions from deforestation and **degradation**, including the contribution of roads, pesticides, herbicides, burning of slash, etc. While difficult to estimate, forest degradation plays a significant role in emissions. Notably, the UN REDD+ programme recognizes degradation as an emissions source that needs to be reduced⁶. Methods for monitoring degradation have been employed in tropical rainforests (see Houghton 2012). Comparable methodologies are needed in the US in order to comply with global accords such as the Paris Climate Change Agreement and the Aichi biodiversity and sustainable development targets⁷, in addition to ensuring that emission estimates are accounting for all significant atmospheric contributions.

⁵Although removed from most federal websites by the Trump administration, this is still considered a reliable yet conservative cost-basis for emissions in relation to social and economic impacts - https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

⁶<http://www.fao.org/redd/en/>; <https://unfccc.int/topics/land-use/workstreams/reddplus>

⁷In particular, target 5 – “by 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced;” also see Target 15 regarding ecosystem resilience and carbon stocks; <https://www.cbd.int/sp/targets/>

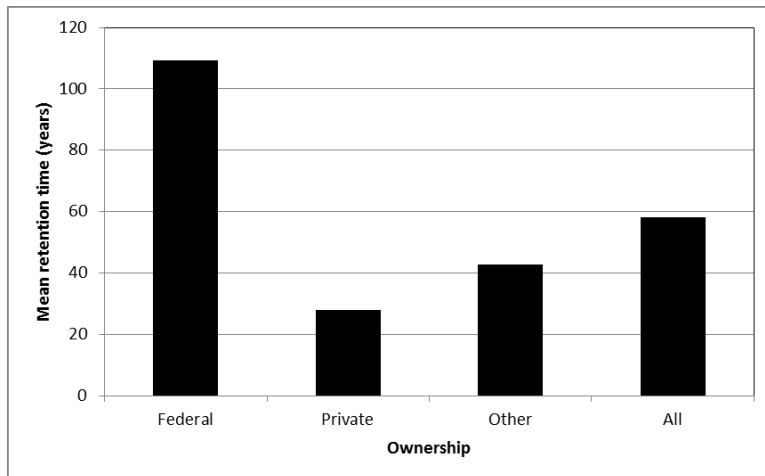


Figure 11. Mean retention time of carbon in live aboveground stores in Oregon’s forest. The longer the mean retention time, the higher stores can become assuming that inputs via gross growth are similar (from attached Memo by Dr. Harmon).

Finally, while not a forestry activity per se, it should be noted that livestock grazing in forest and agricultural settings is a significant source of emissions. How will these be accounted for as part of forestry sector emissions?

CLOSING REMARKS

Thank you for this opportunity to provide suggestions to ODF on developing a forest carbon framework for Oregon. In sum, it is imperative that the ODF report avoids the scientific misgivings of Christensen et al. (2017) and instead builds on the OGWC (2018) by adding additional years and bolstering the report findings via comprehensive literature reviews and recommendations that result in climate-meaningful reforms based not on status quo forestry but what forestry can do to improve via additionality and increased carbon retention times. As a suggestion, additionality can be graphically presented by showing the stores and sequestration available under status quo rotations vs. that which potentially be available if rotations were extended, stream buffers expanded, carbon dense forests set aside in reserves, and harvest on federal lands reduced (see Krankina et al. 2012, Law et al. 2018). In doing so, co-benefits would accrue in the form of wildlife habitat, mature forests, climate refugia, clean water for communities and aquatic systems, stream buffering from flooding, recreation and other ecosystem services (see Brandt et al. 2014, Strassburg et al. 2017). Incentivizing carbon on nonfederal lands and placing a cap on forestry emissions would bring emissions reductions in line with other sectors and make a critical contribution to ensuring forest carbon stores are above baseline scenarios so that Oregon is able to meet ambitious emission reductions targets based on its forestry contributions and sound science.

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**Oregon Global Warming Commission
Forest Carbon Accounting Project
Report to the Oregon Legislature**

**061818 DISCUSSION DRAFT
FOR JUNE 25 OGWC MEETING**

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Introduction

In 2016 the Oregon Global Warming Commission convened a stakeholder task force with support from scientists from the US 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 on earlier recommendations in the Commission's 2010 "Roadmap to 2020" Report to the Legislature outlining 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 US Forest Service Forest Inventory and Analysis (FIA) data collected from 2001 to 2010 and additional data generated by the Oregon State University School of Forestry. With assistance and guidance from members of the Task Force and other sources, the Commission has developed a preliminary assessment of carbon stores and fluxes¹. 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 forwards to the Legislature these broad if preliminary observations:

- 1) Oregon forests hold significant carbon stores. Changes in management through incentives and offset programs that increase 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.
- 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 the best return while integrating carbon capture and storage with other forest values and functions.
- 3) Prevailing analysis of the impacts of harvesting and processing forest carbon into wood products suggests that tracking a wood products carbon sequestration pool is important to measuring and mitigating for the loss of carbon stores resulting from harvest, but it is not an effective strategy

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.

for maintaining or increasing overall forest carbon storage. Finding ways to better align harvest with carbon goals, such as increasing harvest rotation periods, is likely to be more effective mitigation for harvest-related carbon losses.

- 4) There is ongoing discussion of how to align forest fire policies and active forest health restoration treatments 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.

I. Key Takeaways for the Oregon Legislature:

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 US forest carbon stocks; and where indicated on subsequent 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 CO₂e²), variously in carbon pools that include standing live trees, standing and fallen dead trees, forest floor vegetation, and soils³. How we manage our state's forest carbon stores

² "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.

³ 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.

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 1990’s, 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 2018) 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 2018). Nationally, carbon stored in forests increased by 10% between 1990 and 2013; and Pacific Northwest forests were among the most productive in showing gains in forest carbon capture⁴. 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% and live trees at 35% 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% and 41% respectively⁵. Soil carbon

⁴ Per EPA “Inventory of US Greenhouse Gas Emissions and Sinks”, 2015, relying on USFS FIA data.

⁵ 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

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%) of net carbon stores are found in publicly-owned (mostly federal) Oregon forests comprising 65% of total forested acres; carbon stores are increasing on these lands. During the ten year period for which FIA data are available, 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. Privately owned forests comprise 36% of forested acres and account for 28% 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

forest carbon into seven pools: Live Trees, Standing Dead Trees, Coarse Woody Debris, Fine Woody Debris, Shrubs, Litter and Duff, and Mineral Soil.

harvest⁶. 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).

- 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
- 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 very large, severe fires can be meaningful and substantial⁷. However, on average, for the period 2001-2015, forest fires in Oregon appears to have released around 6.9 million tons CO₂e annually⁸ to the atmosphere, or a quantity equal to about 11% 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; and the effects of climate change can upend many assumptions about forest management overall. That said, wildfire is an essential and unavoidable element in Oregon forest ecosystems, so

⁶ 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.

⁷ Between 14 and 18 million tons of carbon dioxide were released in the 2005 Biscuit fire, an amount equal to roughly a quarter of Oregon's overall non-forest emissions in 2005. (Campbell, Donato et al, "Pyrogenic carbon emission from a large wildfire in Oregon", 2007

⁸ Law et al, PNAS January 22, 2018

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 available evidence today, forest harvest does not result in material net carbon conservation when compared to carbon retention in forests. And 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 does 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; while Oregon will need to find ways to conserve and increase forest carbon storage.

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 trees⁹. While individual trees will die and release their carbon, the forest can continue to renew itself and maintain its quantities of sequestered carbon.

The Commission acknowledges that there is active disagreement and debate on the life cycle valuation of carbon stored in wood products (including substitution effects), and is prepared to modify this takeaway, and any other, as compelling new evidence and analysis may become available. The Commission supports active research into these questions,

⁹ 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 2018)

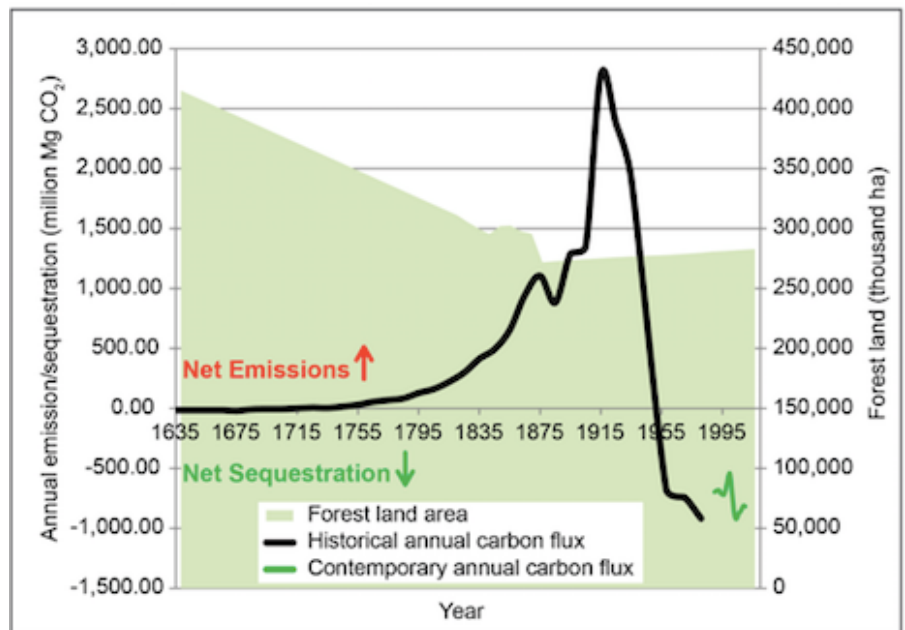
as well as ongoing efforts by the forest products industry to continue introducing practices that improve carbon efficiencies at harvest and product fabrication.

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.

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.

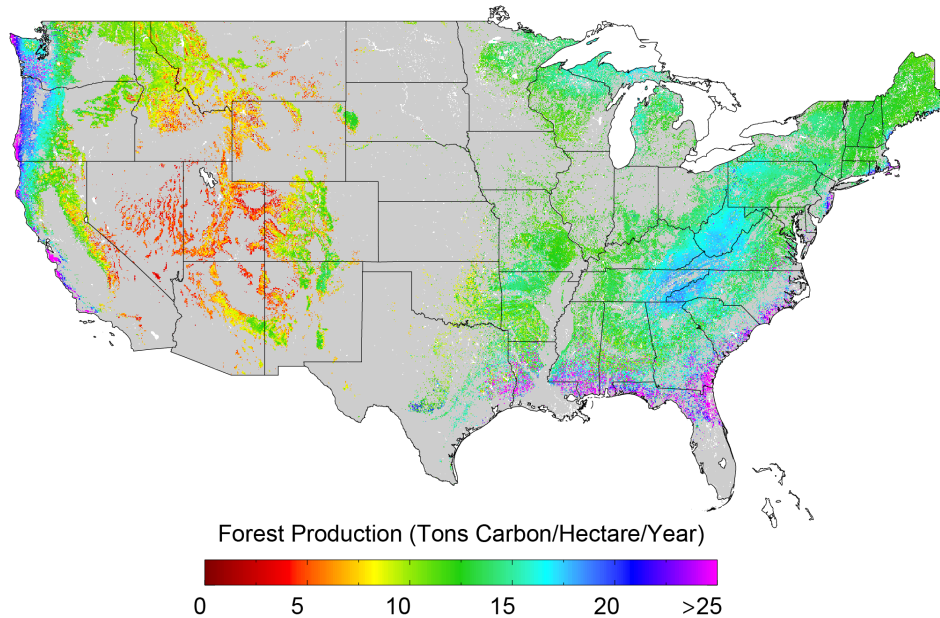
Forests and Carbon



It notes as well, however, 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."¹⁰

¹⁰ From National Climate Assessment 2014, Chapter 7 Forests, pp. 180-181.

Forest Growth Provides an Important Carbon Sink



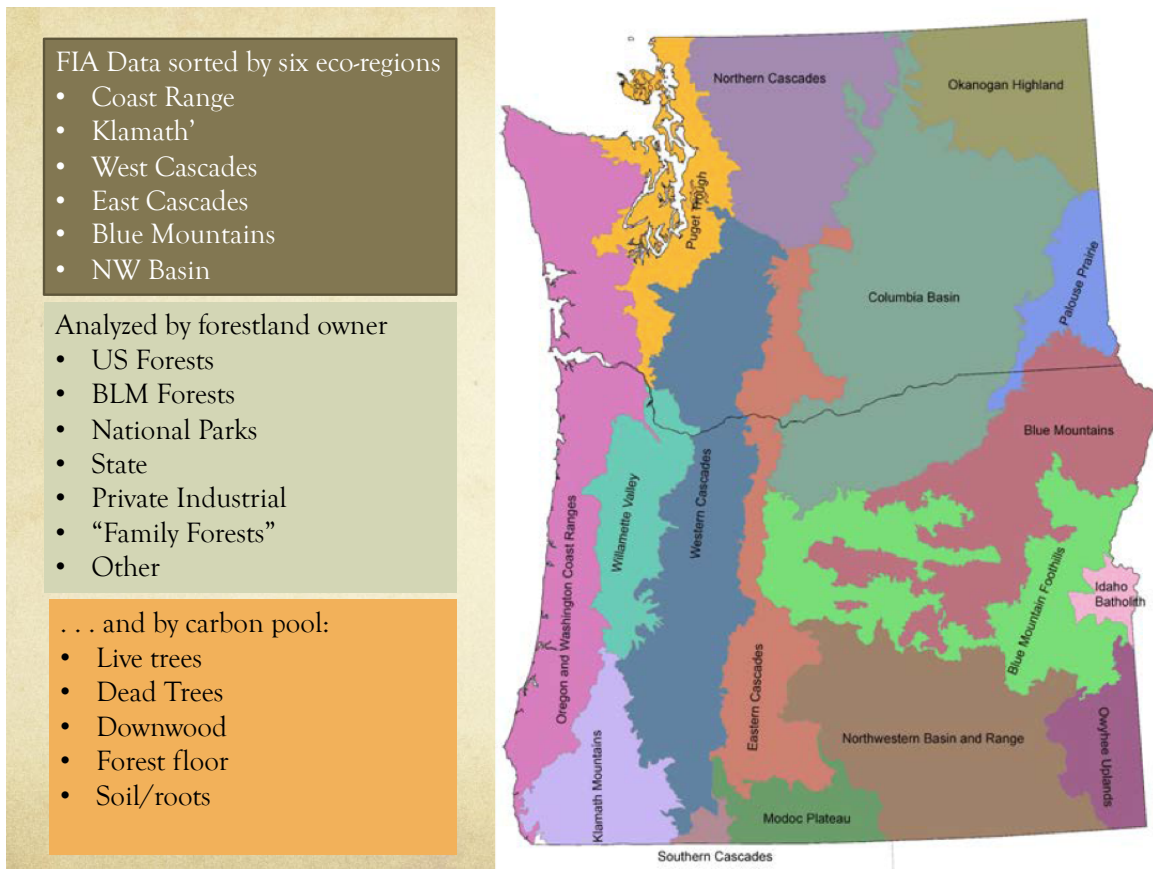
If Oregon wishes to realize increased carbon uptake and sequestration in its forests as a key part of global forest carbon sequestration strategies, it will have to develop goals, and ways and means for achieving those goals. It will further have to weigh optimizing for carbon acquisition against other 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 figure and table below describe Oregon’s forest lands by eco-region and ownership. Carbon data referenced below generally use the Forest Service FIA categories for five in-forest carbon pools – standing live trees, standing and fallen dead trees, forest floor vegetation, and soils.



Ownership distribution is provided in the table below:

Acres / % of Oregon forestland by ownership¹¹

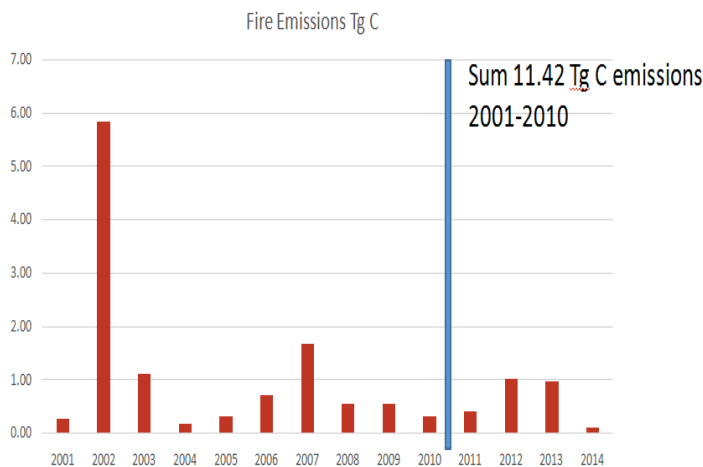
Public	Private	Other
64%	36%	--
<i>By Owner</i>		
	<i>Acres (000)</i>	<i>%</i>
US Forest Service (USFS)	14,180	47
US Bureau of Land Management (BLM)	3,621	12
US Park Service	166	1
State of Oregon + Local Government	1,205	4
Private Industrial Forests	5,984	20
Private Non-Industrial Forests (woodlots)	4,799	16
Other	29	--
Totals	29,984	100

¹¹ USDA: Oregon's Forest Resources, 2001-2010: Ten Year Forest Inventory and Analysis Report; November, 2017.

III. Priority Forest Carbon Considerations

1. 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. In fact amounts of carbon released to the atmosphere in certain very large fires can be meaningful and substantial¹². However, on average for the period 2001-2015 forest fire appears to release around 6.9 million tons CO₂e annually¹³ to the atmosphere, equal to about 11% of all Oregon non-forest greenhouse gas emissions.



Law et al. PNAS 2018 (SI Table S4 extends quantities through 2015)

This amount is more than offset by the annual net carbon gains in our forests. “Black Carbon” (soot particulate) released in forest fires also functions as a greenhouse gas, but with a modest effect as it remains in the air for only a short period of time. Fire is also an historical and necessary element in forest ecosystems, renewing forest health through multiple interactions. At low to moderate intensities, forest fires appear to release moderate amounts of greenhouse gases while performing important ecosystem rejuvenation functions.

¹² Between 14 and 18 million tons of carbon dioxide were released in the 2005 Biscuit fire, an amount equal to roughly a quarter of Oregon’s overall non-forest emissions in 2005. (Campbell, Donato et al, “Pyrogenic carbon emission from a large wildfire in Oregon”, 2007

¹³ Law et al, PNAS January 22, 2018

Overall and on average, most Oregon forest fires appear to release $\pm 5\%$ of the carbon contained in a given acreage. Most of this comes from the small percentage acreage subject to high intensity (vs. low to moderate intensity) burning.

