SCIENCE REVIEW ON CARBON, MANAGED FORESTS AND WOOD PRODUCTS

Oregon Forest Resources Institute

CARBON IN OREGON'S MANAGED FORESTS

Mike Cloughesy and Edie Sonne Hall, Technical Editors

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Carbon in Oregon's Managed Forests

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CHAPTER 1: Overview of Carbon and Forests

Mike Cloughesy, Oregon Forest Resources Institute, and Edie Sonne Hall, Three Trees Consulting

1.0 Introduction – background

1.0.1 Who is OFRI?

The mission of the Oregon Forest Resources Institute (OFRI) is to educate Oregonians about forests and forest management, and to inform the forest sector about the public's expectations about forest management. OFRI was established in 1991 by the Oregon Legislature and is structured as a commodity commission. OFRI is funded by a forest products harvest tax, which is paid by timber owners or timber purchasers when timber is harvested. OFRI is overseen by a board with members representing diverse interests and appointed by the State Forester.

1.0.2 Why we are doing this science report?

This report, *Carbon in Oregon's Managed Forests,* synthesizes the current information on carbon sequestration and storage in Oregon's working forests and in harvested wood products. Managed forests, also called working forests, are those forestlands that are managed for producing timber products and other benefits. These include private, state and some federal lands. Research shows that most Oregonians are concerned about climate change. They recognize that climate change is happening, driven to a large part by human-caused (anthropogenic) increases in the concentration of greenhouse gases in the atmosphere from the combustion of fossil fuels, and that average temperatures around the planet have been increasing as a result.

The public is less familiar with the role forest ecosystems and harvested wood products play in the planet's carbon cycle, and that with appropriate long-term management these forest-related elements have the potential to mitigate some of the increase in atmospheric carbon dioxide. This report is intended to help fill that gap in knowledge: to help the public, and especially policymakers, understand how managed forests and harvested wood products sequester and store carbon. This is especially important as policymakers in Oregon and other states consider legislative and administrative changes to address climate change.

1.0.3 What is in this science report?

This science report consists of five content-rich chapters that follow this introductory chapter.

1.0.3.1 Carbon sequestration and storage in Oregon's forests – Chapter 2

This chapter summarizes the recent report by the Oregon Department of Forestry (ODF) and the USDA Forest Service's Forestry Inventory and Analysis (FIA) program. The report examines carbon storage and fluxes in Oregon's forests, by eco-regions and ownership groups (Christensen et al. 2019a).

The chapter gives an overview of FIA forest inventory sampling design, and describes how carbon storage and flux estimates are calculated by carbon pool, including:

- live trees
- dead trees
- belowground live and dead tree roots
- down woody debris
- above- and belowground understory vegetation
- forest floor
- organic soil carbon

1.0.3.2 Managing forests to increase their carbon storage, productivity and resiliency – Chapter 3

This chapter summarizes the literature on forest management as a way to increase carbon sequestration and storage in our forests. It gives an overview of forest sector strategies to reduce carbon emissions and increase carbon removals from the atmosphere, including:

- avoiding carbon emissions from forests that could occur through conversion to other land uses
- avoiding carbon emissions from uncharacteristically high-severity fires
- avoiding carbon emissions from uncharacteristic mortality due to pests, pathogens and disease
- increasing forest area
- increasing carbon sequestration and storage in existing forests
- increasing carbon storage in wood products

1.0.3.3 The role of wood products and biomass energy in carbon stores and emissions – Chapter 4

This chapter summarizes the literature on the role of wood products in carbon storage, and the role of biomass energy in reducing carbon emissions. It includes a discussion of:

- environmental impacts of building with wood
- life cycle analysis (LCA) of wood products
- LCA of buildings
- carbon displacement efficiency of using wood products
- choosing energy sources to reduce carbon emissions
- energy use in wood products production
- substitution effects on carbon emissions

1.0.3.4 Harvested wood products carbon accounting – Chapter 5

This chapter examines the carbon impacts of long-term harvested wood products storage, as well as accounting methodologies used to assess this, including:

- description of IPCC/EPA historical methodology
- description of 100-year-average methodology

1.0.3.5 Current and future markets for carbon and co-benefits from Oregon forests – Chapter 6

This chapter summarizes the scientific literature on the role of carbon markets in mitigating climate change. It includes a discussion of:

- regulatory, voluntary and incentive programs
- current and future market mechanisms to mitigate climate change
- international mechanisms
- federal and state policy mechanisms
- private sector mechanisms, including corporate policies and regulated and voluntary carbon offset registries

1.0.4 Forests, carbon and climate change – a synthesis of science findings

In 2006 OFRI published its first science report on carbon and forests. Under the leadership of Hal Salwasser, former dean of the Oregon State University College of Forestry, OFRI published *Forests, Carbon and Climate Change – A Synthesis of Science Findings* (OFRI 2006). This publication looked at three important relationships: forests and carbon; carbon and climate change; and climate change and forests.

Forests, Carbon and Climate Change included these chapters:

- Introduction: Forests, Carbon and Climate – Continual Change and Many Possibilities
- Atmospheric Carbon Dioxide
- Climate Change at Multiple Scales
- Global Warming: A Skeptic's View
- Forest Management Strategies for Carbon Storage
- Keeping Land in Forest
- Using Wood Products to Reduce Global Warming
- Emerging Markets for Carbon Stored by Northwest Forests
- Carbon Accounting: Determining Carbon Offsets from Forest Projects
- Governor's Global Warming Initiative

The current report focuses more narrowly on current scientific information related to the relationship between forests and carbon in Oregon's working forests and harvested wood products. The relationships between carbon and climate change and climate change and forests are still important, but are thought to be well documented and summarized in the existing literature.

1.0.5 What has changed since 2006?

A great deal of scientific literature on carbon and managed forests has been published since 2006, as evidenced by the bibliographies in this report. Major studies on the carbon sequestration of Oregon forests and harvested wood products have been commissioned by the Oregon Legislature and the Oregon Department of Forestry. Major studies on the role of forest management in increasing carbon storage, including multiple reports by the Intergovernmental Panel on Climate Change (IPCC) and a report by the United Nations Food and Agriculture Organization, *Forests for a Low-carbon Future* (FAO 2016). New attention is also being paid to using wood products in buildings to replace more energy-intensive products, resulting in growing North American adoption of mass timber for commercial and multifamily residential buildings.

The general public's perception of climate change and Oregon's forest sector has also evolved since 2006. Surveys on values and beliefs commissioned by OFRI have shown that most Oregonians believe climate change is happening, and that anthropogenic greenhouse gases are partly responsible. However, recent focus groups in Portland and Bend show that people don't understand the link between forests/wood products and atmospheric carbon (DHM Research 2019). The public is unfamiliar with much of the information that describes the role of trees in the carbon cycle.

The public policy arena has also changed greatly since 2006. The Oregon Legislature devoted a great deal of effort and on cap and trade bills in the 2019 and 2020 legislative sessions.

1.1 Why carbon sequestration and storage in forests and forest products is important

1.1.1 Climate change is happening

The IPCC has updated its earlier reports and confirmed that climate change is happening: The hottest years on record have occurred in the past decade; unusual weather events such hurricanes and droughts have been increasing; ice caps on Greenland and Antarctica, as well as montane glaciers, are decreasing in size; and the ocean is warming. It reports that the rate of change is increasing, and earlier modeling predictions are thought to be accurate (IPCC 2019).

1.1.2 Climate change impacts forests

Much research has been done on the impacts of changing climate on forests. This research has been summarized by Oliver et al. (2016) in a Pacific Northwest Research Station Science Findings titled *Predicting the Unpredictable: Potential Climate Change Impacts on Vegetation in the Pacific Northwest*.

Key findings include:

- New vegetation communities may be produced as plant species differ in their responses to climate change.
- Drought, fire and insect outbreaks will likely drive vegetation change.
- Climate influences vary greatly among ecosystems, and responses will differ; alpine and subalpine forests appear to be the most at-risk.
- Longer fire seasons start earlier and end later than historical averages.
- Forest types are changing on the margins.
- Exotic-plant invasions are possibly increasing.

1.1.3 Forests sequester carbon

Carbon cycling and storage is one of the ecosystem services forests provide. Others include biodiversity, clean water, wildlife habitat, recreation and timber. There can be trade-offs in managing to maximize a single ecosystem service, though many are complementary to each other. Some forest managers consider carbon storage in the forest to be the most important ecosystem service, while others consider timber for wood products the most important.

What do we mean by working forests, and why are they important? The term “working forest” has come to be used as a label for forests, usually privately owned, that are managed primarily for economic purposes and rely on harvesting wood products to produce revenue. Working forests also produce revenue from non-timber forest products, recreation and, more recently, carbon. However, timber production remains the primary source of revenue. While this report is focused on working forests, it presents findings that are relevant to all forest types and ownerships in Oregon, many of which do not manage primary for producing timber.

1.1.3.1 Timber volume and growth

One simple way to estimate the carbon sequestered in a forest is by looking at the standing volume and growth of forest trees. The USDA Forest Service periodically estimates forest volume and growth through the FIA program. The carbon changes on these national long-term plots are summarized annually in the EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA 2020). Every 10 years, as part of the Resources Planning Act (RPA) Assessment, the Forest Service publishes a summary of forest volume and growth statistics for all 50 states. The latest version covers data for 2017 (Oswalt et al. 2019).

Oregon's forests grow the most wood in the U.S., according to this latest comparison. Total or gross growth in Oregon's forest is about 2.7 billion cubic feet (10.7 billion board feet) per year (Oswalt et al. 2019). Net annual growth, a commonly used measure of timber productivity, is defined as the average annual growth in tree volume, less the volume lost through mortality. Mortality is the average annual net volume of trees dying over a given period due to natural causes such as fire, insects and diseases. Even with a mortality of about 545,000 cubic feet per year, Oregon's net annual growth of more than 2.1 billion cubic feet still leads the country.

Table 1.1 shows the net annual timber growth (from Table 36, Oswalt et al. 2019) and the net volume of timber on timberland (from Table 17, Oswalt et al. 2019) for the 10 states with the highest net annual growth rates. The years required to regrow the standing timber volume at the annual growth rate has also been calculated for each state listed, and for the nation as a whole.

Table 1.1: Top 10 states for net annual growth and net volume of timber on timberland.

State	**Net annual timber growth** (billion cubic feet/year)	**Net volume of timber** (billion cubic feet)	**Years needed to regrow standing timber volume**
Oregon	2.13	94.90	45.6
Georgia	1.82	43.70	24.0
Alabama	1.81	38.61	21.3
Mississippi	1.71	34.00	19.9
Washington	1.58	71.95	45.5
North Carolina	1.55	40.73	26.3
South Carolina	1.20	25.39	21.2
Arkansas	1.09	30.61	28.1
Virginia	1.06	36.05	34.0
California	1.05	72.54	69.1
Total – United States	**25.01**	**1,116.01**	**44.6**

Oregon has both the highest net annual timber growth rate and the highest net volume of standing timber. Timberlands are defined as forestland capable of productively growing commercial-grade timber (Bechtold and Patterson 2005). This means Oregon has a lot of stored carbon in its forests, and is sequestering carbon at a high rate.

It is interesting to note that many Southern U.S. states have annual growth rates that are comparable to rates in the Pacific Northwest; however, the volumes of standing timber are much lower, generally because the trees are smaller and younger. The Southern states also generally have "times to regrow their standing timber volume" in the twenties, which equates to their typical industrial rotation age. Oregon and Washington have "times to regrow" in the mid-forties, also near the industrial rotation age in those states. This indicates that Southern forests tend to be much younger than their Northwest counterparts, and explains the lower amount of wood or carbon stored in their forests.

1.1.3.2 Carbon sequestered in our forests

Forest ecosystems are the earth's greatest source of terrestrial carbon storage, and forests in the Pacific Northwest stand out as having high rates of growth and carbon storage. Carbon stored in forests can offset a significant portion of a state's other emissions. For example, Table 1.2 shows a comparison for the Western states, put together by the Forest Climate Working Group (Cleaves 2019). Table 1.2 shows the mean annual carbon sequestration in forests from 2010-17, the total CO_2 emissions from fossil fuel in 2016, and the percentage of CO_2 emissions offset by forest carbon sequestration for the 11 contiguous Western states and the U.S. as a whole.

Table 1.2: Western states' forest carbon sequestration and CO_2 fossil fuel emissions, in MMT CO_2e.