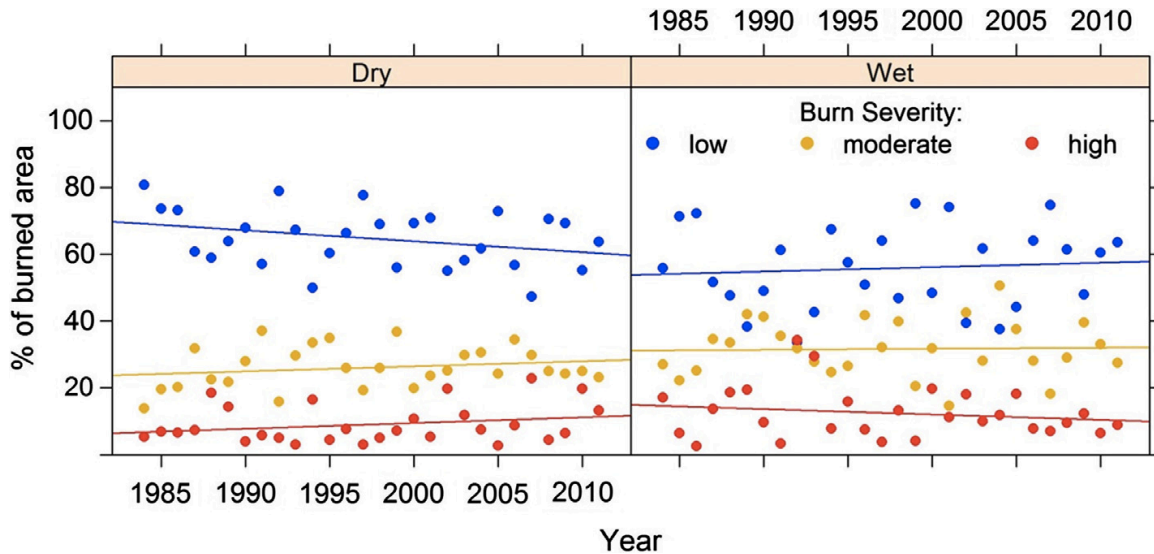


Fig. 2. The percentage of total area burnt within each burn severity class from 1984 to 2011 for dry (left panel, less than 600 mm year₋₁) and wet (right panel) ecoregions in the Pacific Northwest. High severity fire accounted for an average of 9–12% of the total burn area and did not change significantly 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, Waring 2015)

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).

2. 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 does 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 rotations¹⁴ on private forestland, expanded riparian buffers and use of variable retention harvesting, 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 1990’s; 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 health 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

¹⁴ 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 2018;and Hudiberg, 2009)

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 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 stored in forests. 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% between 2001 and 2015¹⁵ (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% of total forest area in Oregon account for 20% of the net carbon stores increase while Federal lands with 60% of the total area account for 79% of the increase in net stores¹⁶.

Given the low harvest levels on federal forests, there are fewer opportunities to increase carbon stores on these lands (although climate change could alter risk of disturbances affecting carbon stores on some Federal timberlands). In contrast, the prevailing higher harvest levels on private lands may also offer greater opportunities to increase carbon stores here while continuing to harvest fiber at sustainable levels. Oregon State's School of Forestry notes that harvest cycles in west side privately-held Oregon forests has shortened from 120 years to 45 years, notwithstanding that "net primary productivity peaks at 80-125 years (Law et al, 2018). For illustrative purposes, the Community Land Model calculated that "if

¹⁵ See below for a discussion of post-harvest carbon stored in wood products.

¹⁶ Harmon, 2018. For more detail and discussion, see pp. 36-37 below.

harvest cycles were lengthened to 80 years on private lands and harvested area was reduced 50% on public lands, state-level (carbon) stocks would increase by 17% to a total of 3,600 Tg C (or 14.56 MM short tons CO₂e) and NECB (Net Ecosystem Carbon Balance) would increase 2-3 Tg C (8.2 to 12.2 MM tons CO₂e) by 2100 (Law et al 2018).”

Oregon could 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. However, the State could elect different forest management practices on State-owned forests so long as it stayed within statutory limitations. 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. The Oregon Department of Forestry has been tasked by the Legislature with giving us more such specificity.

3. 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. By one recent calculation, “Net wood product emissions” from 2001 to 2015 were equal to fully half of Oregon’s Net Ecosystem Carbon Balance (NECB) (Table S4, Law, Hudiberg et al, PNAS 2018)¹⁷.

These losses may be 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 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 as structures are demolished can hold their carbon for decades in a properly-operated landfill.

Table 13a (page 95) of the just-issued California Forest Carbon Plan (May 2018) notes that almost 100% 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%, and non-durable products (e.g., “landscaping products,” “pulp,” etc.) at 69%.

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

¹⁷ 101.66 million tons CO₂e out of 199.71 million tons CO₂e from 2001-2015 (Law et al 2018)

- and release their carbon back to the atmosphere (estimated at 35% of total contained carbon in a tree, per Harmon 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.

4. Forest Restoration Treatment as a Carbon Source

There is discussion and disputation over forest management practices that include “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 (including burning in place) and prescribed fire. The Forest Service and other owners, in order to generate revenues to cover the

costs of treatments, may combine the treatments with commercial harvesting of live trees. “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 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 – 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 forests¹⁸ 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 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 below 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” DBH¹⁹ and 20% 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.

¹⁸ Thinning and/or prescribed fire may be appropriate in west side forests also, especially in proximity to human habitation.

¹⁹ “diameter at breast height”

There are safety, industry and science – and cultural²⁰ -- 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 reductions in the amounts of carbon stored in the forest and a significant delay in recovery of pre-thin carbon levels.

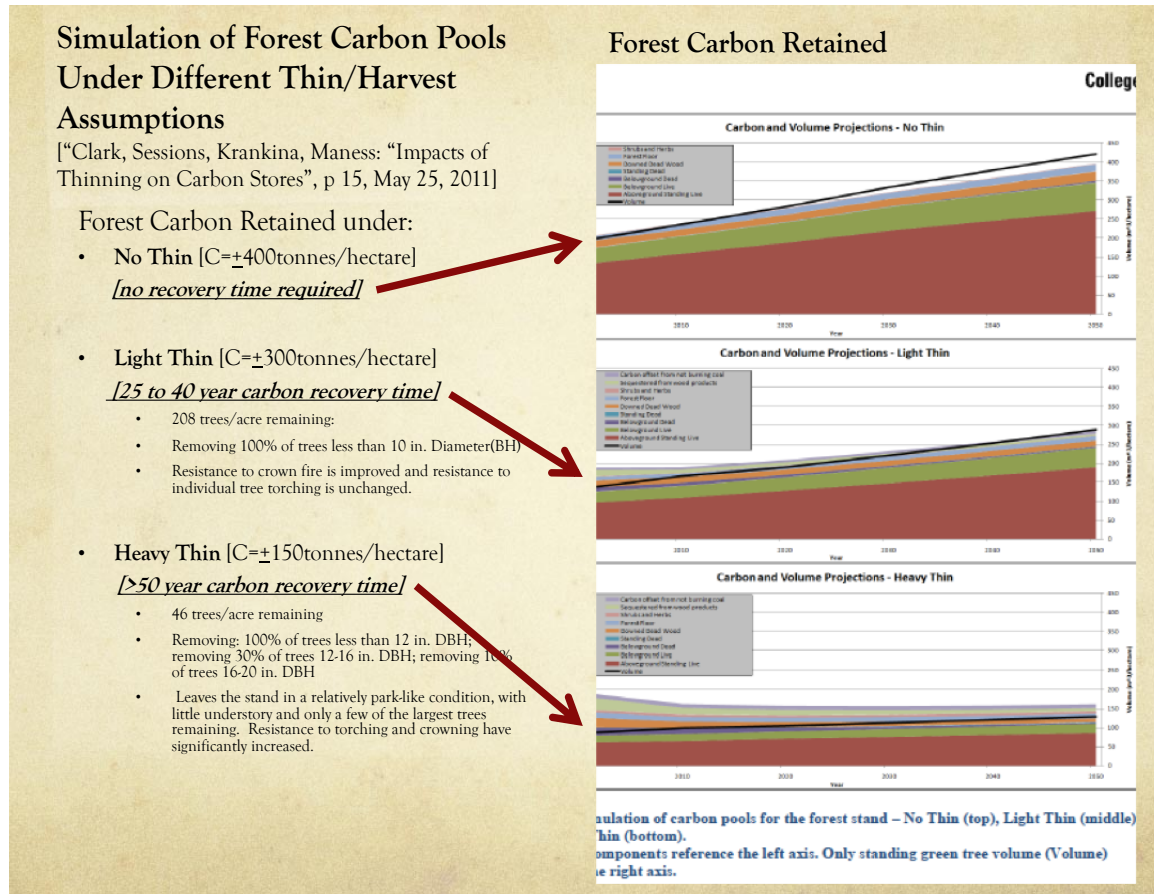


Figure 6 from “Impacts of Thinning”, Clark et al, Oregon State University School of Forestry 2011. Simulation of carbon pools for the forest stand – No Thin (top), Light Thin (middle) and Heavy Thin (bottom). All carbon components reference the left axis. Only standing green tree volume (Volume) references the right axis.

²⁰ 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 (Anna King, NW News Network, May 4, 2018)

5. 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% (8.5mm) of the new homes built in the US, have been located in the WUI, resulting in around 46 million homes now occupying the defined areas²¹. Over the period in question the average number of structures burned has increased an order of magnitude (from 405 structures in the 1970's to 4500 in 2015; while California's Tubbs Fire in October 2017, by itself destroyed some 3000 Santa Rosa homes). Managing and controlling fires that threaten public health and safety has put intense pressure on agency forest fire management budgets²², 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 1% annually²³. FIA data from 2016 tables documents an annual average loss of 51,000 forest acres, or 0.2% of total forested acres (again, an outcome likely influenced by the shift to more conservation-minded Federal forest planning in the 1990's).

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

²¹International 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.

²² From ± \$1B/year in the 1990s to ±\$3B/year in the 2000's.

²³ "Forests, Farms & People"; Oregon Department of Forestry and USFS, June 2016.

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 zero²⁴. 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 from fires in British Columbia, then from the Eagle Creek Fire forty miles east up the Columbia River Gorge.

6. 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% reduction in harvest on public (federal and state) lands. These measures are primarily applicable to wetter, denser west side forests²⁵. Combined, these measures (at levels proposed

²⁴ 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.

²⁵ “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)

by the authors) were calculated to increase Net Ecosystem Carbon Balance (NECB) in Oregon's forests by an additional 890 tons CO₂e by 2100.

The State could identify lands that would lend themselves to reforestation (e.g., in areas affected by fire and beetle kill) or afforestation (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).

III 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 al²⁶). 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.,

²⁶ 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 US Forest Service.

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 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 was 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 Tg²⁷ 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% to 15% 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 to 2015 period. For that 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% to 8% 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. It also likely that state-wide total carbon stores have been increasing on federal forestlands

²⁷ 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 greenhouse gas inventories that are expressed as MMCO₂.

since the inception of the 1992 Northwest Forest Plan, due to significant reductions in harvest of federal forests. However, there are not similar FIA-based analyses at this time on which to base this historical conclusion.

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 forests²⁸ The Blue Mountain, east Cascades, and Other (a mixture of areas with low forest cover 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% higher than the state-wide average, whereas the Blue Mountain and East Cascades ecoregions are 35% lower than the state-wide average.

²⁸ “. . . 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 life span of carbon in an Oregon forest is “87 - 200 years” per direct communication from Dr. Mark Harmon, 2018.

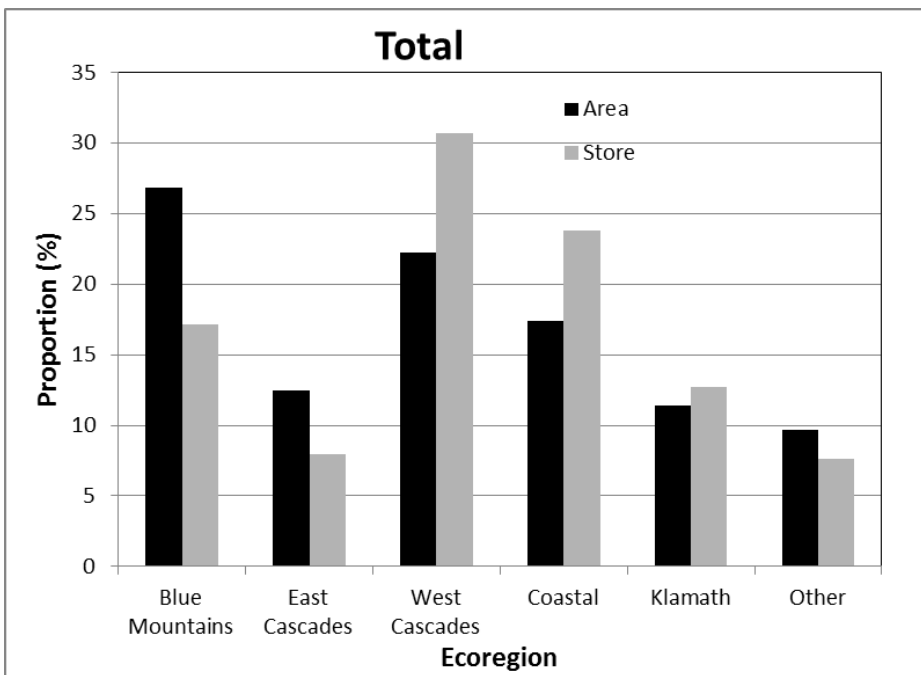


Figure 1. Proportional distribution of area and total carbon stores by forested area within each ecoregion.

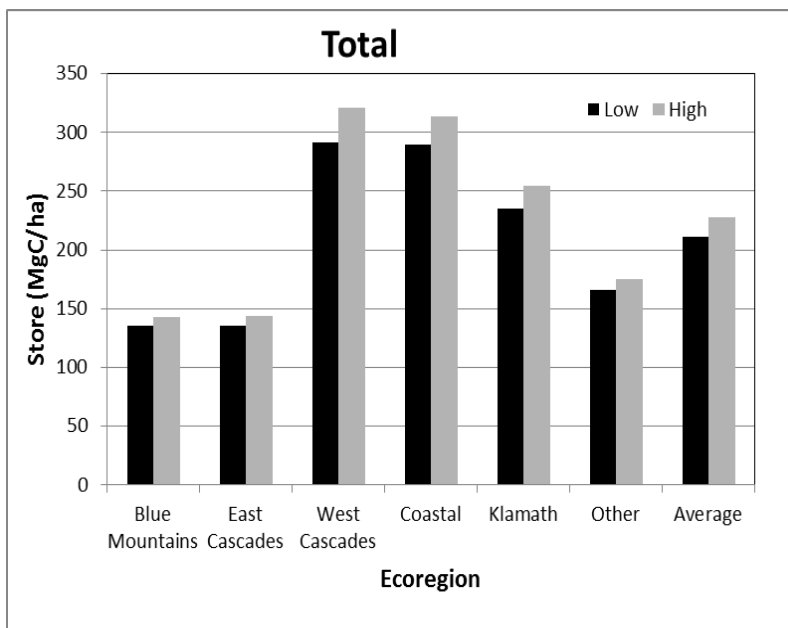
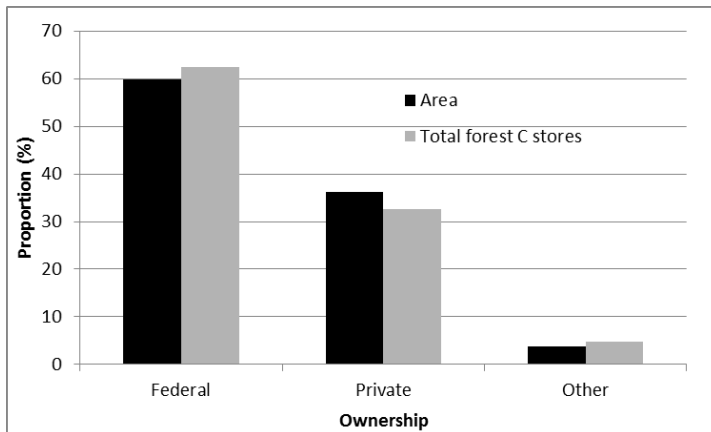


Figure 2. Density of total forest carbon stores by ecoregion. The column furthest to the right represents the state-wide average. The “low” and “high” estimates reflect the range of certainty associated with adjustments and correction factors used²⁹.

²⁹ 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

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 Other³⁰ owners (Figure 3).



This pattern was consistent across all ecoregions.

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

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; with those included the and so may be slightly higher than reported here by about 0.5% (Harmon 2018a).

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)

³⁰ “Private” owners include industrial timberland and smaller, often family-owned, woodlots. “Other” owners include State of Oregon and tribal forest lands.

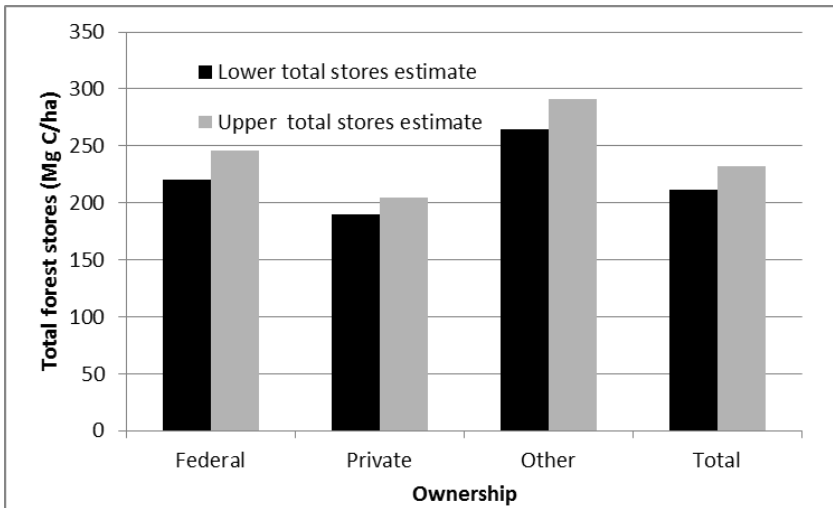


Figure 4. Carbon density in all forms in Oregon’s forests by ownership³¹.

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.

³¹ 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% of total Oregon forested acres.

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% and 41% respectively) (Figure 5). Dead wood and forest floor stores comprised the remaining 17%.

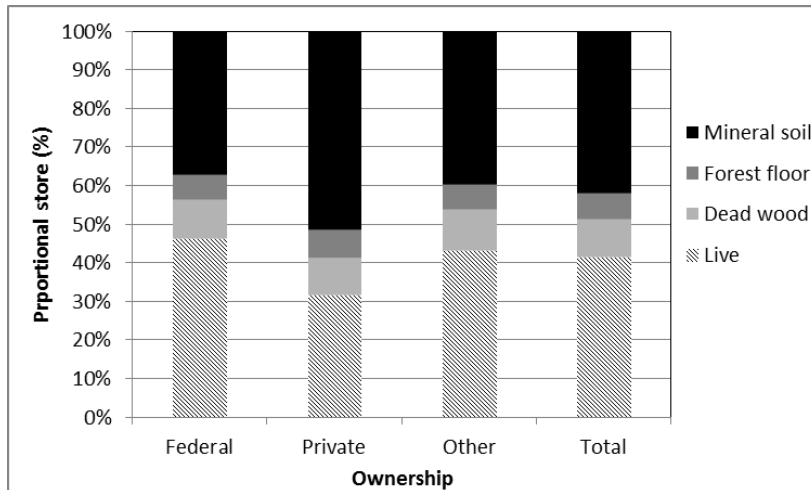


Figure 5. Proportional stores of carbon in Oregon's forests by major pool and ownership. Total indicates the distribution among pools for the state as a whole.