Western state	**Forest carbon sequestration mean 2010-17** (MMT CO_2e)	**Forest carbon sequestration as percent of U.S. total**	**2016 CO_2 emissions, fossil fuels** (MMT CO_2e)	**2016 CO_2 emissions as percent of U.S. total**	**Forest carbon sequestration as percent of CO_2 emissions**
Arizona	- 7.6	- 1.3%	86.8	1.7%	-8.8%
California	13.7	2.4%	366.4	7.0%	3.7%
Colorado	- 6.2	- 1.1%	88.5	1.7%	-7.0%
Idaho	22.0	3.8%	18.4	0.4%	119.6%
Montana	13.8	2.4%	30.8	0.6%	44.8%
Nevada	- 0.5	- 0.1%	36.7	0.7%	-1.4%
New Mexico	11.8	2.1%	48.7	0.9%	24.2%
Oregon	**34.3**	**6.0%**	**37.9**	**0.7%**	**90.5%**
Utah	0.7	0.1%	58.5	1.1%	1.2%
Washington	**27.2**	**4.7%**	**81.1**	**1.6%**	**33.5%**
Wyoming	- 29.0	- 5.0%	60.7	1.2%	-47.8%
Total – U.S.	**575.2**	**100%**	**5,216.7**	**100%**	**11.0%**

Table 1.2 shows carbon sequestered or emitted as CO_2 equivalents (CO_2e). See section 1.7.2 for a discussion of CO_2 equivalents. [1]

Column B of Table 1.2 includes both positive and negative numbers. Negative numbers in Column B represent carbon being emitted to the atmosphere from the forests. This a sign that more carbon is being emitted to the atmosphere due to wildfire, decay or harvest than is being removed through growth. Positive numbers represent carbon being removed or sequestered from the atmosphere. Most states have positive numbers in Column B. However, some of the Rocky Mountain states have negative numbers in Column B, indicating that the forests in these states are net emitters of carbon. Much of the carbon emission is due to wildfires. Column D shows fossil fuel emissions, and are all positive numbers.

Oregon forests are sequestering more carbon than any other state in the West, and our CO_2 emissions from burning fossil fuels are comparatively very small. For example, Washington and Oregon have similarly high rates of carbon sequestration, and account for only 4.7% and 6%, respectively, of the carbon sequestered by forests nationally. However, Washington produces more than twice the total CO_2 emissions of Oregon.

Another way to look at this is in Column F of Table 1.2, where carbon sequestration in a state's forests is shown as a percent of CO_2 emissions. Oregon's forests sequester an amount of carbon dioxide equivalent to over 90% of the CO_2 emitted in burning fossil fuels in the state; Idaho's forests sequester nearly 120% of the CO_2 emitted; and Washington's forests sequester the equivalent of about 33% of the CO_2 emitted. Except for Montana, the rest of the Western states sequester less than 25% of the CO_2 they emit; the states whose forests are actually net emitters of CO_2 end up with a negative percent of CO_2 emissions.

Chapter 2 reports on a study by the USDA Forest Service's Forest Inventory and Analysis (FIA) program to document carbon sequestration and storage in Oregon's forests (Christensen et al. 2019a). The FIA program has also completed similar studies in California and Washington (Christensen et al. 2018 and 2019b). These studies show that both sequestration (also called flux) and storage (also called stocks) are similar in Oregon and California, but that Washington has lower stocks and nearly half the rate of flux than the other two West Coast states. The decline in California's forest carbon flux or sequestration from 27.2 MMT CO_2e/year (Table 1.3) to 13.7 MMT CO_2e/year (Table 1.2) may be explained by the recent large fires.

Table 1.3: Carbon stocks and annual carbon flux by states for the Pacific region.

State	**Total forest carbon storage** (MMT C)	**Annual carbon sequestration** (MMT CO_2e/year)
Oregon	3,240	30.9
Washington	2,718	16.0
California	3,256	27.2

[1] Note: These sequestration numbers differ slightly from the numbers found in Chapter 2, as a function of when the FIA measurements were compiled.

1.1.4 Wood products store carbon

Working forests on private land annually produce about 88% of the timber harvest in Oregon's forests (OFRI 2019a). Oregon's timber harvest has averaged about 3.9 billion board feet per year for the past five years. This harvested timber is used to make many different wood products (Simmons et al. 2016), including softwood and hardwood lumber and plywood.

The harvest of timber and the production of wood products are important drivers in Oregon's economy, particularly in rural areas (OFRI 2019b). The Oregon forest sector employs about 61,000 people, or about 3% of the state's workforce. However, in rural counties the forest sector employs more than 10% of the workforce.

Oregon leads the country in production of lumber and plywood, and has for many decades (OFRI 2019a). In turn, the U.S. is one of the world's most significant sources of wood products: In 2018 the U.S. supplied 19% of the world's industrial roundwood, making Oregon's production globally significant (FAO 2018).

Wood products are important not only because they store carbon, but also because they can be used as an alternate to other materials that use more energy and generate more emissions during their production. This is known as the benefit of substitution. FAO estimates the global increase in wood-product carbon storage is estimated to be 421 MMT CO_2e, and when wood is used rather than other building materials this avoids emissions of 483 MMT CO_2e annually (FAO 2016).

In Chapter 4 (section 4.1), we see an estimate of 10.2 MMT CO_2e/year stored in Oregon-produced lumber and plywood in 2017. We also see in section 4.2.2 that an additional amount of carbon – approximately 5.5% more than is stored in lumber – is stored in coproducts made from the residue of lumber production. A Department of Energy study (Puettmann 2019) estimates that 65% of these coproducts are made into long-term coproducts such as particleboard that store carbon. In Table 1.4, we use these estimates to calculate an estimate of the total stored carbon in Oregon lumber, plywood and long-term coproducts to be 18.6 MMT CO_2e/year for 2017.

Table 1.4: Estimate of carbon stored in lumber, plywood and co-products, 2017.

Logs with bark	Lumber and plywood	Coproducts	Long-term coproducts	Lumber and plywood plus long-term coproducts
100%	44%	56%	.65 (56%) = 36%	80%
23.2 MMT CO_2e/year	10.2 MMT CO_2e/year	13.0 MMT CO_2e/year	8.4 MMT CO_2e/year	18.6 MMT CO_2e/year

In Chapter 2 (Table 2.6) we see that total removal of carbon from the forest ecosystem by timber harvest is estimated at 1.21 MT CO_2e per acre per year. This 1.21 MT CO_2e times 29.656 million acres equals 35.9 MMT CO_2e /year in total removals.

The storage of 10.2 MMT CO_2e/year in lumber and plywood, and the total of 18.6 MMT CO_2e/year in total wood products, would increase the annual carbon sequestration for Oregon (reported in Table 1.3

above at 30.9 MMT CO_2e/year) to either 40.4 MMT CO_2e/year for lumber and plywood or 48.8 MMT CO_2e/year for all wood products.

We summarize these estimates of carbon sequestration and storage in Table 1.5.

Table 1.5: Carbon sequestration in forests and storage in wood products.

	Oregon lumber and plywood	**Oregon lumber and plywood plus long-term coproducts**
Removals from forest	35.9 MMT CO_2e/year	35.9 MMT CO_2e/year
Wood products storage	10.2 MMT CO_2e/year	18.6 MMT CO_2e/year
Percent of removals	28.4%	51.8%
Net forest carbon sequestration	30.9 MMT CO_2e/year	30.9 MMT CO_2e/year
Total carbon storage	41.1 MMT CO_2e/year	49.5 MMT CO_2e/year

Another way to think about this is that the 35.9 MMT CO_2e/year in total removals are partially offset by the 10.2 to 18.6 MMT CO_2e/year stored in wood products. This equates to 28% to 52% of the removed carbon being sequestered in wood products each year in Oregon.

Long-term storage of carbon in forests and wood products is not permanent. As shown in Chapter 3, long-term storage of carbon in forests can be uncertain. In Chapter 5, we see that long-term storage of carbon in wood products is also uncertain, but there are metrics available to make it predictable

Harvesting timber to be made into wood products is not the only, or even the best, choice for working forests. However, it is the dominant choice of most private forest owners in Oregon, and it's important that carbon stored in wood products is appropriately recognized in the state's carbon policies.

1.2 The process of carbon sequestration in trees and forests

Through the process of photosynthesis, trees take in CO_2 from the atmosphere as all plants do, storing the carbon and releasing oxygen to the atmosphere. Joseph Priestly, an English scientist and philosopher, discovered the miracle of photosynthesis in the 1770s, through two famous "bell jar" experiments. In the first, he placed a lit candle inside a sealed glass jar and observed that the flame eventually burned out before the wick was gone. He then placed a plant beside the candle; the candle again burned out, but after a few days was able to be relit. He conducted a similar experiment with mice and observed that the mouse without the plant died, but the mouse with the plant lived. He wrote, "I have been so happy, as by accident to have hit upon a method of restoring air, which has been injured by the burning of candles, and to have discovered at least one of the restoratives which nature employs for this purpose. It is *vegetation*." (Priestley 1790)

Although the science is not new, it can be hard to understand how carbon in the atmosphere moves into trees and forests. How can carbon in a gaseous form in atmospheric CO_2 become carbon in solid form in the wood of trees and then wood products? The following is a brief discussion of the underlying science.

1.2.1 Photosynthesis

Photosynthesis is the process plants use to take CO_2 from the atmosphere. The magic takes place in chloroplasts in the leaves and needles of trees. In the process, carbon dioxide plus water plus energy from light produces glucose, a simple sugar, and oxygen. The balanced chemical equation looks like this: $6\ CO_2 + 6\ H_20 + (\text{energy}) \rightarrow C_6H_{12}O_6 + 6\ O_2$

The simplified version of the photosynthesis equation is shown in Figure 1.1

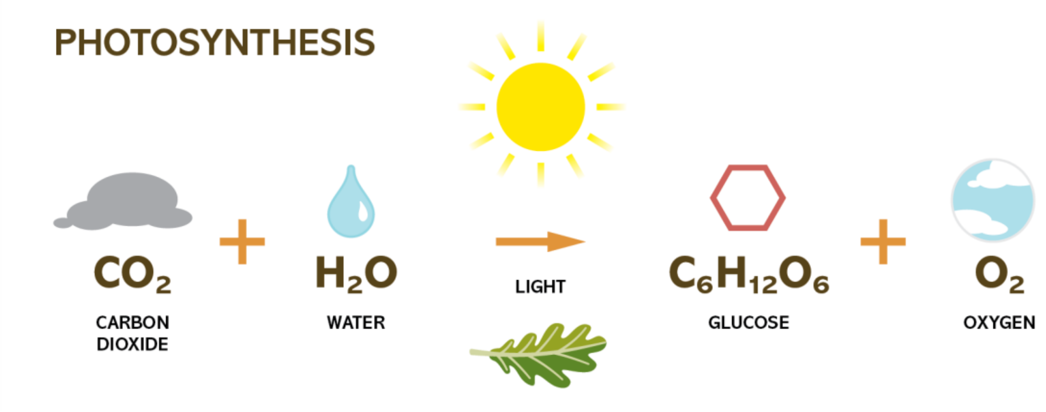

Figure 1.1: Photosynthesis equation simplified.

The carbon dioxide comes from the atmosphere, where it is plentiful. The water comes from the soil and is brought to the leaves via transpiration that pulls the water through the tree's sapwood from the roots to the leaves. The energy, of course, comes from sunlight. The tree uses the glucose to make wood, as discussed below. The oxygen is released to the atmosphere.

Figure 1.2 shows a graphical representation of the process of photosynthesis in a tree and a leaf.