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.

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.

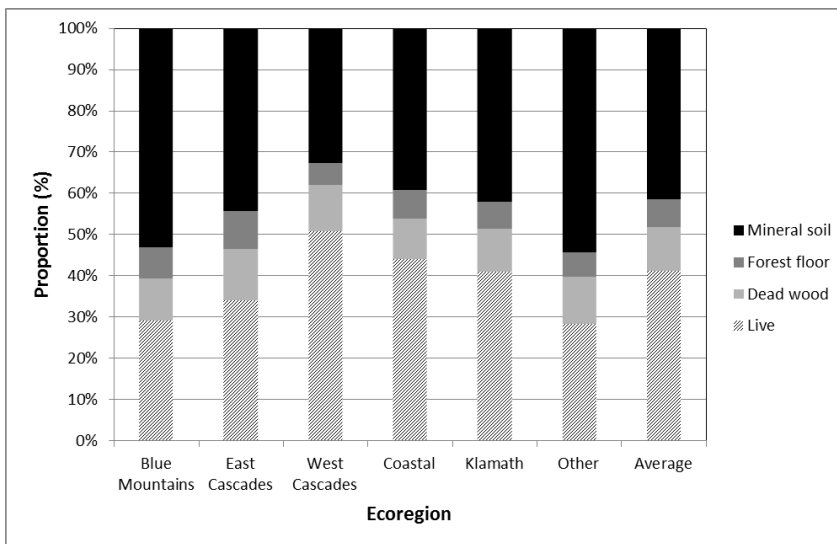


Figure 6. Distribution of total carbon stores for each major pool by ecoregion. The far right-hand column is the statewide “average” of ecoregions

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

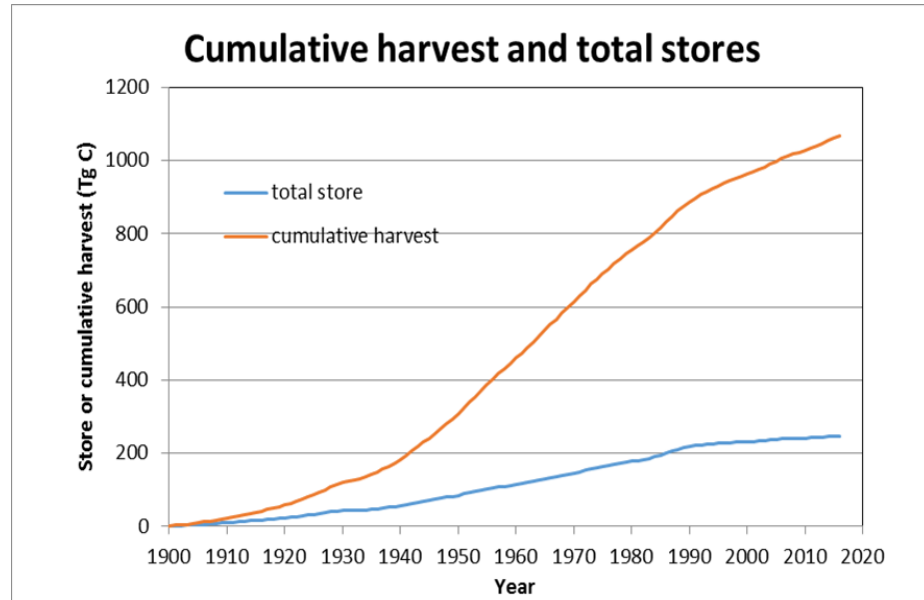
old, disposed of and decomposing products is returned to the atmosphere. The amount of carbon stored in this pool (as in all the pools) is the net of carbon flowing in minus the carbon flowing out; and the storage duration varies with the product and/or form of disposal. For structural lumber in a building this duration may extend as much as 230 to 345 years but the average is much shorter: 50 – 75 years (Harmon 2018). However, well-buried landfilled debris from demolished structures can take 200 to 900 years to decay and release carbon to the atmosphere (Harmon 2018). 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 stem wood is 100 – 110 years (Harmon 2018).

Answering 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% 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%) 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% (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 C³² of wood products have accumulated over this same period (Harmon 2018a). This is 7 to 19% of the value accumulating in the forest itself over the same period.

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

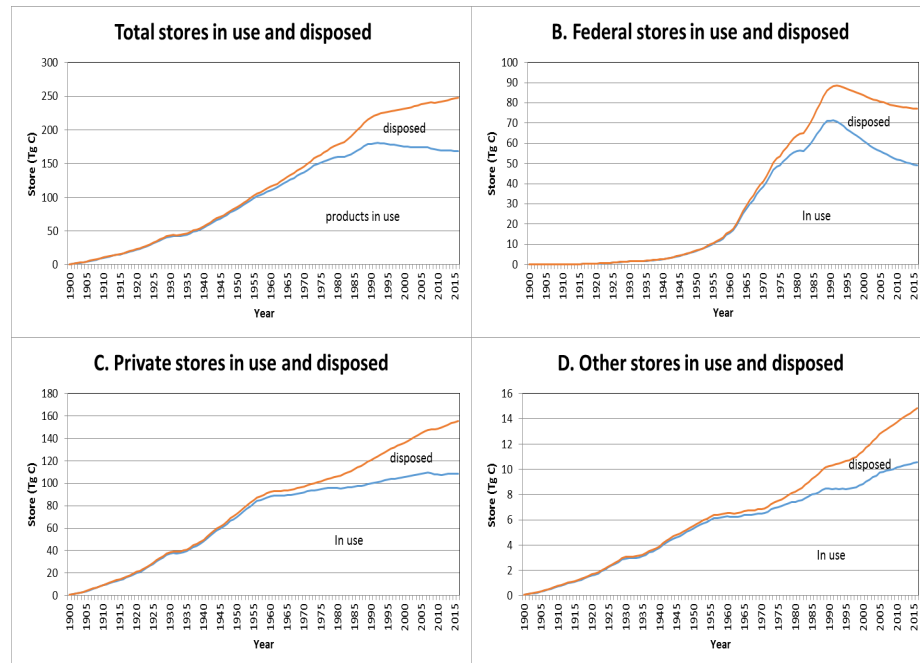
³² The average annual increase in wood products was 1.13 Tg C/y. Multiply by 14 years to get 15.8 Tg C. The 1.13 Tg C figure is derived by beginning with harvest cuttings per year (9.56 Tg C/y), less 15% to account for branches not harvested, times 0.14 (rounded up). The product of that calculation is 1.13 Tg C/y.

the baseline assessment of harvested wood products conducted by the USDA Forest Service, Pacific Northwest Region (Anonymous, 2013).

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% 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% and 31.9% 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% 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 TgC³³. 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.

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% was lost within a year to plant respiration, 28% was allocated to short-lived plant parts (leaves and fine roots), and 22% 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.

³³ 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).

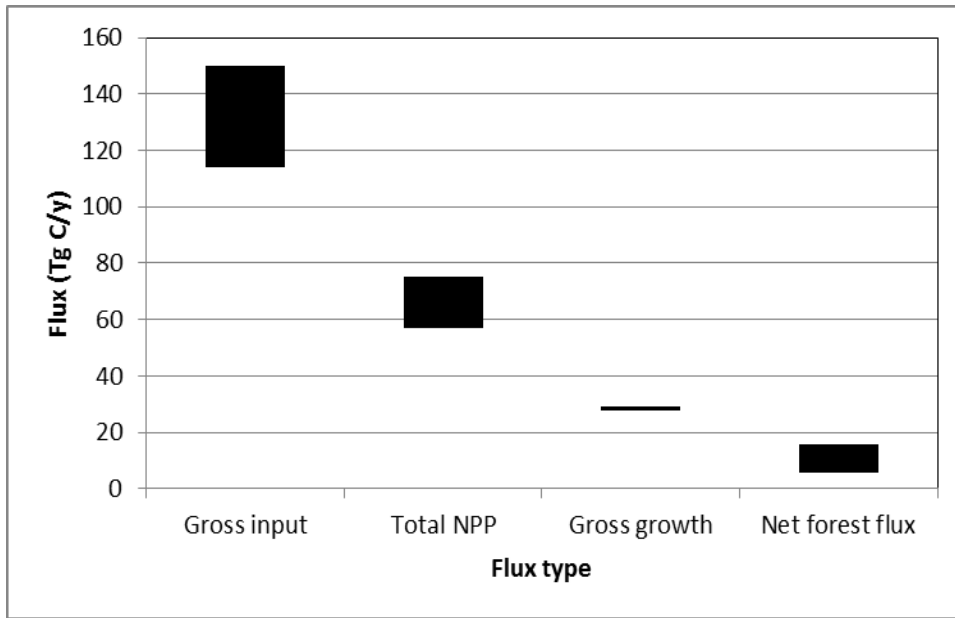


Figure 10. Quantities, expressed as ranges, in estimates of carbon fluxes associated with Oregon forests

Gross Input (gross growth) is a forestry term for the amount of usable wood produced in a forest. This stem wood, plus branches, roots, and forest floor growth, comprise the carbon entering the forest system via photosynthesis. To get to an annual Net Forest Flux value (also termed NECB, or Net Ecosystem Carbon Balance), we begin with a 2001-2015 Net Primary Production (NPP, or average annual carbon flux) and subtract plant respiration and other losses (e.g., animal respiration associated with plant consumption, harvest, fire, insect and disease; and decomposition). This ending net forest flux (or NECB) value in Figure 10 overlaps with the 18.15 TgC/y (73.4 short tons CO₂e) estimate by Law et al. (2018). Net forest flux (NECB) includes changes in all forest pools and assumes (in Figures 10-13) that the net change in live stores is representative of the overall forest net change. Additional analysis would be required to calculate net change by ecoregion or owner.

Converting from TgC/y to short tons CO₂e/y yields 73.5 million tons CO₂e/year net gain in Oregon forest carbon.

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 net amounts of carbon from the atmosphere and storing it 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 are 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 (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.

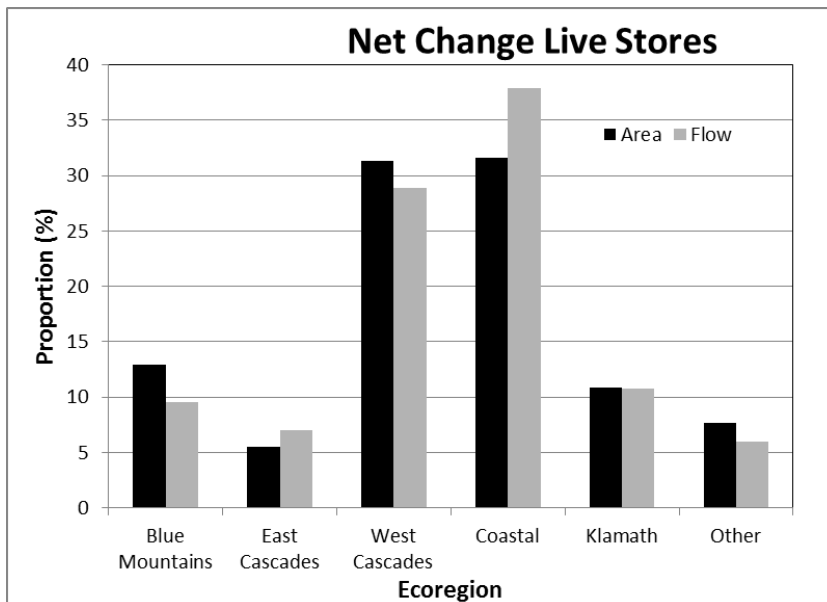


Figure 10. Figure 3. Proportion of net change in live carbon stores *in forested areas within* different ecoregions *and contributed by each ecoregion*. Total low and

high include roots and represent low versus high correction factors to account for roots.

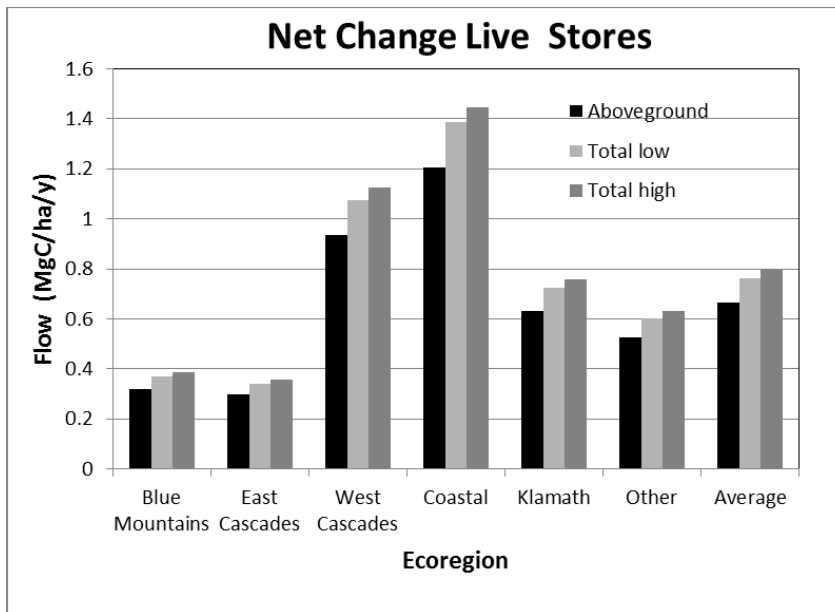


Figure 11. Average per area net change in live stores by ecoregion, expressed as a flow (MgC/ha/yr). The “average” ecoregion represents the state-wide average. Total low and high include roots and represent low versus high correction factors to account for roots.

How do these 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% of the area, but 79% of the overall net change in live stores (Figure 12). In contrast, private lands comprise 36% of the area, but 20% of the net change in live stores. For other land ownerships, the proportions of area and net sink are similar.

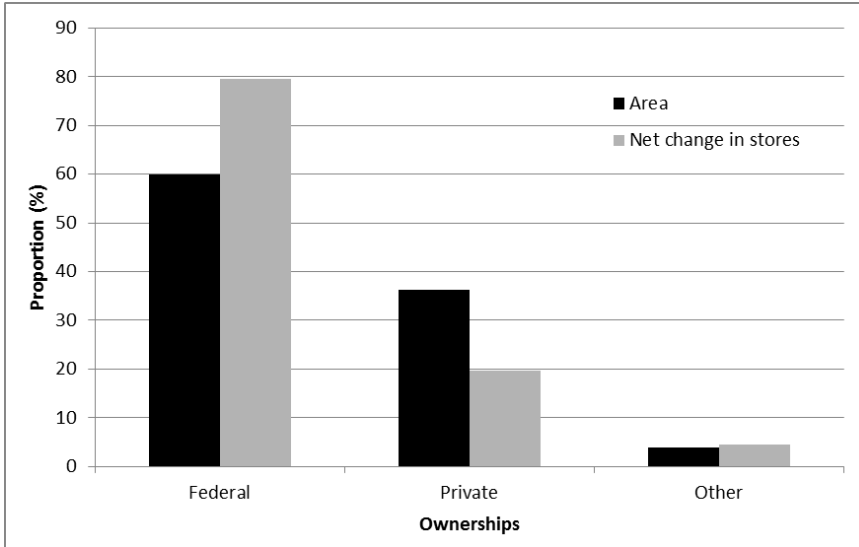


Figure 12. Proportion of area and net change in aboveground live stores by ownership of Oregon's forests.

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.

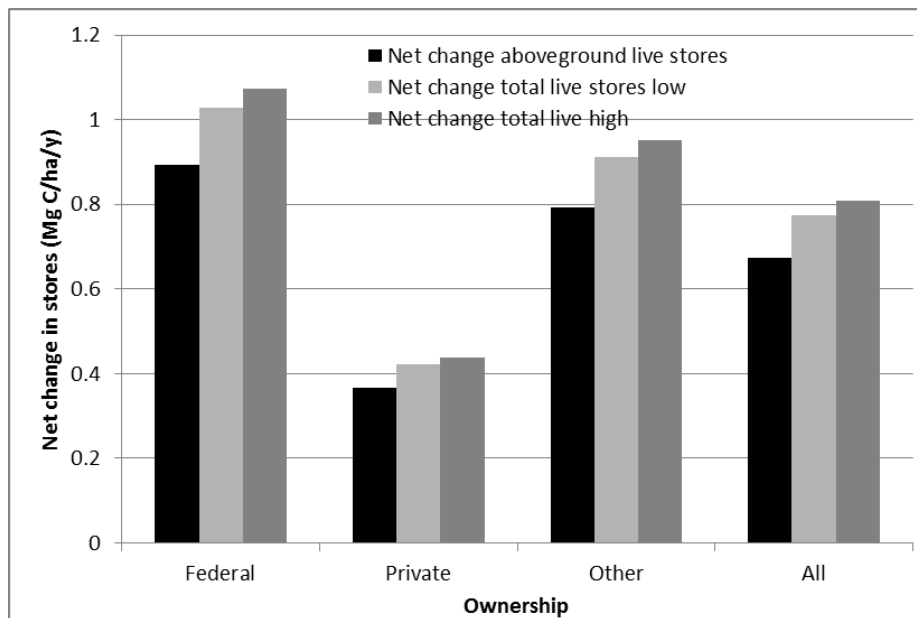


Figure 13. Net change in live stores for different Oregon forest ownerships. Total low and high include roots and represent low versus high correction factors to account for roots.

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 would be 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% 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% change, whereas private ownerships could tolerate a 6% 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% by 2100, with the latter two actions contributing the most." That would increase NECB by some 807 million metric tonnes CO₂e by 2100, or an average of around 10 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% of Oregon's present annual emissions from all sources, combined, including forest sector emissions from decomposing wood products³⁴. Other factors, including unanticipated climate change factors, could increase or reduce these gains. But the figures suggest the significant potential contribution forests in Oregon and elsewhere could be making toward global goals to reduce greenhouse gas concentrations in the earth's atmosphere.

³⁴ 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 98 million tons CO₂/CO₂e. Law estimates a present net rate (NECB) of carbon uptake by Oregon forests of about 69 million tons. Adding another 9.5 million tons/year (807 million tons CO₂e over 85 years) would increase forest uptake to 78 million tons/year, or about 80% of the 98 million tons of energy + forest product emissions.

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

The change in products stores estimated from a process-based model of solid wood products was equivalent to 14% of the stem harvest removals or 1.13 Tg C/y. It should be noted that this estimate does not have an estimate of 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. These were not assessed in this analysis but could be at least as high as 20%.