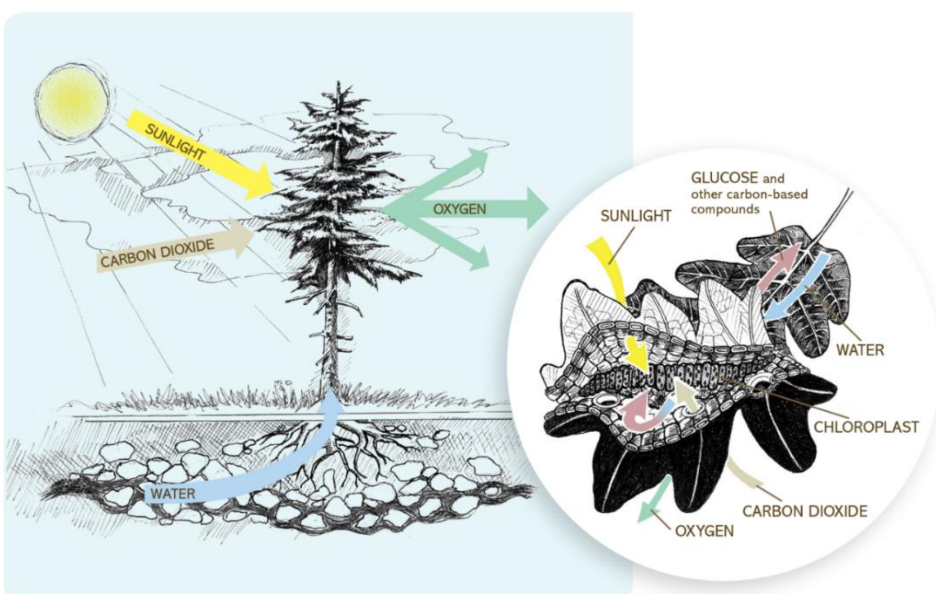

Figure 1.2: Photosynthesis in a tree and a leaf.

1.2.2 Carbon storage

Carbon is stored in trees and forests from the glucose produced by photosynthesis. Glucose moves through a tree's inner bark or "phloem" to where it is needed for growth. (We recognize it as sap.) In the growing parts of the tree's cambium, this simple sugar is transformed into three complex carbohydrates: cellulose, hemicellulose and lignin. These three compounds make up the cells of wood. Cellulose is the principal structural matrix of plants, and as such is most abundant organic (carbon-containing) compound in the world.

Thus, through photosynthesis carbon from the atmosphere is transformed into wood, which contains carbon, hydrogen and oxygen in a stable, solid and durable form. The layers of the trunk, from outside in, are shown in Figure 1.3.

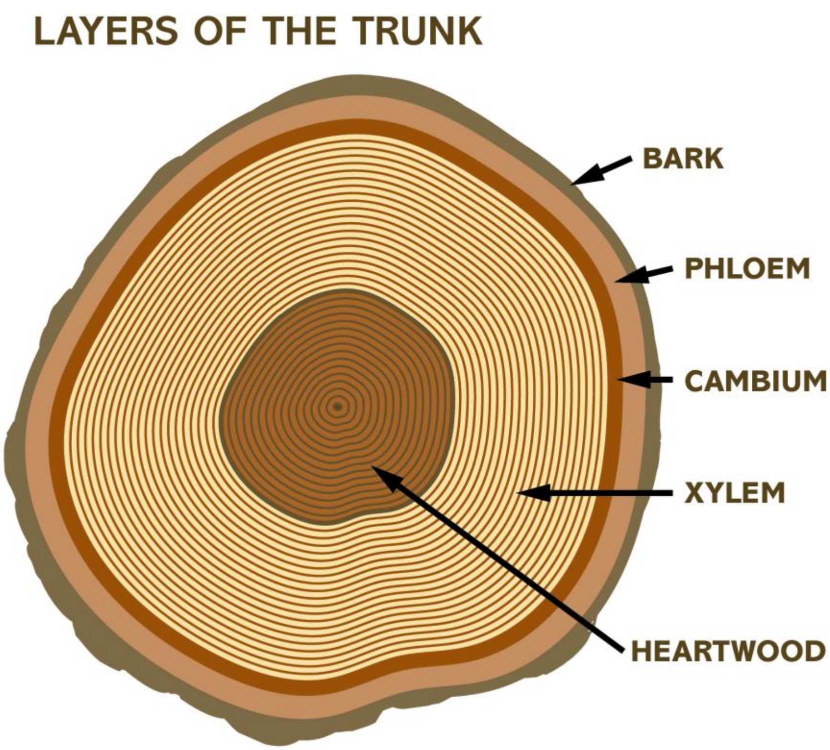

Figure 1.3: **The layers of the tree trunk.**

Bark protects the tree, and heartwood supports the tree. The other three layers are important to tree growth and development as well as carbon storage:

- The phloem or inner bark is responsible for moving sugar made in photosynthesis to various parts of the tree.
- The cambium, a narrow layer of cells found between the inner bark and the sapwood, is the site of actual wood formation. Cambium cells divide laterally to cause trees to grow in diameter. New phloem cells are laid down on the outside and new xylem cells are laid down on the inside.
- The xylem or sapwood is responsible for transporting water and nutrients from the soil to the leaves and other parts of the trees where they are needed.

1.2.3 Carbon is released from trees and forests through respiration

While trees are growing, they take in CO_2 and release oxygen through photosynthesis. But trees – and forests – also do the opposite: a process called respiration, in which trees take in oxygen and release CO_2. This occurs to some extent during a tree's life, but then takes over as a tree decays and dies. Respiration is the process through which plants turn glucose and oxygen into water, carbon dioxide and energy. The balanced chemical equation looks like this:

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$ + ATP (energy).

It is important to note that CO_2 is released during respiration. In discussing photosynthesis relative to climate change, it's also important to consider *net* photosynthesis; that is, photosynthesis minus respiration. Research indicates that higher CO_2 in the atmosphere increases photosynthesis. However, higher temperatures increase respiration.

1.3 Main findings from Chapters 2-6

The following summaries of Chapters 2-6 take material directly from those chapters. Sources are not always listed in order, to keep from repeating the literature cited from those chapters in this chapter. Readers should be able to easily identify the references used in the appropriate chapters.

1.3.1 Carbon sequestration and storage in Oregon's forests – Chapter 2

The USDA Forest Service's Forest Inventory and Analysis (FIA) program has recently completed a comprehensive analysis of Oregon's forest carbon stocks and flux in partnership with the Oregon Department of Forestry (Christensen et al. 2019a). Chapter 2 summarizes the results of this analysis.

Oregon's 30 million acres of forestland currently store 3.2 ± 0.03 billion metric tons (BMT) of carbon in all pools, including forest floor and forest soils, across all ownerships. National forests store over half of the total carbon (52%) and comprise just under half of the state's forestland (47%), while privately owned forests store 30% of the total carbon and account for 36% of the forestland. Forests owned by state and local government store 4.5% of the total carbon and comprise 3.9% of the forestland.