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)

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. Given the "tolerance" of the forest sector to change noted above, 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 these practices as discussed above (e.g., harvest cycles) 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.

- A. See also Appendix B to this Report (page 51, below): 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 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 Content 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 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: This would leave changes in mineral soil stores as the only ones that cannot be reduced with re-measurement data. 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 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% to 23%, 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: What is the status of carbon stores on State of Oregon-owned forestlands, and the potential for increasing these stores? How would such a policy interact with other historic and/or mandated goals for management of these forests?

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Attachment 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%. 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.

Attachment B: 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).

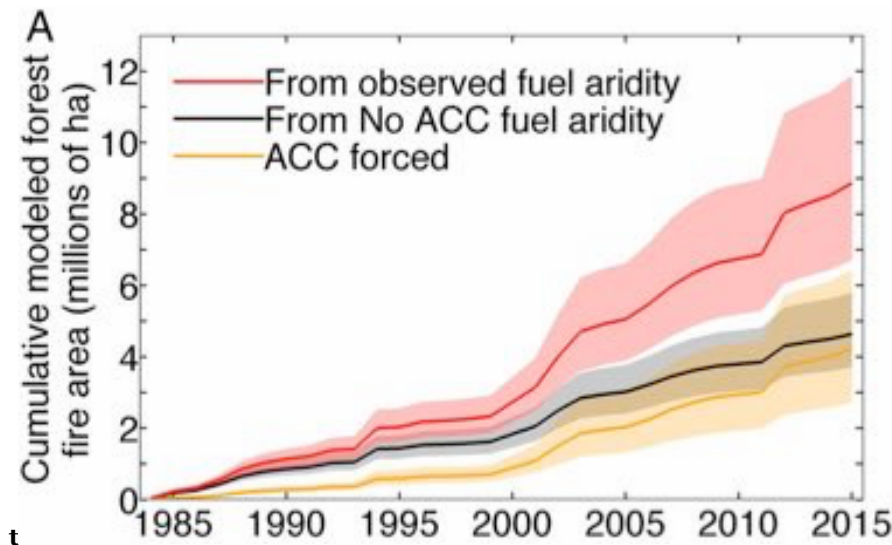


Figure 5.1: Attribution of western US forest fire area to anthropogenic climate change (ACC). Cumulative forest fire area estimated from the (red) observed fuel aridity record and (black) the fuel aridity record after exclusion of ACC (No ACC). The (orange) difference in the forest fire area forced by 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% 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%, while the annual percent area burned is projected to increase by 36%, 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).

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Analysis of Forest Ecosystem Carbon Stores, Flows, and Net Balances

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Summary

A preliminary analysis of the carbon stored and flowing through Oregon's forests was conducted using Forest Inventory and Analysis (FIA) based data on live and dead trees, forest floor, and mineral soil for the 2001-2015 period. In addition, information about past changes on national forest lands, process rates such as litterfall and decomposition, and the net change in forest product stores were used to provide a range of estimates for gross and net carbon exchange of Oregon's forests with the atmosphere.

A total of 12,167,082 ha (30,065,488 acres) are classified as forests in Oregon, the largest share 59.9% are in federal ownerships (Forest Service, BLM, and National Park Service), with private and other ownerships (i.e., state, tribal, and other agencies) contributing 36.2 and 3.9%, respectively.

The total store of carbon in Oregon's forests was estimated to range between 2582 and 2865 Tg C (2847 to 3159 million tons of C). This included stores in above- and belowground live carbon (41.3%), dead wood that is standing, downed, and in coarse roots (10.3%), the forest floor (6.6%), and mineral soil (41.7%). Of the three major ownerships, federal ones stored the most forest carbon (62.5%), private ones next highest (32.6%) and other ownerships the least (4.8%). For some of the pools the difference between the fraction of forests owned and the proportion stored was substantial (live carbon and standing dead), whereas in others the differences were small (dead and downed wood, the forest floor).

The total amount of carbon flowing into Oregon's forests via photosynthesis was estimated to be 114 to 150 Tg C/y (141 to 165 million tons C/y). Of this 50% was lost within a year to plant respiration, 28% was allocated to short-lived plant parts (leaves and fine roots), and 22% was allocated into longer-lived woody tissues. Gross growth, which represents the latter flow, 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 woody parts. Natural mortality of woody parts was estimated to be equivalent to 25% of gross growth. Harvest-related mortality was estimated to be equivalent to 40% of gross growth. This indicates that live carbon stores are increasing in Oregon's forest as a whole, although there was variation among ownerships. Changes in dead and soil pools could only be approximated at this point, but there is evidence that at least on federal lands that the store of dead wood has also been increasing.

If all pools other than the live ones are remaining constant, then the net rate of exchange with the atmosphere would be 9.4 and 9.8 Tg C/y (equivalent to 34.5 to 35.9 Tg/y of carbon dioxide). 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 carbon dioxide). If the net accumulation from solid wood products (i.e., paper, wood in buildings, etc) is included, then the total net uptake of Oregon's forest sector would have been 6.9 to 16.9 Tg C/y (equivalent of 25.3 to 62.0 Tg carbon dioxide/y). The main uncertainties in these estimates

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that can be readily addressed are largely related to the dead wood pools and the proportions of live and dead carbon belowground. Despite these uncertainties, it is highly certain that Oregon's forests are removing carbon from the atmosphere.

Introduction

This is an analysis based on FIA derived estimates provided by Dr. Jeremy Fried and Dr. Andy Gray. It also draws on work done by Dr. Gray on National Forest lands and generally known relationships among pools and flows of forest carbon. The intent is to provide an example of how this information can be used to estimate the carbon balance of Oregon's forest lands and to explore the effects of uncertainties. It focuses on the carbon in the forest ecosystem and not that stored in solid products or those associated with substitutions of energy or products. In addition to examining carbon in forests for Oregon as a whole, it contrasts different ownerships, but not different regions within Oregon.

Methods

Live Carbon

Live carbon in forests consists of above- and belowground forms (coarse and fine roots). The FIA estimates provided by Dr. Fried only consider the aboveground components such as stem wood, bark, branches, and leaves. These estimates of aboveground stores are based on the national generalized biomass models that use field measurements of diameter to calculate the store of aboveground organic matter. It should be noted that these biomass models give estimates that are 19% higher than those using regional-based models (Gray and Whittier 2014). The aboveground store was then converted to carbon assuming that 50% of the organic matter was carbon. Since these estimates exclude roots, the total live stores and flows are therefore higher than reported. Typically roots are equivalent to 15 to 20% of the aboveground carbon (A. Gray, personal communication) To estimate total live stores and flows the aboveground value was multiplied by either 1.15 or 1.20 to reflect this level of uncertainty.

The gross growth term reported by Dr. Fried was equivalent to the net primary production related to aboveground woody tissues. This term excludes major flows of carbon associated with leaves and fine roots. To approximate the NPP associated with leaves the rate of litterfall observed in conifer forests was used. Based on unpublished data for western hemlock, Douglas-fir, and ponderosa pine dominated forest this flow ranges between 1 and 2.5 Mg C/ha/y. Very few estimates of the NPP related to fine roots are available. However, the most likely approximation is that it at least equals litterfall rates. To estimate the total amount of carbon flowing into Oregon's forests it was assumed that net photosynthesis (gross primary production or GPP) is approximately twice that of NPP (the sum of gross growth and NPP related to leaves and fine roots). Although these are approximations, they do give a sense of how much carbon is flowing into Oregon's forests and how that carbon is being lost or used.

Dead Carbon

Dead carbon was in three forms: dead standing trees, dead and downed trees, and the forest floor. Standing dead trees were based on live biomass equations, included branches and belowground parts

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(i.e., coarse roots), but did not deduct for losses from respiration or fragmentation. These estimates are therefore too high. To roughly adjust these stores it was assumed that loss of volume and branches related to fragmentation would reduce the store by 50 to 60%. Losses from respiration were taken into account by reducing this store by another 20 to 25%. Combined this would reduce the standing dead store by 60 to 70%. Although these are approximations, they do provide a more accurate estimate than the original assumption of no volume or density losses.

Surface dead and downed fine woody debris (<7.6 cm) was included in the downed woody material. Dead coarse roots belowground were not included in the dead and downed wood. To get some idea of how large this pool might be it was assumed that dead coarse roots were equivalent to 0.1 to 0.2 of the aboveground dead and downed. Yatskov (2015) estimated that dead coarse roots were equivalent to 14% of the dead downed stems. This expansion factor is based on the ratio of live roots to stems for live trees, but adjusted downward to account for the fact coarse root decomposition is faster than stem decomposition.

In addition to reporting the values given by the FIA, a lower and upper total estimate for these pools was estimated by adding in or subtracting the mass needed to account for either missing parts (in the case of dead and downed) or lack of fragmentation or other decomposition-related losses. It should be kept in mind that these numbers are underestimates because the dead roots associated with cut stumps were excluded. For some ownerships, such as private ones, there may be a substantial pool of carbon in the form of dead roots associated with cut stumps. However, without some accounting for the volume or mass of stumps, it is nearly impossible to directly estimate this pool size using the FIA inventory. A preliminary estimate of the stump-related pool was made using the amount of historical harvest removals and assuming that stump roots were 15 to 20% of this value and that 5 to 10% was lost each year was used to roughly estimate this store.

The mass of the forest floor represented accumulations of decomposing leaves, branches <7.6 cm, and buried dead wood. The flow of carbon leaving this pool was estimated by assuming that 10 to 15% of this pool was lost each year. These values were taken from unpublished data on the rate confined blocks of forest floor decomposed over a 4 year period in western hemlock, Douglas-fir, and ponderosa pine forests. This was contrasted to a rough estimate of the carbon flowing into this pool via litterfall, which was assumed to range between 1 and 2.5 Mg C/ha/y based on unpublished data.

Soil Carbon

The stores reported for soil C were to a depth of 1 m, but included the forest floor. Thus using the unadjusted value would double count carbon to some degree. The forest floor stores were not reported for this source of soil C (i.e., the FORCARB model). To approximate the value the forest floor estimate provided by the FIA was subtracted from the initial soil c estimate. The flow of carbon coming into and out of the mineral soil was approximated by assuming 50% of the fine root death eventually entered the mineral soil pool and that the carbon in mineral soil has an average lifespan of 100 years. The latter is based on an order of magnitude estimate from the literature.

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Net Flows

The most certain value in terms of net flows is the net change in live aboveground stores. While this is an important metric, it cannot be assumed to equal the net flow (or rate of change) for the forest. The net change in aboveground stores is not even an accurate estimate of the change in live stores, let alone the forest as a whole.

To get a sense of how uncertain the total net change in forest carbon is I accounted for the missing terms. To add in the gross growth associated with live belowground carbon I assumed this term was equivalent to 15 to 20% of aboveground gross growth. While natural and harvest-related mortality removes carbon from the live pools it does not necessarily lead to losses to the atmosphere. To get some sense of how much mortality-related carbon might be accumulating I used the ratio of net change of dead wood pools reported by Gray and Whittier (2014) to mortality losses reported by Dr. Fried. This is only an approximation, but does indicate that at least for national forest lands that dead wood carbon stores are increasing, which means that mortality is more than replacing losses via decomposition. To get a sense of how much more carbon uptake might be occurring I assumed that all forests are accumulating carbon stores at this rate. There are no data to suggest how much that the forest floor and mineral soil carbon might be changing. In addition to the scenario in which these two pools have no net change, I explored cases in which they might increase or decrease by a fixed percentage. I converted these changes into annual values using the approximate timeframe these pools respond to changes (10 years for the forest floor and 100 years for the mineral soil). While these are rough approximations, they do give a sense of whether the sign and magnitude of the overall forest net change is sensitive to changes in these pools.

Results and Discussion

Live Carbon

The FIA inventory conducted in 2001-2010 indicates that a total of 926.6 Tg C (equivalent to 1021.6 million tons) of live tree aboveground carbon was stored in Oregon's forests. If the belowground tree live carbon is also included another 139 to 185 Tg of C was also stored, bringing the total live tree store to 1,065 to 1,112 Tg C depending on the ratio of below- to above-ground live carbon used. Expressed as a carbon density (i.e., amount of carbon per unit area), the average store live aboveground carbon was 76.2 Mg C/ha (equivalent to 33.98 tons C/acre). Including live tree belowground carbon would bring the average carbon density of total live carbon to 87.6 to 91.3 Mg C/ha. Some additional carbon would be stored in understory plants such as herbs and shrubs. This would likely increase the total live store by less than 5%, but was not considered in this analysis.

Proportional stores of live tree aboveground carbon varied by ownership, but this was largely determined by the area in these ownerships (Figure 1). However, federal and ownerships other than federal or private ones store proportionally more carbon than their area would suggest and private lands store less.

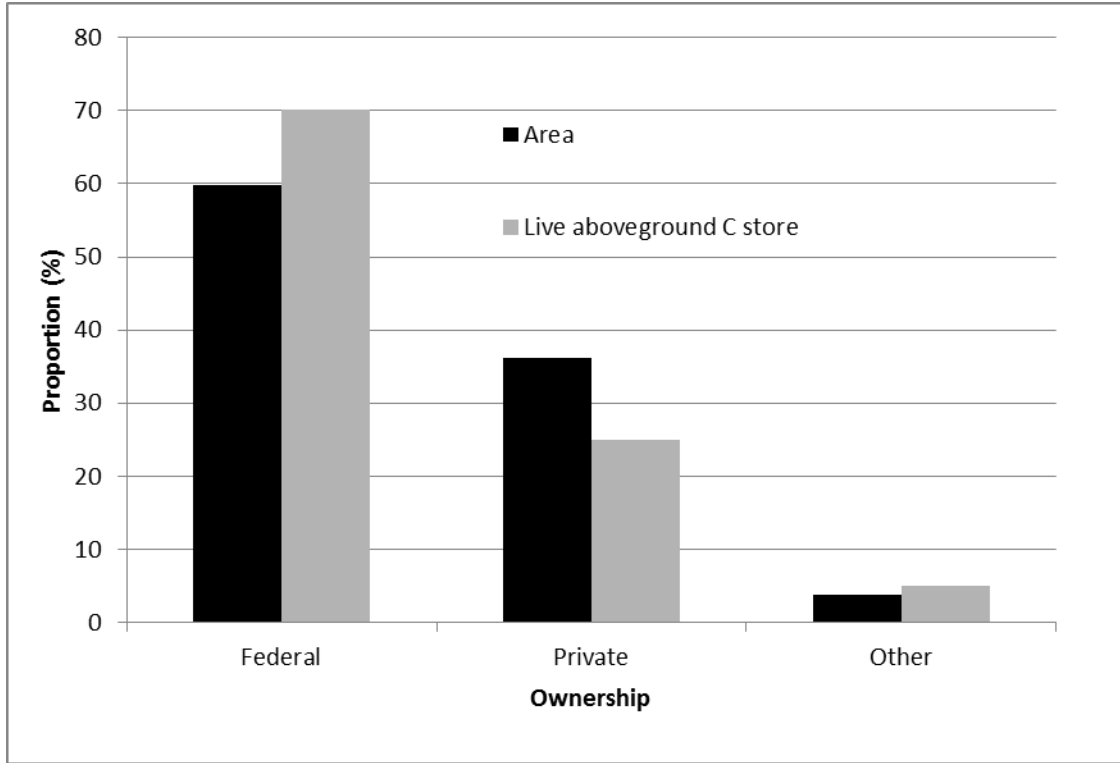


Figure 1. Proportion of area and live aboveground carbon stores by general ownership.

Expressed as a carbon density, that is on a unit area basis, ownerships other than federal or private ones stored more live aboveground (99 Mg C/ha) and total live carbon (114 to 142 Mg C/ha) than the other two ownerships with (Figure 2). The density of live aboveground carbon was slightly lower on federal lands with 89 Mg C/ha and lower still on private lands (52 Mg/ha). Including live belowground carbon would increase these values 15 to 20% depending on the expansion factor used.

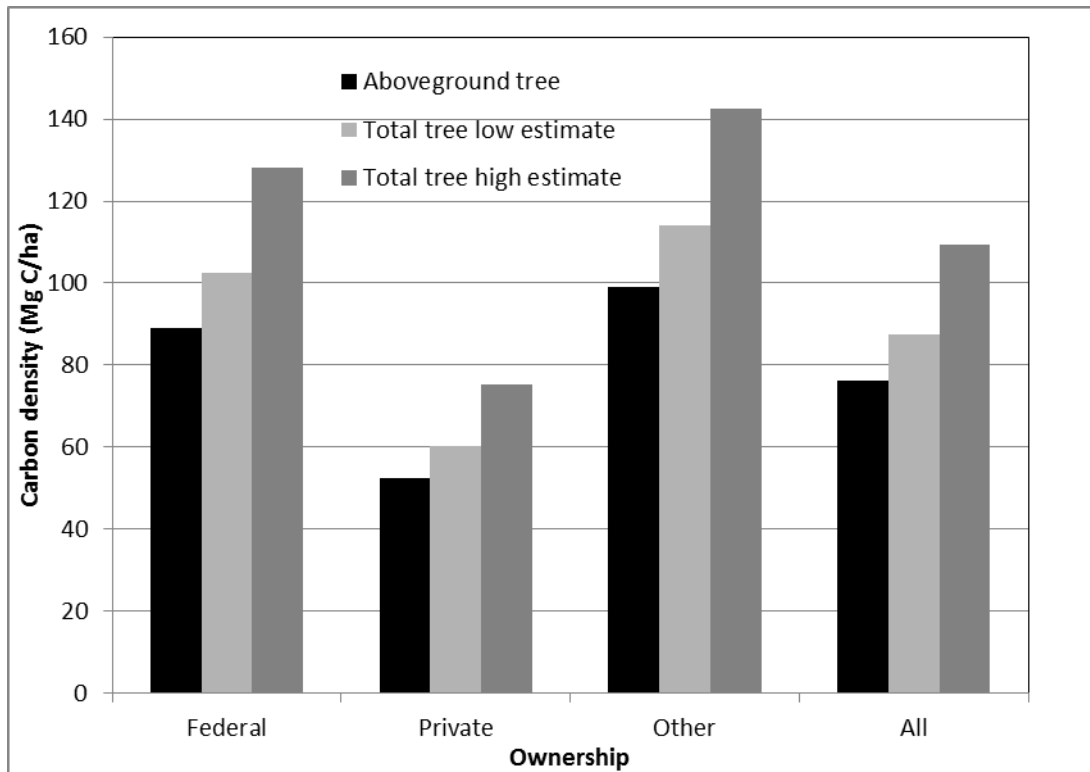


Figure 2. Carbon density of live aboveground and total live carbon for different ownerships of Oregon's forests.

The differences in live aboveground carbon density can be explained by examining the flows coming into this pool versus out. These data contrast two periods 2001-2005 and 2010-2015 to determine the net change in the stores, inputs via gross growth (net primary production), and losses via harvest and other forms of mortality.

Based on these data the total gross growth of aboveground woody tissues for Oregon's forests was 24.2 Tg C/y. If belowground woody parts are included, the gross growth in Oregon's forests would range between 27.8 and 29.0 Tg C/y. However, this is an underestimate of the total flow into Oregon's forests because it neglects carbon flowing into leaves and fine roots and also neglects plant respiration. If litterfall ranges between 1.2 to 1.9 Mg C/ha/y, then an additional 14.6 to 23.1 Tg C/y was coming into the live aboveground pools. If the flow into live fine roots is similar, then the total NPP of Oregon's forests might be 2 to 2.6-fold higher (57 to 75.2 TgC/y). Including the flow of carbon associated with plant respiration would roughly double this value again. This means that the total flow of carbon into Oregon's forests would have been on the order of 114 to 150 Tg C/y. Although gross growth underestimates that total carbon flow into Oregon's forests (it is around 22% of the total), it is still a very important metric. This is because roughly half the total carbon flowing into plants is lost via plant respiration within a period of days to weeks. Of the fraction remaining, gross production represents the flow into woody parts such as stems, branches, and coarse roots which together account for over 95% of the live carbon store. Flows into leaves and fine roots are also important, but do not accumulate large amounts of carbon in their live form (approximately 5% of live stores). They are quite important as

sources of carbon to the forest floor and soil carbon, the latter being a very large fraction of total forest ecosystem carbon stores.

As with live stores, the proportion of gross growth contributed by ownerships was largely determined by their areal extent (Figure 3). However, some of these differences are related to other attributes related to ownership such as soil fertility, forest age structure, and management. This is best seen by comparing gross growth for a standardized area (Figure 4) which indicates that gross growth of aboveground live carbon was lowest on federal lands (1.71 Mg C/ha/y) and highest on lands other than federal or private ones (3.12 Mg C/ha/y). The latter result was related to lands owned by the State as other kinds of public ownerships are slightly above average (2.04 MgC/ha/y). Gross growth of live aboveground carbon on private lands was estimated to be 2.24 Mg C/ha/y, which is above the overall average of 1.98 Mg C/ha/y.

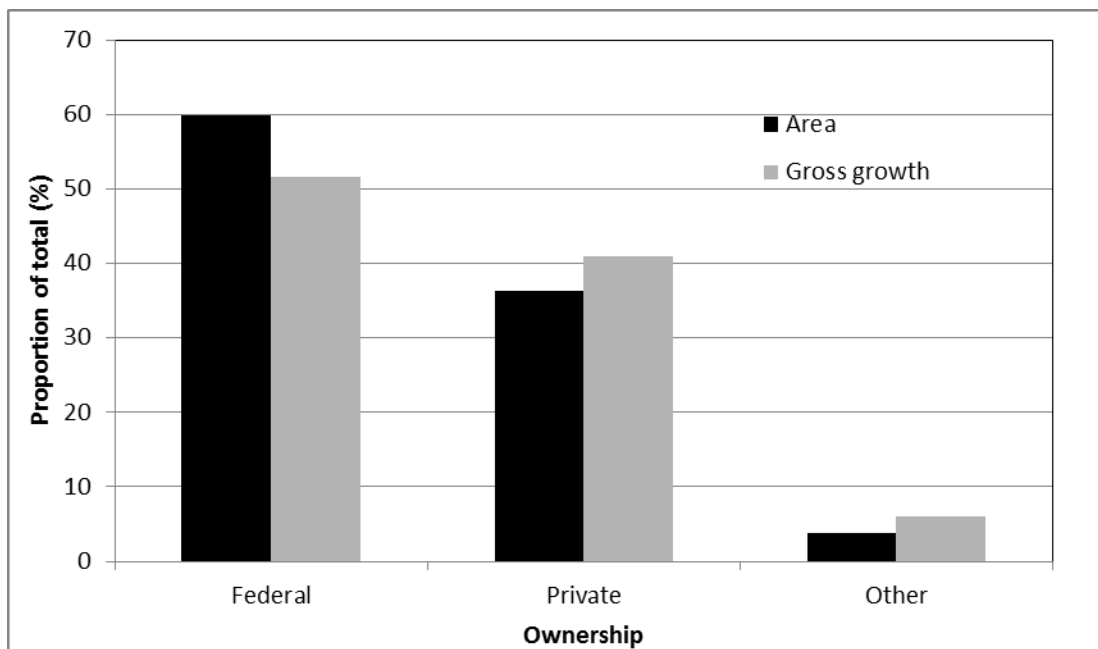


Figure 3. The proportion of area and gross growth of aboveground live carbon contributed by ownerships of Oregon's forests.

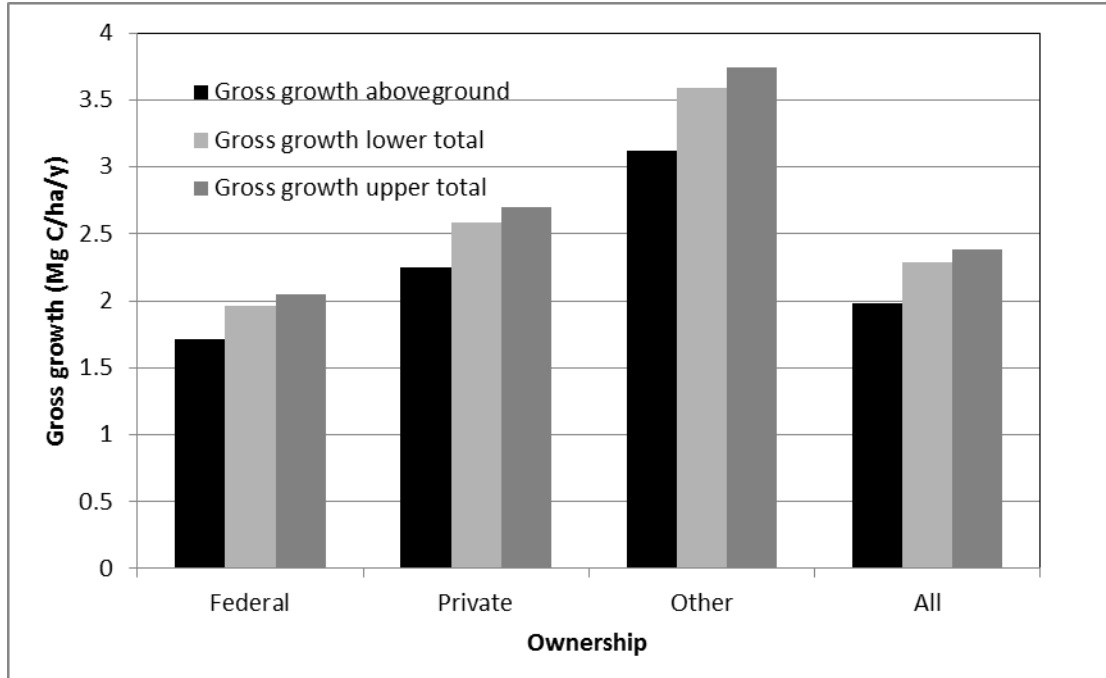


Figure 4. Average gross growth for aboveground live and total live carbon in different ownerships for Oregon's forests.

Losses from live carbon in Oregon's forest are caused by mortality from cutting and natural causes; these losses cannot be assumed to be emissions to the atmosphere because some of these losses from the live pool are added to the wood products and dead wood pools.

Losses by natural mortality from the live aboveground store were estimated to total 6.4 Tg C/y in Oregon's forests; equivalent to about 25% of gross growth. Expressed as a fraction of the live aboveground carbon dying, mortality for all forest was 0.7%/y. If mortality related to belowground woody parts is included, then the overall natural mortality flow for Oregon's forests would range between 7.4 and 7.7 Tg C/y. These estimate neglects losses from leaves and fine roots which if included would increase the estimate by a factor of 4 to 9; total natural mortality of all forms (stems, branches, roots) would range 36.6 to 53.9 Tg C/y. However, these flows do not influence the live store substantially because most of these losses are offset by a similar sized flow into these pools as noted under gross growth.

Federal lands contributed the largest share of mortality losses and proportionally more than expected from area alone (Figure 5). Private lands showed the opposite trend with less of a contribution than area would suggest. These patterns are caused by the higher mortality flow on federal lands, which average 0.67 Mg C/ha/y for aboveground woody parts (Figure 6). The lowest rate of natural mortality of aboveground carbon occurred on private lands, with 0.26 Mg C/ha/y. Overall the average mortality rate of aboveground live carbon was 0.53 Mg C/ha/y and if belowground woody parts were included this flow would be 0.60 to 0.63 Mg C/ha/y.

Expressed as a proportion of live aboveground carbon lost per year, natural mortality ranged between 0.5% on private lands and 0.7% on federal ones. While this is a 40% difference, the rate on federal lands was within the range expected for forests of the PNW region (i.e., 0.5 to 1% per y).

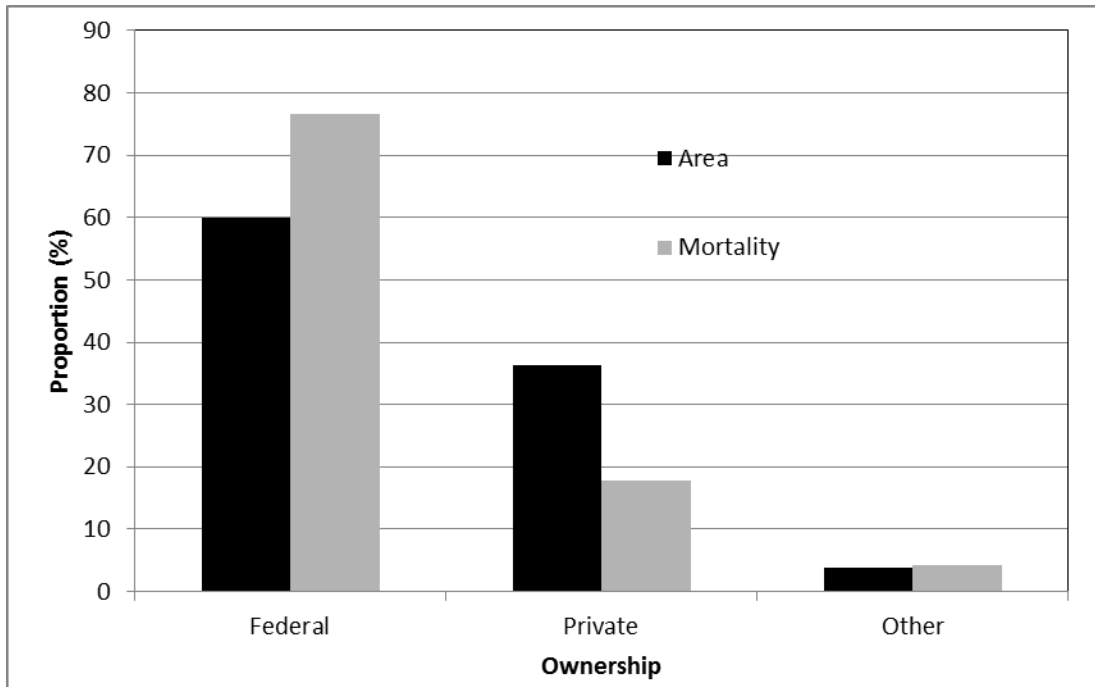


Figure 5. Proportion of area and natural mortality by ownership in Oregon's forests.

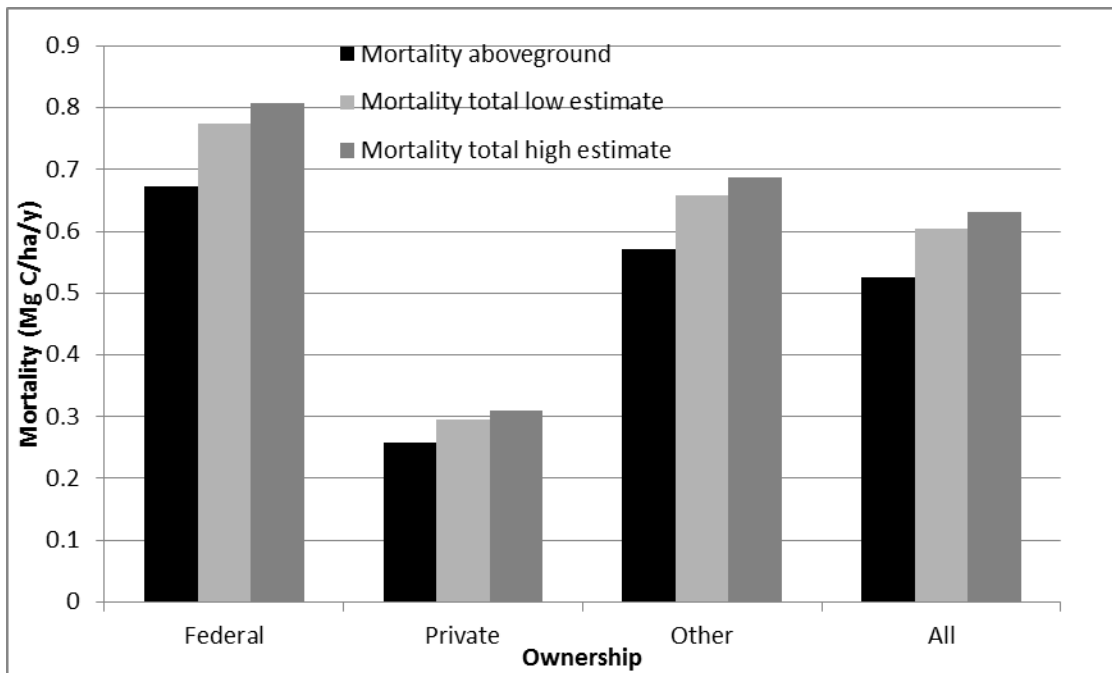


Figure 6. Average flow caused by natural mortality of live wood by ownership of Oregon's forests.

Losses related to cutting for harvest in Oregon’s forest from aboveground live carbon were estimated to be 9.6 Tg C/y which is equivalent to approximately 40% of gross growth and approximately 50% higher than natural mortality. If belowground carbon killed by cutting is included this loss from the live carbon store would have ranged between 11 and 11.5 Tg C/y. The value based on state-wide log harvest volume reports was 6.4 Tg C. This discrepancy with the FIA based numbers might be related to the fact not all the cut carbon is necessarily removed from the forests in the form of stems (probably something between 80 to 85%). It is also likely that the conversion from log board foot to carbon mass was imprecise given that the conversion factor depends on species, size, age of stands, etc. all which changes over time and space.

The proportion of harvest coming from private and other ownerships was over twice the value that area would suggest (Figure 7). In contrast, harvest cuttings from federal lands are proportionally about 20% that suggested by the proportional area in that ownership. On a per unit area basis for live aboveground carbon, harvest related cuttings on federal lands were 0.14 Mg C/ha/y as opposed to 1.62 and 1.75 Mg C/ha/y on private and other ownerships, respectively (Figure 8). This indicates at least a magnitude of order difference in harvest levels between federal and other ownerships.

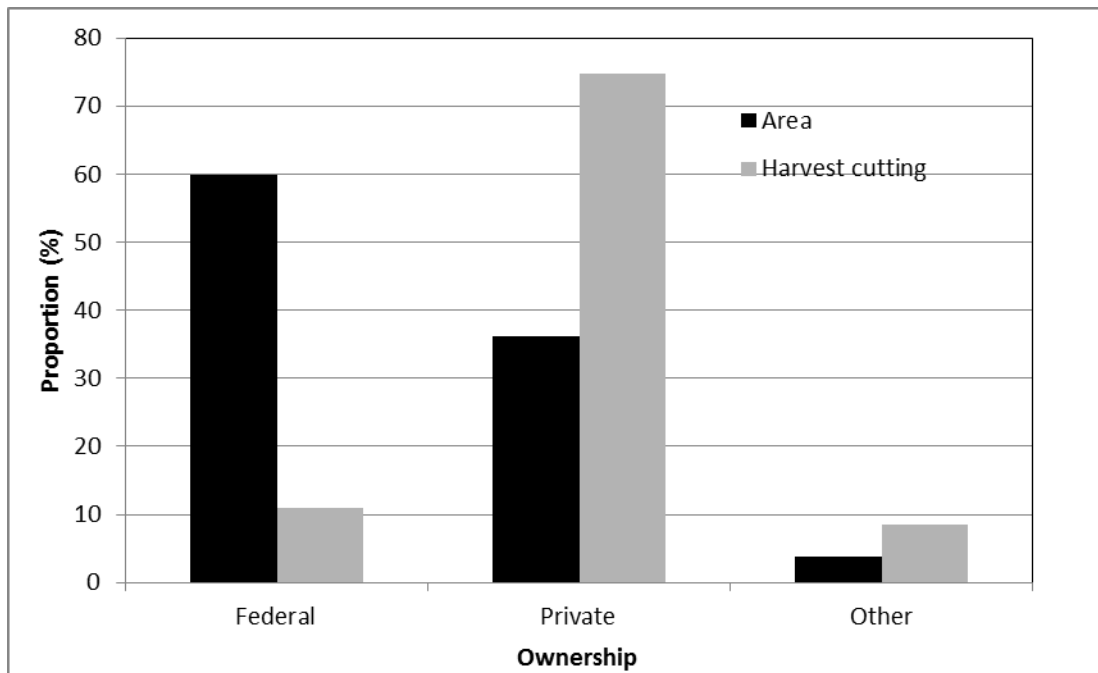


Figure 7. Proportion of land area and harvest-related cutting by ownership in Oregon’s forests.

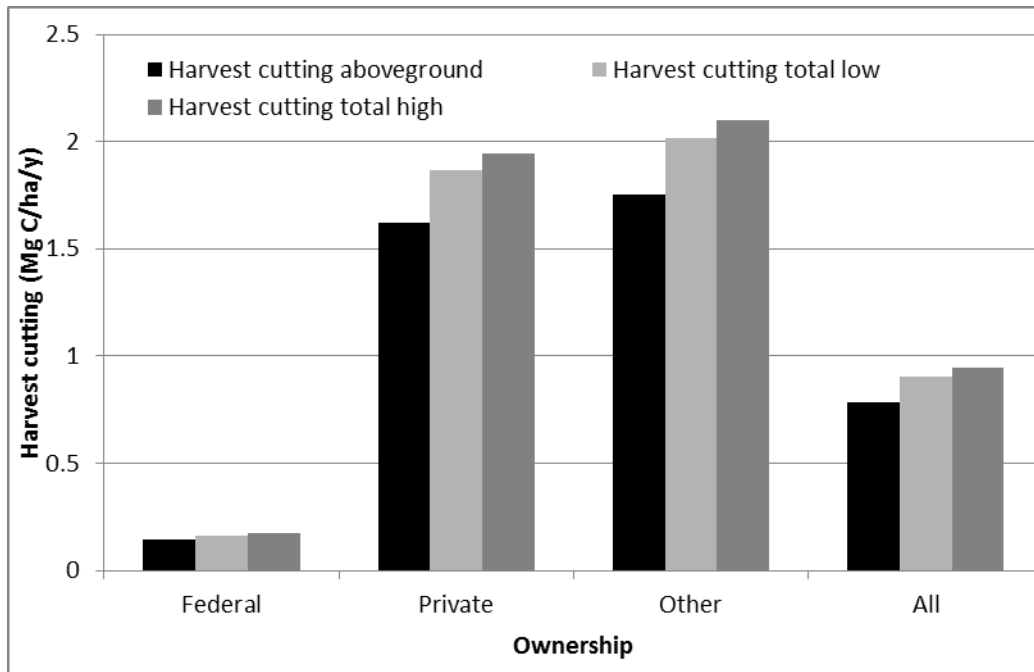


Figure 8. Harvest-related cutting flows by ownership of Oregon's forests.