The greatest proportion of Oregon's forest carbon stocks are found in the forests of the western ecoregions, with the Western Cascades and the Oregon Coast Range ecoregions accounting for over half of Oregon's forest carbon stocks (52%). Douglas-fir forest types make up about 47% of Oregon's total forest carbon stocks, followed by fir/spruce/mountain hemlock forests and ponderosa pine forest types.

The rate of annual growth in Oregon's live forest vegetation carbon pools exceeds annual losses, with annual growth of living vegetation sequestering carbon at a rate of about 37.9 ± 5.8 MMT CO_2e/year, while non-living vegetation, including standing dead trees, dead roots and down wood as fallen logs or other decaying woody material, is losing CO_2e to the atmosphere or to other forest ecosystem pools at a rate of 7.3 ± 2.1 MMT CO_2e/year, making an annual net vegetation flux of 30.5 ± 3.8 MMT CO_2e/year.

Per acre, Oregon's forest lands are net-sequestering an average of 1.0 ± 0.4 MT CO_2e/acre/year. This includes gross growth minus removals (harvest) and mortality (fire, insects and disease, or natural/other). Private corporate lands harvest the most per acre and have the least amount of mortality, while National Forests experience the most loss of carbon per acre due to mortality.

1.3.2 Managing forests to increase their carbon storage, productivity and resiliency – Chapter 3

Given the capacity of forests and forest products to capture and store carbon, the forest sector is frequently discussed as an important element of reducing atmospheric carbon. Forests both sequester and emit carbon dioxide, through both natural and human drivers, making their contributions hard to separate.

International research communities have long discussed the role forests can play in mitigating climate change. Detailed summaries of the latest research and recommendations are compiled by the Intergovernmental Panel on Climate Change (IPCC), and they acknowledge multiple strategies for carbon in forests and forest products. Forest management strategies can be separated into two broad categories: 1) Reduce emissions – put less carbon dioxide (either biogenic or fossil fuel) into the atmosphere; and 2) Increase sequestration – take more carbon dioxide out of the atmosphere.

The strategies specific to Oregon's forest sector are summarized below.

Avoid emissions from land conversion – IPCC has identified a potential reduction of 0.41-0.58 BMT CO_2e/year in emissions by reducing land conversion away from forests, and Fargione et al. (2018) estimates the United States could save 39 MMT CO_2e/year by reducing forest conversion. Oregon's land-use laws have placed strict limits on conversion in lands zoned as resource lands, which has resulted in less conversion relative to some other states, such as Washington.. Strategies to reduce conversion include preferential tax programs and voluntary incentives such as conservation easements and transfer of development rights, as well as landowner stewardship and assistance programs that help make forest ownership more feasible.

Reduce emissions by reducing risk of fire, disease and mortality – Disturbances including extreme weather events, drought, fire, tornadoes, heat waves and ice storms are a natural part of the forest cycle, though many are predicted to increase in frequency and intensity as a result of climate change (IPCC 2019). In Oregon, the biggest disturbances impacting forests are fire, insects and drought, and there is evidence that these disturbances are increasing in frequency and intensity relative to historic levels. Fires not only reduce carbon storage potential through damage to trees, but also diminish the pools of stored carbon. Management strategies that focus on creating healthy, resilient forests can lower the risk of high-severity burns, which create the most damage to existing trees. Globally, IPCC estimates 0.48-8.1 BMT CO_2e/year in emissions savings from better fire management for resiliency (IPCC 2019). Across the United States, Fargione et al. (2018) estimate carbon savings of approximately 18 MMT CO_2e/year through removal of small-diameter trees and/or prescribed burning in overstocked forests with high fire frequency. In Oregon, these are generally limited to forests on the eastern side of the Cascade Mountains or in southwest Oregon.

As with fire, insects and disease are natural phenomena that can cause large-scale transformations in species composition, forest productivity and carbon stocks. Climate change can exacerbate impacts of pests and disease by increasing the likelihood of pest survival, with warmer winters and reduced tree resistance resulting from drought-induced stress. The USDA Forest Service predicts that 81 million acres of U.S. forests are at risk of losing at least 25% of their basal area in the next 15 years due to insects or disease, without management intervention. This correlates to a reduction of 21 MMT C/year (77 MMT CO_2e/year) in live biomass in the next 15 years. Oregon has a high risk of the following pests and diseases: western spruce budworm and balsam woolly adelgid in northeastern Oregon; root disease, western spruce budworm and Douglas-fir beetle in north central Oregon; mountain pine beetle and western pine beetle in south central Oregon; and Swiss needle cast on the Oregon Coast, among others. Generally speaking, a management strategy that focuses on stand resilience includes matching species and stocking to sites, retaining or increasing species diversity, and forest thinning to maintain forest vigor.

Increased sequestration by expanding forest area – Globally, expanding forest area through afforestation/reforestation has the most potential to increase the contribution from the land sink, ranging from 0.5-10.2 BMT CO_2e/year (IPCC 2019). U.S. reforestation potential is also the largest pathway, with estimates of 300 MMT CO_2e/year, though activity cost per ton of CO_2 is predicted to be high if fully implemented (Fargione et al. 2018). Planting trees indiscriminately does not necessarily help mitigate global warming, and in fact could do the opposite if, for example, planted trees replace natural peatlands or areas where forests are not suitable. Reforestation has the most potential for co-benefits (biodiversity, water filtration, flood control, enhanced soil fertility) on lands that have been previously forested. In Oregon, these include riparian buffers of farmland and pasture, understocked stands in non-fire-prone areas, lands not naturally regenerating after high-severity fire, and urban reforestation. Oregon has a few mechanisms already in place to fund reforestation efforts, though all could be expanded. For example, Oregon's Emergency Forest Restoration Program (EFRP), which provides payments to nonindustrial private landowners to conduct restoration efforts, including tree planting, after a natural disaster; and Oregon's Conservation Reserve Enhancement Program (CREP), which incentivizes tree planting in agriculture riparian buffers.

Increase carbon in existing forests and products through silviculture – Globally, improved forest management has the potential to mitigate 0.4-2.1 BMT CO_2e/year (IPCC 2019). In the United States, Fargione et al. (2018) estimate improved forest management could sequester up to an additional 260 MMT CO_2e/year. Forest management strategies include increasing the interval between harvests or decreasing harvest intensity; increasing forest growth through intensive management such as planting with improved seedlings, fertilization and stocking control; and increasing soil carbon. Increasing carbon storage in existing forests can sometimes decrease harvest levels, which impacts carbon storage in harvested wood products and potential emissions from using more energy-intensive materials instead of wood (IPCC 2019). Strategies for increasing carbon stocks depend on initial site conditions, site productivity, risk of disturbance, product end-uses and substitution factors.

Carbon sequestration should be looked at as one of many ecosystem services provided by forests, including biodiversity, clean water and timber. Carbon strategies that focus on creating healthy, resilient productive forests offer the greatest alignment between climate benefit and other ecosystem services.

1.3.3 The role of wood products and biomass energy in carbon stores and emissions – Chapter 4

Oregon plays a major role in providing a wood resource for manufacturing the many different products used in residential construction and mass timber buildings. Nearly 88% of Oregon's timber harvest is further processed into lumber and plywood at facilities in the state (Simmons et al. 2016), providing enough lumber to make 374,000 single-family homes. This 5.6 MMT of wood contains one-half carbon by weight, so it stores 2.8 MMT of carbon, equal to 10.2 MMT CO_2 equivalent.

For the past 20 years there has been extensive documentation on the environmental impacts of producing wood products "from cradle to gate" (e.g., www.corrim.org). These are assessed through ISO standards that govern life cycle assessment (LCA), a data-based process of quantifying energy and raw material requirements, air emissions, waterborne effluents, solid waste and other environmental releases occurring within the system boundaries. Differing results of LCAs are often due to misalignments of system boundaries, leading to inaccurate comparisons with other materials. A common impact indicator reported in LCAs is global warming potential (GWP). GWP, reported in CO_2e, is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon, relative to carbon dioxide. The lower the CO_2e, the less greenhouse gases emitted. According to the most recent LCAs of the five major solid-wood products produced in the Pacific Northwest (PNW), softwood lumber has the least amount of GWP (61 kg CO_2e), followed by glulam (136 kg CO_2e), softwood plywood (176 kg CO_2e), laminated veneer lumber (LVL) (254 Kg CO_2e) and engineered I-joist (295 kg CO_2e)(CORRIM 2017). The higher carbon emissions in the engineered wood are the result of higher energy use in processing due to pressing and resin production. These results include forest management and harvesting emissions, transportation and manufacturing, and are expressed per cubic meter (m^3) of product. Transportation accounts for between 5% and 17% of total GWP, and doubling hauling distance has the potential to increase emissions accordingly.

Wood can be compared to other materials by comparing assemblies (e.g., wall or floor components) that perform the same function. For wall components, substituting a PNW wood stud component for a PNW steel stud component displaces 1.54 units of carbon emission for every unit of carbon used in the wood stud, including the biofuel used for processing. Comparing a PNW wood stud and plywood sheathing wall assembly with a concrete block assembly results in a higher efficiency (3.94), due to mortar required for concrete walls to meet West Coast seismic codes. Floor displacement efficiencies are generally higher than for walls, given the higher-gauge steel that must be used. However, the addition of a common floor cover to steel or wood joists adds a large amount of carbon content (wood fiber) to both, lowering the efficiency displacement in all assembly scenarios.

Wood contains biogenic carbon, and the accounting of biogenic carbon follows the requirements set out in the UL 2018 PCR Part A, which follows requirements in ISO 29130 (ISO 2017). Per these requirements, biogenic carbon enters the product system (is removed) as a primary or secondary material. When forest carbon stocks are found to be stable, the carbon removal is considered a negative emission and is characterized with a factor of -1 unit CO_2e/unit CO_2 of biogenic carbon in calculating the GWP. The biogenic carbon leaves the system (is emitted) as a product or coproduct(s), and/or is directly emitted to the atmosphere when combusted, and is characterized with a factor of +1 kg CO_2e/kg CO_2 of biogenic carbon in calculating the GWP. These mass flows of biogenic carbon from and to nature are listed in the life cycle inventory (LCI) and expressed in units of CO_2. Emissions other than CO_2 associated with biomass combustion (e.g., methane or nitrogen oxides) are characterized by their specific radiative forcing factors, and are included in calculating the GWP.

When a log is harvested and sent to a sawmill in the Pacific Northwest, 43% of the CO_2e harvested ends up in lumber, 45% goes to producing long-term coproducts such as particle board, and 12% goes into the biofuel used for energy to produce the lumber, displacing the use of fossil fuels.

Within the U.S. softwood lumber industry, approximately 22 MMT of dry mill residues are produced annually. Oregon's primary wood product facilities produced around 5.7 MMT of dry residues. Simmons et al. (2019) reported that less than 1% of the residues were not utilized, which means nearly all the residues are not considered waste and go to produce products such as pulp and paper (62%) and to produce on-site energy. In recent surveys of PNW mills, 22% of the residues produced during lumber manufacturing were used internally for energy, while PNW plywood mills in similar surveys reported utilizing 35% of their dry residues to produce heat energy for log conditioning, veneer drying and panel pressing. Energy from using renewable wood residues for both lumber and plywood, combined for western Oregon and western Washington, is estimated at 43 billion MJ (millijoules) annually, which is equivalent to 1,240 million liters (328 million gallons) of gasoline – which equates to more than 8 billion passenger miles.

We are just beginning to assess the environmental impacts of mass timber components and their environmental performance in buildings. The carbon mitigation potential of mass timber buildings goes well beyond the embodied carbon from cradle to gate. We will not know the true carbon benefit until we assess the different applications for mass timber in high-rise buildings that can displace steel and concrete, the potential for a longer service life, and the opportunities for reuse and recycling. One can expect many innovations in how a mass timber wall or floor can be used, given that its use is still at the beginning of a technology-driven learning curve. Early studies show a reduction in total embodied carbon, compared to similar concrete designs.

1.3.4 Harvested wood product carbon accounting – Chapter 5

When trees are harvested and used to produce wood products, carbon remains stored in the product while in use and in landfills. The length of time of storage varies by end-use and wood product. There is a long history of literature devoted to this subject and well-established methods for measuring and monitoring harvest wood product (HWP) carbon storage over time. This chapter summarizes basic accounting principles and data from the US Forest Service (USFS) that are used to estimate changes in yearly HWP carbon pools. It provides an overview of the IPCC/EPA National HWP reporting methods used by the United States and presents options for smaller scale assessments that include the IPCC method and the 100-year average "California Forest Protocol"(CFPP) approach.