Regardless of whether there is mortality via harvest-related cutting or natural causes, both are considered losses from the live store. When combined these losses are estimated to be 15.96 Tg C/y for just the aboveground portion of live carbon. This is equivalent to approximately 65% of the gross growth flow of aboveground live carbon. If belowground losses are also factored in, this total flow could have ranged between 18.3 and 19.1 Tg C/y. When mortality from cutting and natural causes were combined, federal lands contributed less than their area would suggest (Figure 9). Conversely, private and other ownerships contributed more, a trend related to their high rate of harvest-related cutting.

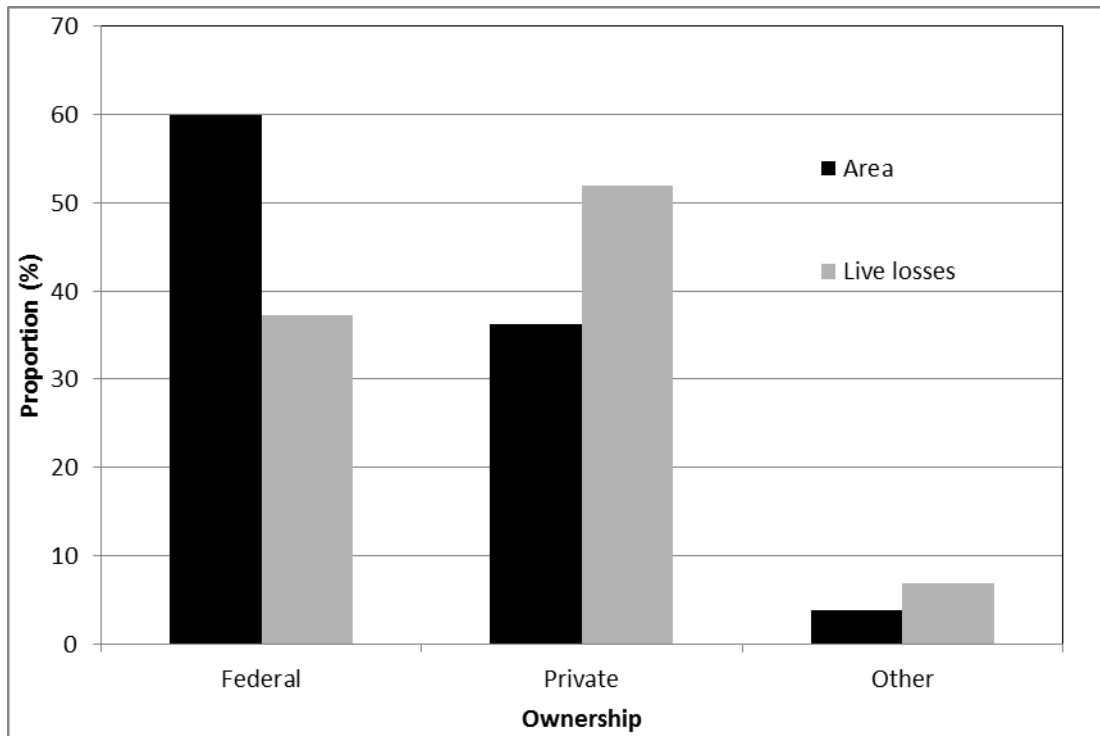


Figure 9. Proportion of area and total losses from live aboveground carbon by Oregon forest ownership.

On a per unit basis, combined flows from live aboveground carbon caused by natural mortality and harvest-related cutting on federal lands (0.81 Mg C/ha/y) were less than half that on private and other ownerships (1.88 and 2.32 Mg C/ha/y, respectively) (Figure 10). The ratio of the stores to the total losses gives an indication of how long carbon resides on average in live aboveground stores. This metric suggests that carbon entering live aboveground carbon resided on average for 58 years in Oregon's forests, but could reside on average as short as 28 years in private lands and as long as 109 years in federal forests (Figure 11). This indicates that despite the fact input of live carbon to federal forests is lower than other forests, there is a higher store on federal lands; this is largely related to the very long time that live aboveground forest resides in these forests compared to the other ownerships (almost four times longer).

Subtracting losses via natural mortality and harvest-related cutting from the gross growth flow indicates the net balance for live tree stores. This is equivalent to the net change in these stores which for Oregon's forests was 8.2 Tg C/y for the aboveground live tree stores. If belowground stores are also considered, the net change in total live stores would range between 9.4 and 9.8 Tg C/y. While this suggests that overall Oregon's forests are removing carbon from the atmosphere, the changes in other pools storing carbon have to be considered before reaching this conclusion.

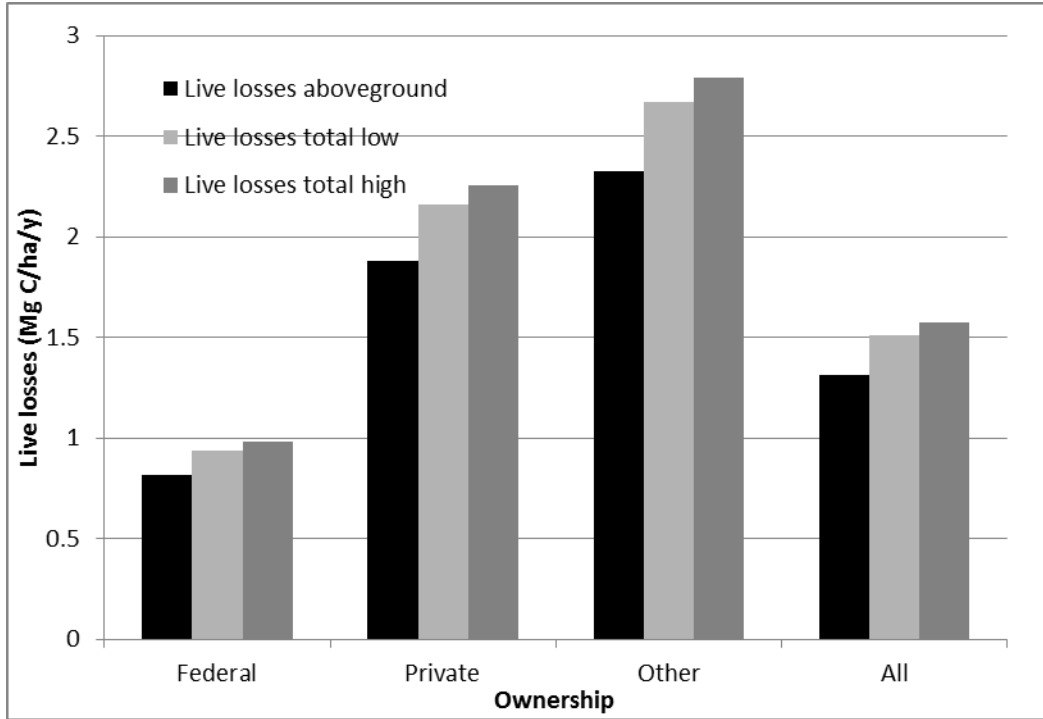


Figure 10. Combined flow of live carbon via harvest-related cutting and natural mortality for Oregon’s forests.

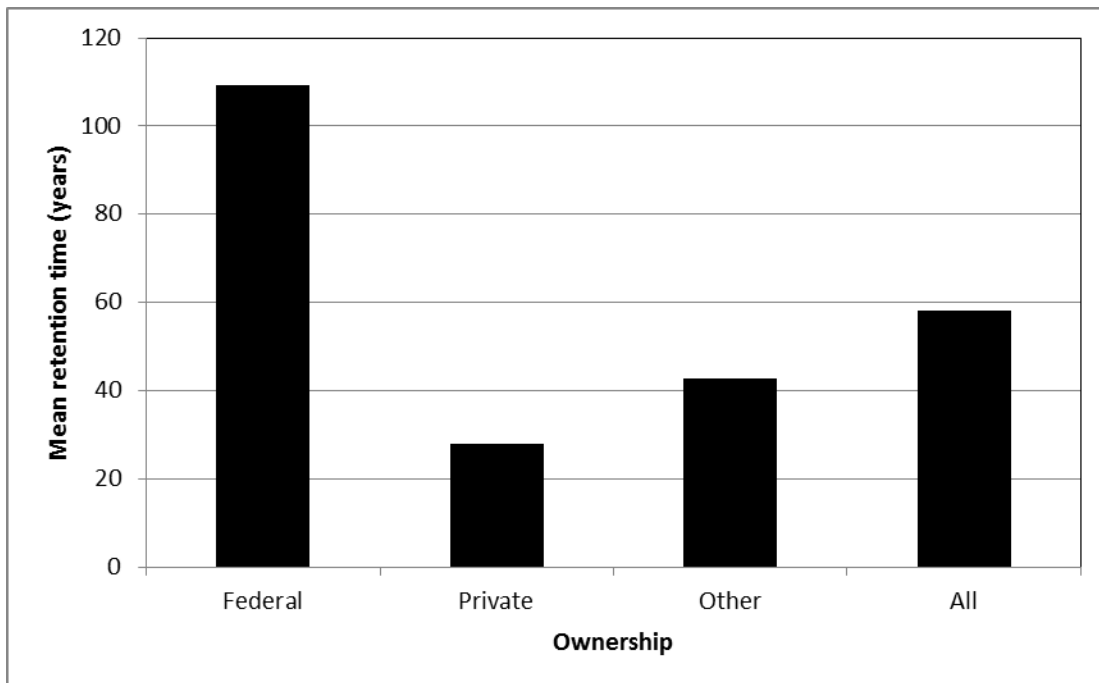


Figure 11. Mean retention time of carbon in live aboveground stores in Oregon’s forest. The longer the mean retention time, the higher stores can become assuming that inputs via gross growth are similar.

The proportional contribution ownerships to net change follows proportional area to some degree: federal land comprise 60% of the area, but 79% of the overall net change in live stores (Figure 12). In contrast, private lands comprise 36% of the area, but 20% of the net change in live stores. For other land ownerships, the proportions of area and net sink are similar.

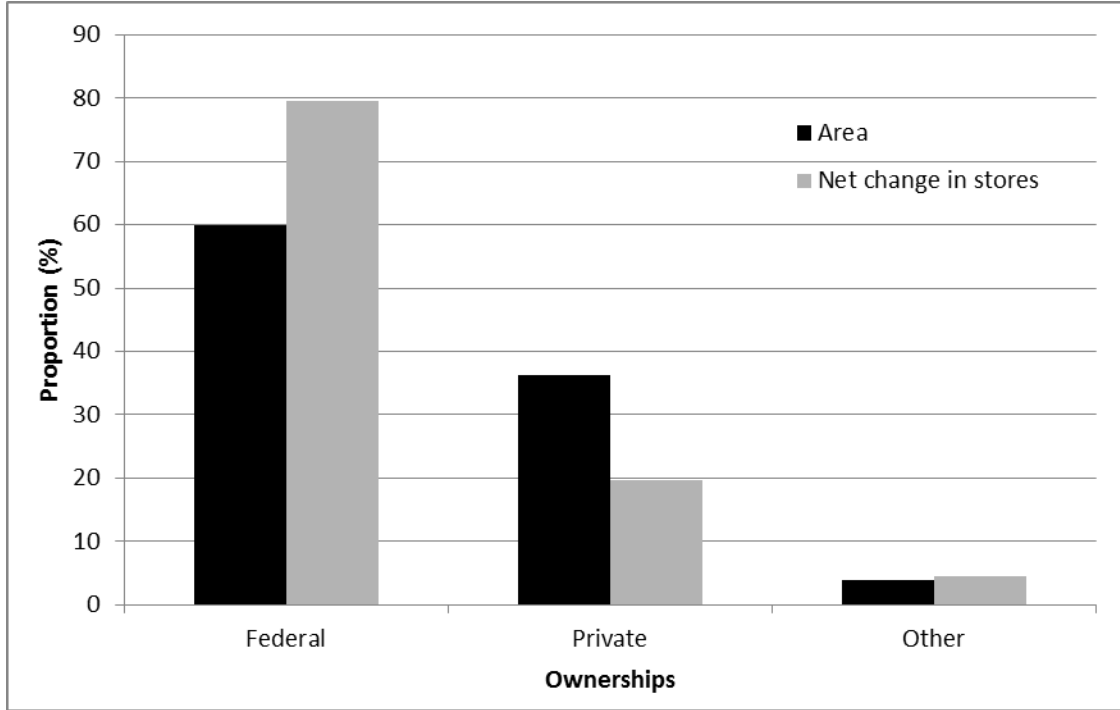


Figure 12. Proportion of area and net change in aboveground live stores by ownership of Oregon's forests.

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 despite the high rate of harvest-related cutting. This may be caused by the higher gross growth flow on those lands relative to private and federal ownerships.

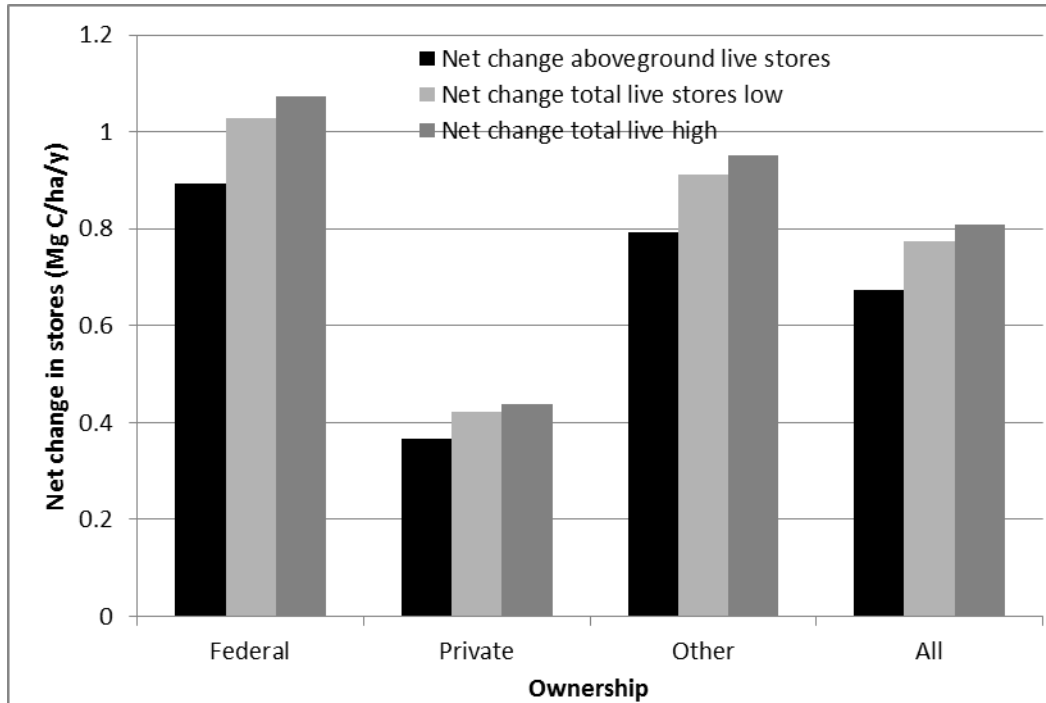


Figure 13. Net change in live stores for different Oregon forest ownerships.

Dead wood

Dead wood pools may be either standing or downed. In addition there are belowground dead wood pools in the form of dead coarse roots associated with these two pools. Standing dead stem stores without any adjustment for decomposition losses were estimated to be 101.4 Tg C in Oregon's forests. If losses associated with volume losses and changes in density associated with decomposition are accounted for, then the total store of carbon associated with standing dead trees would be 30.4 to 40.6 Tg C.

Federal ownerships contributed more to these stores than area suggests, whereas private lands less (Figure 14). Considered on a per unit basis, federal ownerships had substantially higher standing dead tree stores (11.6 Mg C/ha) than private ownerships (2.8 Mg C/ha) (Figure 15). Other ownerships were intermediate between these two extremes (7.6 Mg C/ha). If adjustments for decomposition are made the carbon density in standing dead trees would be roughly 30 to 40% of these values.

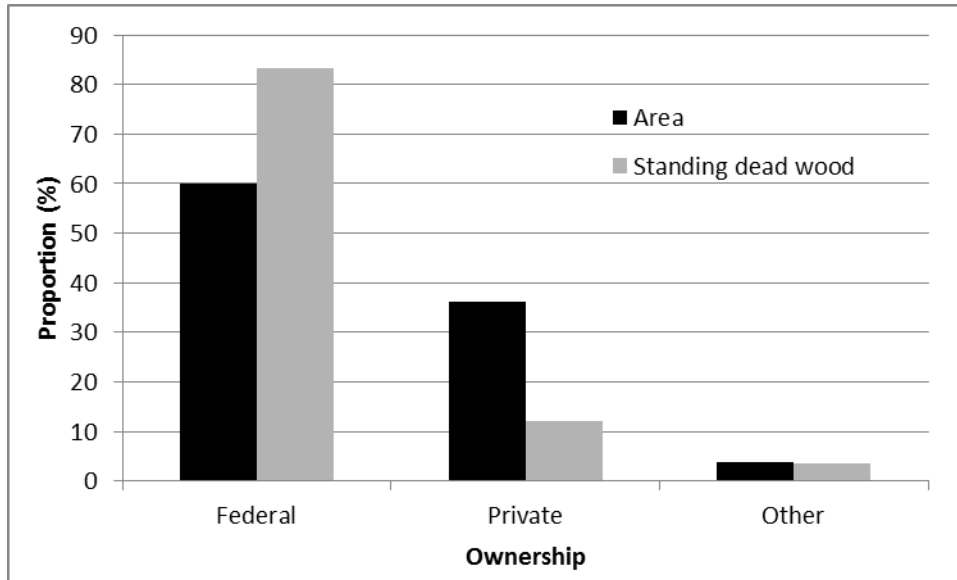


Figure 14. Proportion of area and standing dead stem carbon contributed by different ownerships of Oregon's forests.

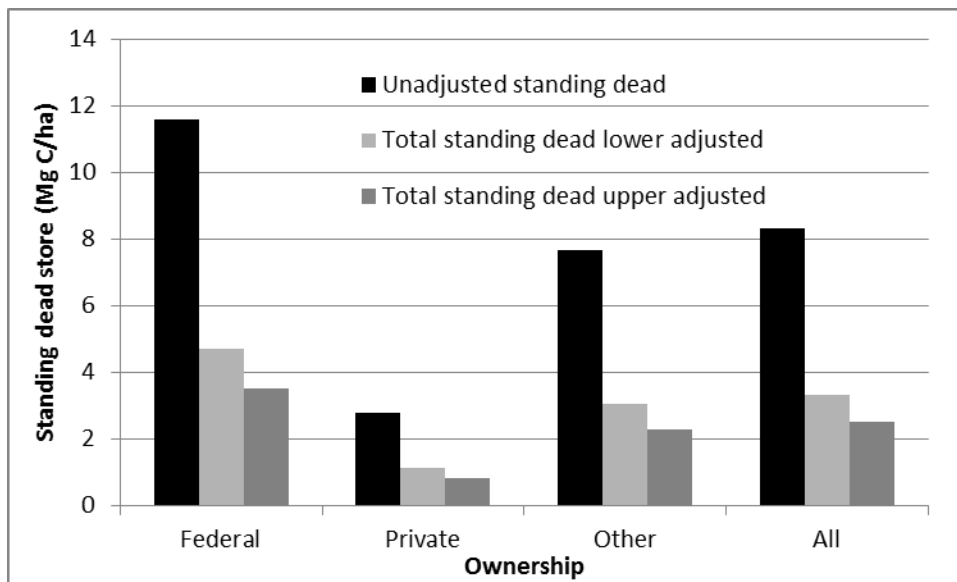


Figure 15. Stores of standing dead trees and associated parts in Oregon's forests.

Downed dead woody aboveground stores were estimated to be 187.5 Tg C in Oregon's forests. If the dead coarse roots associated with this pool are included, then the store would have been 206.2 to 225 Tg C. In contrast to standing dead wood, downed and dead wood was contributed proportionally similarly to area (Figure 16). Considered on a carbon density basis, downed and dead wood store were highest on ownerships other than federal or private (Figure 17) with a carbon density of 21.8 Mg C/ha. Federal and private ownerships had similar per area stores of downed and dead wood with values of 15.6 and 14.5 Mg C/ha, respectively. The high carbon density on other ownerships appears to be associated with state lands and may have been a legacy of the Tillamook fire.

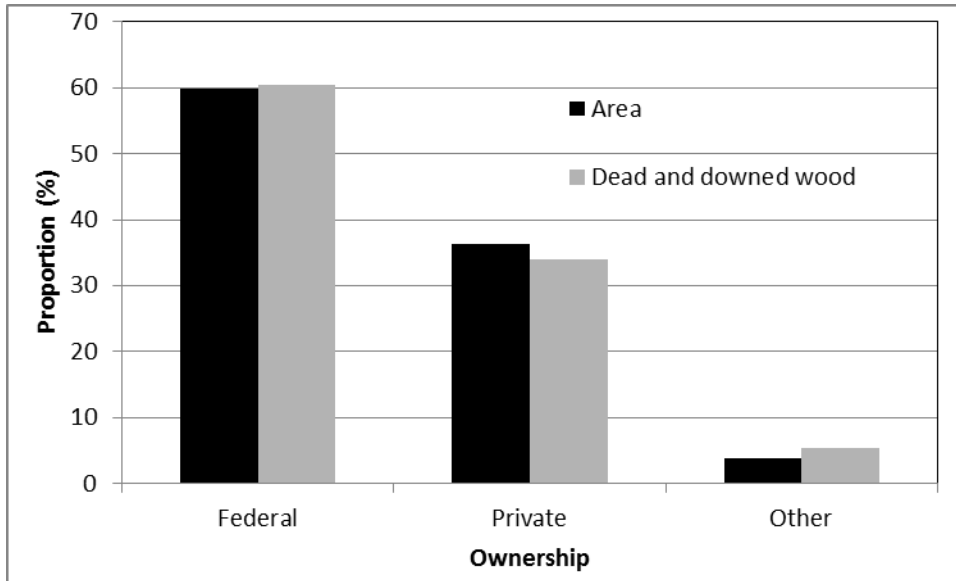


Figure 16. Proportion of area and dead and downed woody stores in Oregon's forests.

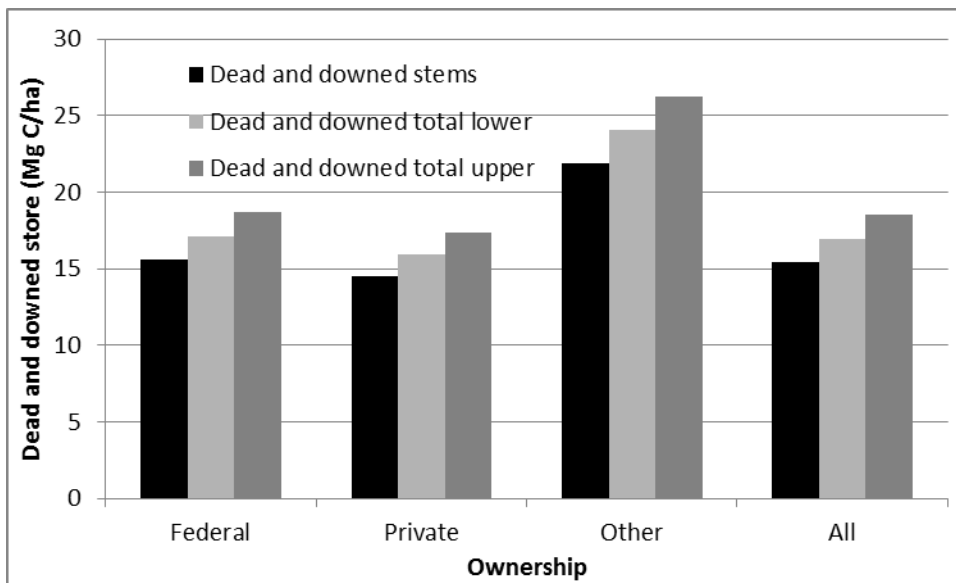


Figure 17. Stores of dead and downed woody carbon in Oregon's forests.

The combined standing and downed dead wood store in Oregon's forest when no adjustments are considered was estimated to be 288.9 Tg C. This was equivalent to 31.2% of the live aboveground carbon and within the range expected for conifer forests. If adjustments for missing parts, fragmentation and respiration are included, then the total store in dead wood was estimated to be 246.8 to 255.4 Tg C giving a dead wood to live aboveground wood ratio of 27 to 28%. Dead wood carbon was largely contributed according to the proportional area, although federal lands had somewhat more and private lands somewhat less than area would suggest (Figure 18). Considered on a

per unit area basis, private lands had the lowest carbon density of dead wood (17.3 to 18.2 Mg C/ha) and federal and other ownerships had similar values (22.7 to 27.2 and 28.5 to 29.5 Mg C/ha, respectively). While adjustments for missing parts and decomposition losses generally decreased the stores from the initial estimates, on private lands the stores were increased. This is due to the fact that downed dead wood dominated the dead wood stores on private ownerships and adjustments for that pool were upwards. It should be noted that dead roots associated with stumps resulting from harvest would add another 11 to 36 Tg C: this is equivalent to 4 to 14% of the estimate excluding them.

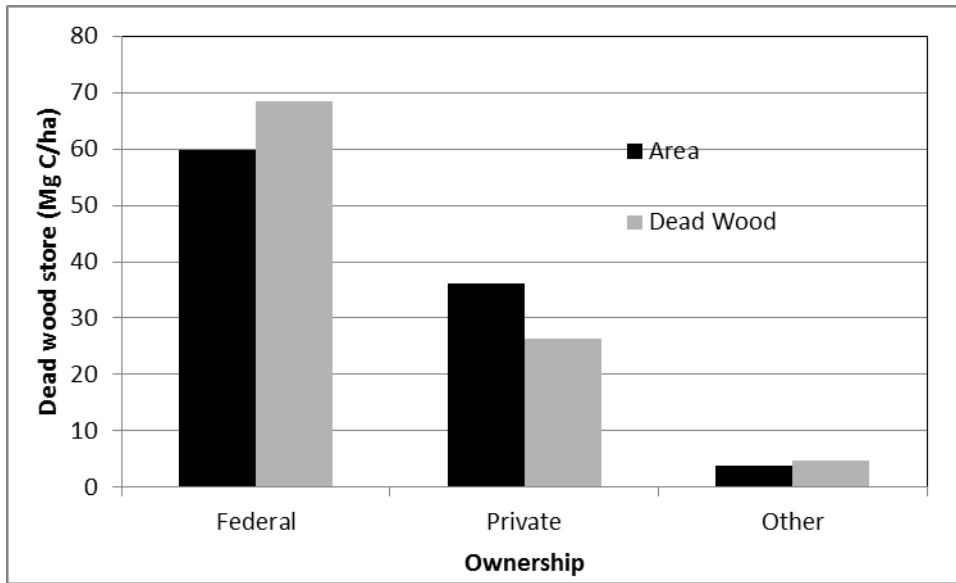


Figure 18. Proportion of area and dead wood stores contributed by different ownerships of Oregon’s forests.

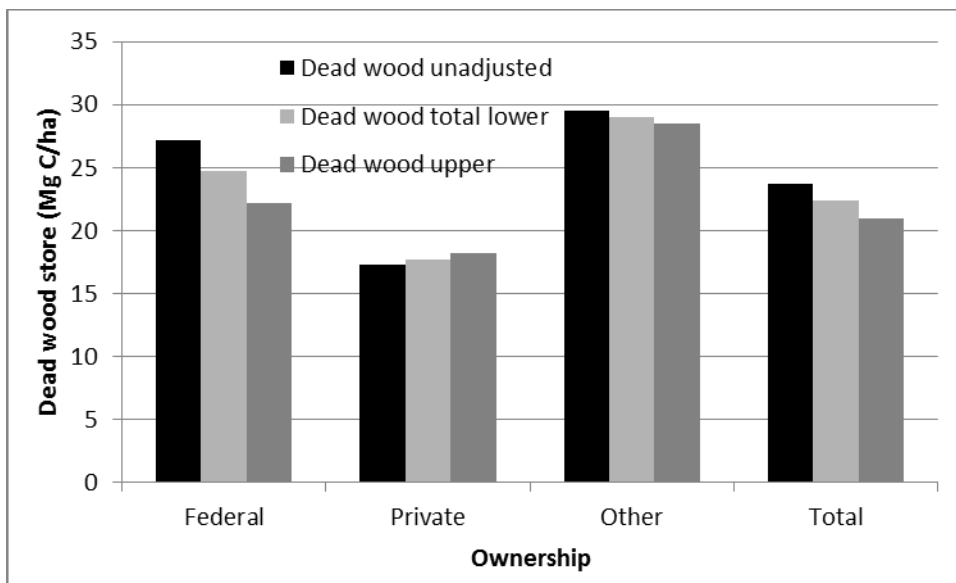


Figure 19. Stores of dead wood in Oregon’s forests. Lower and upper represent estimates adjusted for missing parts and decomposition losses related to fragmentation and respiration.

Although the potential exists to calculate the net change in dead wood stores in Oregon’s forests, this has yet to be done. Preliminary estimates from Dr. Fried of how downed dead wood was changing based on repeat measurements in FIA plots indicated that these stores were increasing on federal lands, but decreasing on private ones. However, without adding in the stores changes associated with standing dead trees, these estimates are incomplete. A previous estimate by Gray and Whittier (2014) indicated that on national forests there had been an increase in both the standing and downed dead wood pools in the 1995 to 2002 period with a total rate of increase of 0.26 Mg C/ha/y. If this trend has continued since, it strongly suggests that at least some of the mortality flows from live trees are resulting in a net accumulation of carbon in Oregon’s national forests. Dividing this rate of change by mortality losses of 0.67 Mg C/ha/y suggests that approximately 39% of the mortality is resulting in an increased dead wood store. Gray and Whittier (2014) noted that on national forest lands in which cutting had occurred, the amount of dead wood had declined (although they did not report the specific numbers).

An approximate mean retention time of dead wood can be calculated from the ratio of the store in dead wood to the input via natural mortality and harvest-related cutting. This indicated that the mean retention time of carbon in dead wood was at least 26 years (Figure 20). Although there was some variation among ownerships, the main difference appears to be related to the parts included. Considering just stems gave a range in mean retention time of 47 to 58 years. This would correspond to a decomposition rate of 1.7 to 2.1% per year. Including branches and roots gave a range in mean retention time of 26 to 30 years. This would correspond to a decomposition rate of 3.3 to 4% per year. Both sets of decomposition rates are within the range suggested by decomposition studies. More precise estimates could be made of both the mean retention time and decomposition rate if the change in these stores is determined from remeasurement data.

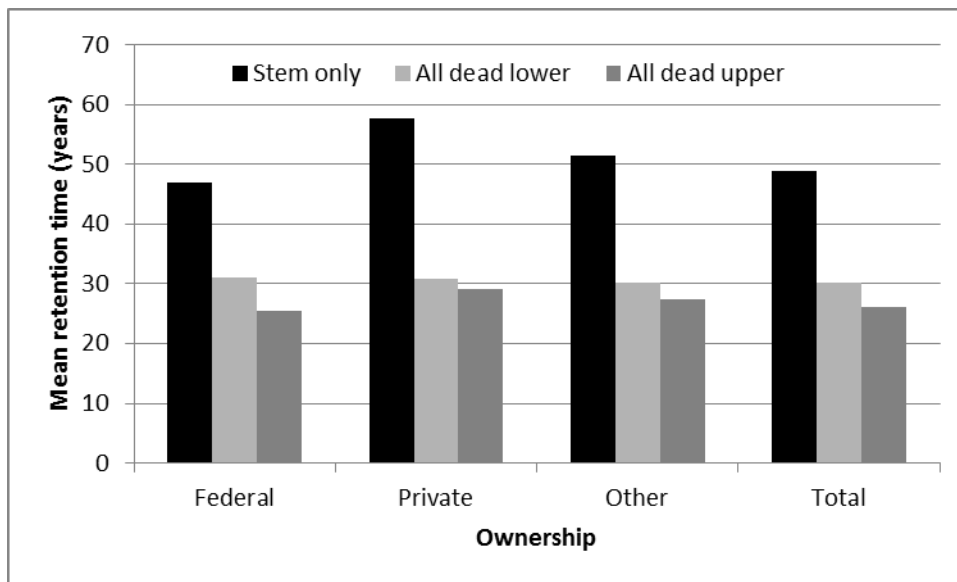


Figure 20. Mean retention time of dead wood in Oregon’s forests.

Forest floor

The estimate of forest floor carbon stores for Oregon’s forests was 171.8 Tg C. This is equivalent to 18% of the live aboveground store. Combined with dead wood, the forest floor estimates indicate that dead material of all sorts (stems, branches, leaves, roots) is 427 to 444 Tg C.

The amount of forest floor carbon store contributed by ownership largely followed that of the proportional area of ownerships (Figure 21). In terms of carbon density, that is store per unit area, ownerships were similar, although federal and private ownerships (13.9 versus 14.0 Mg C/ha) are lower than other ownerships (16.9 Mg C/ha) (Figure 22).

If one assumes that an equivalent of 10 to 15% of the forest floor is lost each year, the approximate flow of carbon out of this pool equaled 17.2 to 25.8 Tg C/y. Assuming a litterfall rate of 1.2 to 1.9 Mg C/ha/y suggested that 14.6 to 23.1 Tg C/y was dying and being input into this pool. These estimates of flows into the forest floor are relatively close, but their uncertainty is large enough that the net change in this store cannot be estimated. Therefore knowing the net rate of change of this pool as determined by field measures would be essential to resolve the direction and size of forest floor stores changes.

Changes in the forest floor are likely to be small, but to get some sense of the possible effect on the total net change one can assume that this store could or decrease or increase 5 to 10% in a decade. That would suggest a possible loss or gain of 0.8 to 1.6 Tg C/y.

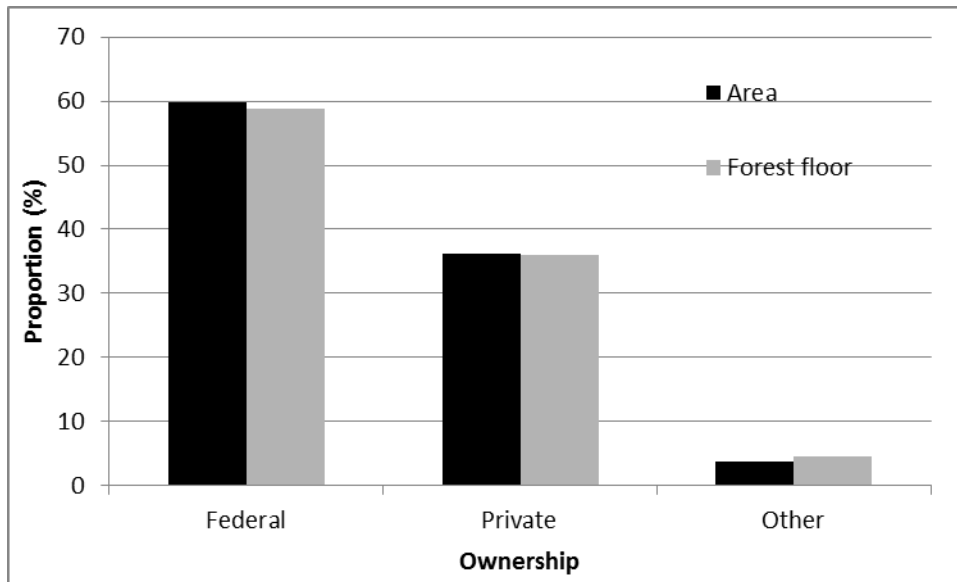


Figure 21. Proportional contribution of area and forest floor stores contributed by different ownerships of Oregon’s forests.

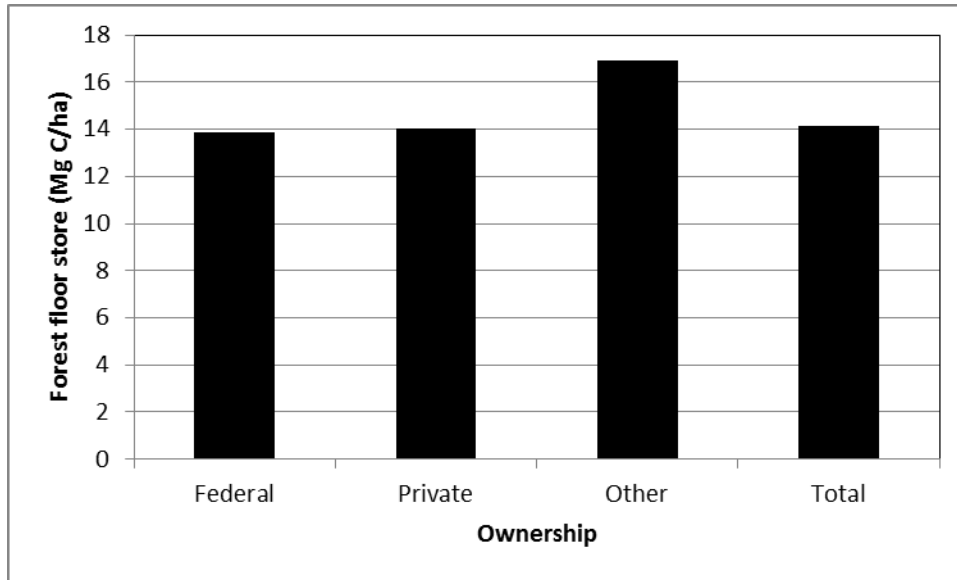


Figure 22. Store of carbon in the forest floor by ownership of Oregon's forests.

Mineral Soil

The mineral soil carbon store, adjusted to remove the forest floor, was estimated to be 1078.1 Tg C. This largely distributed as expected for area of ownership, although private and other ownerships contributed slightly more than area would suggest (Figure 23). Mineral soil carbon density was lowest on federal ownerships (82 MgC/ha), intermediate on private ownerships (97.9 MgC/ha), and highest for other ownerships (104.7 MgC/ha) (Figure 24). These trends are probably more related to the type of soil and environment than the type of management undertaken on these lands.

There is no indication from these data on the degree mineral soil stores are changing over time. Given the average retention time of mineral soil carbon is on the order of 100 years (meaning an equivalent of 1% is lost each year) and amount of store estimated would lead to an approximate loss of 11 Tg C/y. Assuming that half the input via fine root death was equivalent to the input into mineral soil would indicate an input to mineral soil of 7 to 12 Tg C/y; the upper value being roughly equal to the estimated outflow due to decomposition. As with the forest floor, these estimates of flows in and out are not certain enough to estimate a net change in mineral soil carbon stores.

Losses or gains due to changes in management, disturbance, or climatic regimes might be on the order of a 10 to 20% change over a 100 year period. That would indicate that if negative changes were occurring in all of Oregon's forests that approximately 1 to 2 Tg C/y would be lost to the atmosphere. This is equivalent to approximately 10 to 20% of the net change in total live carbon stores. To equal the net change in total live carbon stores, losses from mineral soil carbon would have to be 5 to 10-fold higher, values that are unrealistically high as they imply either large cumulative proportional losses (essentially 100% loss over a 100 year period) or timeframes that are too short (10 years for a cumulative proportional loss of 10%).

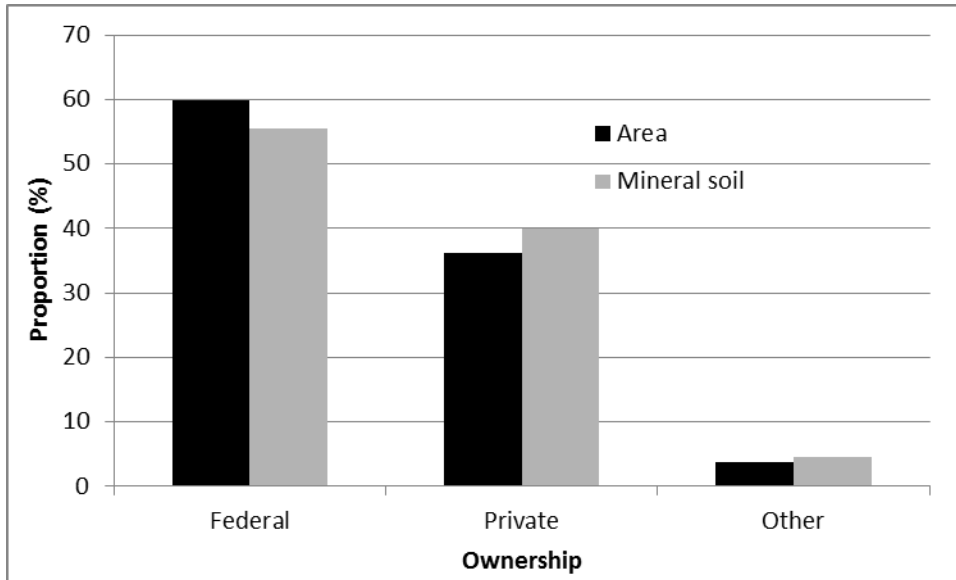


Figure 23. Proportional store of mineral soil carbon for different ownerships of Oregon's forests.

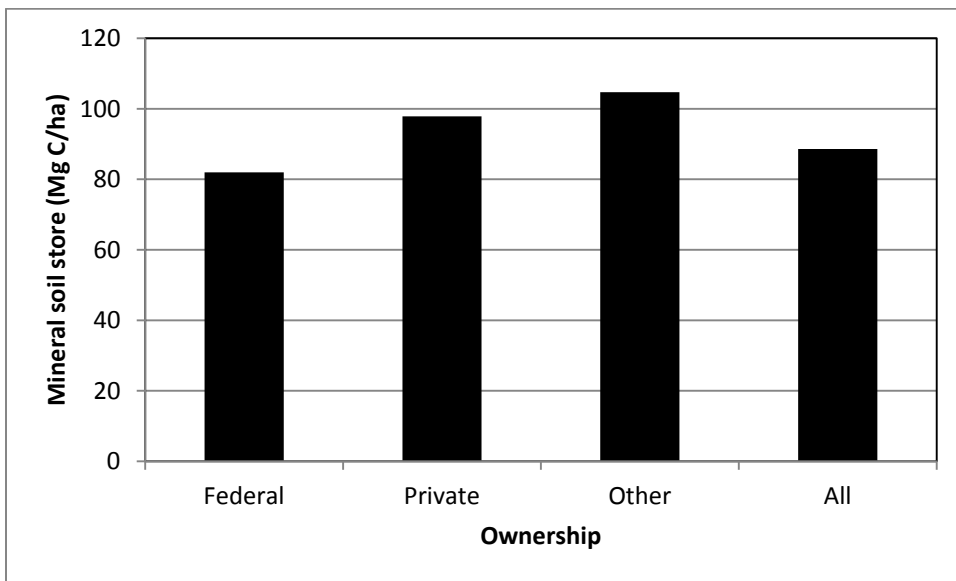


Figure 24. Store of carbon in mineral soils of Oregon's forests to a depth of 1 m.

Total stores

The total amount of carbon stored in Oregon's forest was estimated to range between 2571 and 2829 Tg C if the carbon associated with stump roots is ignored. If that pool is added then the total would have ranged between 2582 and 2865 Tg C. Proportionally, slightly more was contributed by federal ownerships than area would suggest, whereas slightly less was contributed by private ownerships (Figure 25). Other ownerships also contributed more than area alone would suggest.

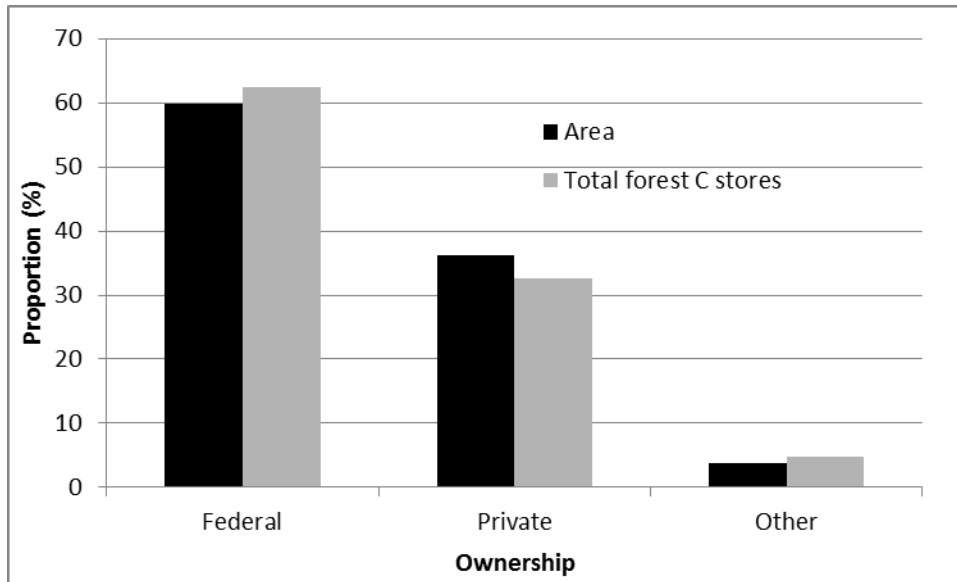


Figure 25. Proportion of total carbon stores in forests contributed by different ownerships.

The carbon density varied among ownerships, with the highest for ownerships other than federal or private (264 to 291 Mg C/ha, respectively) (Figure 26). 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). The higher total carbon density for other ownerships was caused by the fact these lands had consistently high stores in most of the pools estimated. The small difference between federal and private ownerships is largely related to the lower mineral soil on the former compared to the latter. That is, the lower stores of live and snag carbon were countered to some degree by higher mineral soil carbon stores on private lands and vice versa.

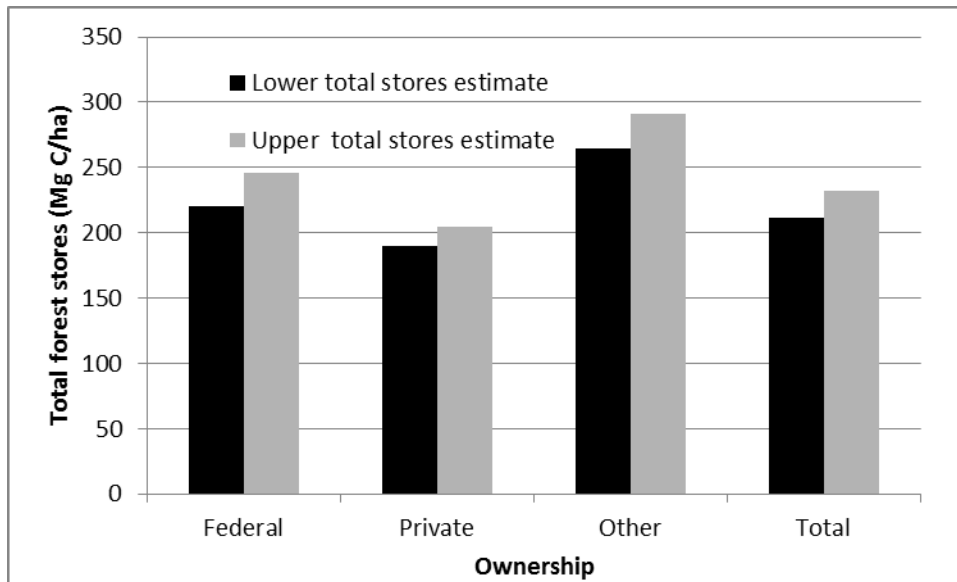


Figure 26. Carbon density in all forms in Oregon’s forests by ownership.

The majority of carbon stored in Oregon’s forests was in mineral soil (42%), but an almost equal share was stored in live carbon (41%) (Figure 27). Dead wood and forest floor stores comprised the remaining 17%. This cannot be taken to mean that changes in the latter pools are unimportant (see net change section below). That is because while these pools are relatively small, a substantial amount of carbon is flowing through them and small changes in their inputs or mean carbon retention time could lead to large net changes that would have consequence for total forest change. For example, the forest floor comprises 7% of the stores, but the carbon flow going into this pool roughly equals that going into live wood.

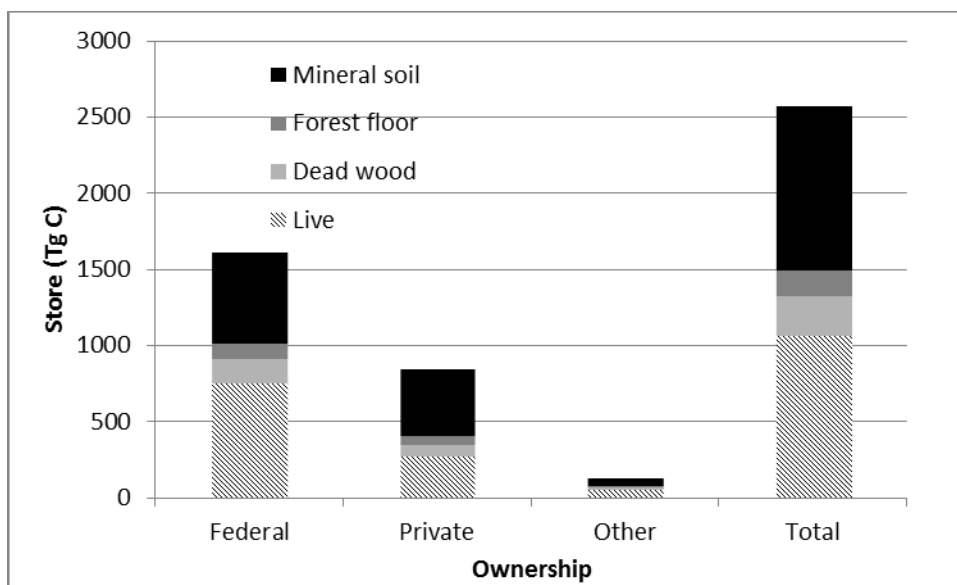


Figure 27. Stores of carbon in Oregon’s forests by major pool and ownership.

Net Balance

Given the lack of information about how pools other than live carbon are changing, it is difficult to determine the exact net carbon balance of Oregon’s forests. However, one can use a series of scenarios to test whether the sign and order of magnitude of the net change is likely to change if additional information is added. Based on the changes in aboveground live carbon stores the net change in stores was estimated to be 8.2 Tg C/y. Adding in the associated changes in belowground live stores increased the net change in live stores to between 9.4 and 9.8 Tg C/y. If none of the other pools were changing this also would be the net change in the forest. However, it is highly unlikely that the other pools are constant in size. As indicated above, past examinations of the national forests in the PNW suggest that dead wood pools are also increasing. If all forests are increasing at this relative rate, then an additional 2.4 Tg C/y might be added. However, it is more likely that dead wood on private ownerships is either steady or decreasing. If we assume that dead wood is only increasing on federal lands, then an additional 1.9 Tg C should be added to the net change estimate. This would be equal to an increase of less than 1% per year in the dead wood pool. Changes in the forest floor are likely to be small, but a decrease or increase 5 to 10% in a decade suggests a possible loss or gain of 0.8 to 1.6 Tg C. One can do similar calculation for mineral soil changes but in this case a 10 to 20% change in a century. This would indicate a possible annual change in this pool of 1 to 2 Tg C/y. Combining terms to get the lowest and highest estimate gave a range of 5.8 to 15.8 Tg C/y (Figure 28). This would be equivalent to 21.3 to 57.9 Tg/y of carbon dioxide.

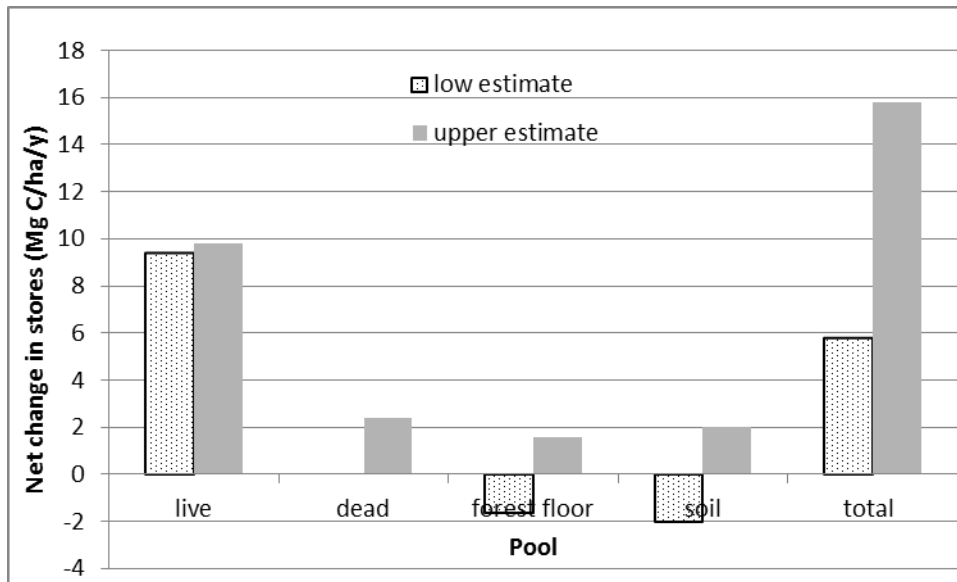


Figure 28. Range of possible net changes in stores in Oregon’s forests using the low and high estimates of net changes for various pools.

If one added in the change in products stores estimated from a process-based model of solid wood products (equivalent to 14% of the stem harvest removals or 1.13 Tg C/y), then the total net uptake of

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Oregon's forest sector would have been 6.9 to 16.9 Tg C/y. That would be equivalent of 25 to 62 Tg carbon dioxide/y. It should be noted that changes in the solid wood products differ by ownerships. The process-based model of wood products suggests that solid wood products associated with federal ownerships are decreasing at a rate of 0.58 Tg C/y; that is harvests are not sufficient to maintain the solid wood products pools associated with these lands. In contrast those associated with private lands are increasing 1.34 Tg C/y. Those with other ownerships are also increasing, but at a rate of 0.22 Tg C/y.

Next Steps

The analysis undertaken in this report could be improved significantly in several ways.

A more complete and precise estimate of stores could be made by:

Accounting for belowground live carbon using species-specific belowground:aboveground ratios.

Adjusting standing dead stores to account for losses in volume and density that are associated with decomposition. Approximate adjustments were made here; more precise ones could be made using the raw data and information about species and decay class.

Estimating the store associated with stump and their roots from field data on the number and size of stumps. While the FIA does not inventory all stumps, harvest records of individual trees in plots might allow one to estimate inputs to this pool that when combined with information about decomposition rates would allow a more precise estimate to be made. Preliminary estimates suggested this is potentially a non-trivial pool of dead carbon.

Use a mineral soils database that does not include the forest floor so that double counting is more precisely eliminated.

A more complete and precise estimate of flow and net balances could be made by:

Directly computing the net rate of change of dead wood pools from FIA data. Given that standing dead and dead and downed pools are re inventoried in FIA plots, a more precise estimate of change is potentially available. While the change in these pools is not as precisely estimated as the live aboveground pools (which are based on tagged trees), they are sufficient to provide reliable estimates of net change.

Gathering more information about the rates of litterfall, decomposition of materials such as leaves, wood, and roots. For pools in which inputs are not directly determined, this information allows one to estimate mean retention time and possible rates of change of stores.

Better estimates of the average life-span of carbon in mineral soil would constrain estimates of the carbon leaving this pool.

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References

Gray, A.N. and Whittier, T.R., 2014. Carbon stocks and changes on Pacific Northwest national forests and the role of disturbance, management, and growth. *Forest ecology and management*, 328, pp.167-178.

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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. 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%. 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.