USFS has detailed statistics on the distribution for each type of wood product across various end-uses as well as the decay functions indicating how quickly products go out of each end use and the fraction of that material that goes into a landfill and their associated decay rates. The USFS uses these HWP data inputs and national level data on wood and paper product production, import and exports to report national level estimates of carbon stored in HWP using guidelines from the IPCC. These estimates are reported annually by the US EPA to the United Nations as required under the United Nations Framework Convention on Climate Change (Skog 2008, US EPA 2020). 100-year average accounting, like the IPCC method for national estimates, uses the same decay functions for tracking HWP carbon fate over 100 years. The 100-year average accounting method was developed to be used by forest landowners, wood products producers, or wood product users who currently produce and use wood products and for project-level accounting, such as in the California Forest Offset Protocol (Hoover et al 2014; CARB 2015).

The 100-year method when applied to U.S. wood products production each year gives the future estimated climate impact of carbon storage in those products. The IPCC/EPA National HWP accounting estimates change in carbon stored in a current year given the current year additions, the dispositions of and emissions from past years products from the products in use and solid waste disposal pools. The IPCC method will yield bigger values compared to the 100-year average when applied to a region that is increasing harvest over time. However, the IPCC method could report negative values if applied to a region that has reduced timber harvest over time, reflecting less HWP entering the carbon pool than leaving through decay and end of service life. Both reporting methods are valid and tell interesting stories. When possible, they should both be done to understand the historic contribution of the HWP pool in an area as well as the current contributions.

The state of Oregon has recently commissioned an Oregon Harvested Wood Products Carbon Inventory 1906-2017 (Morgan et al. 2020 in press), which will report HWP carbon using the IPCC/EPA National HWP accounting method.

Note: The Oregon Harvested Wood Products Carbon Inventory report (Morgan et al. 2020 in press) was still in draft form at the time of this report's publication. This report will be updated online when the Oregon Harvested Wood Products Carbon Inventory report is finalized.

1.3.5 Current and future markets for carbon and co-benefits from Oregon forests – Chapter 6

Markets are an important mechanism to address mitigating climate change. Market-based mechanisms offer flexible instruments designed to achieve environmental goals at a lower cost and in a more flexible manner than traditional regulatory measures.

There are three market mechanisms currently employed across the United States to mitigate climate change:

- Compliance emissions trading
- Voluntary emissions trading
- Incentive programs

Currently, there are two U.S. **compliance carbon markets**, one associated with California's Cap and Trade program and one associated with the Regional Greenhouse Gas Initiative (RGGI) that operates in Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island and Vermont.

The **voluntary carbon marketplace** encompasses all transactions of carbon offsets that are not purchased with the intent to surrender them into an active regulated carbon market. It does include offsets that are purchased with the intent to re-sell or retire to meet carbon-neutral or other environmental claims.

Incentive programs can be powerful mechanisms to drive behavior change. The U.S. federal government offers a range of incentives to forestland owners.

There are a range of **market mechanisms** from international to local levels being operated by governments and the private sector. International mechanisms include the UN Paris Agreement, the Clean Development Mechanism, the International Civil Aviation Organization, international shipping and cloud computing.

The United States Climate Alliance, founded in June 2017, is a bipartisan coalition of governors committed to reducing greenhouse gas emissions consistent with the goals of the Paris Agreement. Smart, coordinated state action can ensure that the United States continues to contribute to the global effort to address climate change. Oregon is a member of the United States Climate Alliance.

The Forest Climate Working Group is the nation's only forest-sector coalition to represent every aspect of U.S. forests' government agencies, landowners, forest products, conservation and wildlife groups, academics and carbon finance experts. It develops and advocates for federal, state and local policy mechanisms that will ensure U.S. forests contribute to mitigating climate change, as well as a source for information and data on the role of forests in mitigating climate change.

Carbon offset projects are one way carbon markets are accessed. A carbon offset project is a third-party-verified activity that either avoids an emission of greenhouse gases or sequesters carbon. A project must follow a set of rules contained in a protocol or methodology approved by the carbon program selected for use by the project proponent.

Carbon offset projects that sequester carbon include forestry, agricultural lands, grasslands and wetlands. All carbon offset projects must demonstrate that they are additional, real, measurable, verifiable and permanent. Each carbon program and its protocols vary in the methods used to demonstrate these attributes.

There are five widely recognized carbon registries operating in the United States. Each registry offers a range of protocols that can generate carbon offsets. These carbon registries include American Carbon Registry, California Air Resources Board, Climate Action Reserve, Gold Standard and Verified Carbon Standard.

Three types of forest projects qualify for offsets under the major carbon programs in the United States: reforestation, avoided conversion, and improved forest management. Forest projects are demonstrated in three Oregon cases: City of Astoria – Bear Creek Watershed Carbon Project; Green Diamond Resource Company – Klamath Forest Carbon Project; and Warm Springs Tribe – Forest Carbon Phase I Project.

1.4 An alternative view of forest management and carbon

Most of the studies cited in this report tell the story of the positive roles of active forest management, wood products and biomass energy in increasing carbon storage in our forests and reducing emissions of carbon dioxide and other greenhouse gases. But lest you think all scientists are of one mind, we want to make sure to mention a couple journal articles that take alternative viewpoints.

Law et al. (2018) examined strategies to mitigate carbon dioxide emissions through forestry activities and concluded that lengthening rotations on private lands and restricting harvest on public lands were the only activities that made large contributions to emission reductions. Reforestation, afforestation and fire prevention made smaller contributions. This view is not consistent with the conclusions reached in Chapter 3.

Law and Harmon (2011) reached many of the same conclusions in a review article discussing forest sector carbon management. They state, "The substitution of wood for more energy-intensive materials has probably been overestimated compared with cases in which additionality, permanence and saturation of wood building stores are considered. GHG emission policies will need to account for emissions associated with bioenergy." This view is not consistent with the conclusions reached in Chapter 4.

1.5 Summary

This *Carbon in Oregon's Managed Forests* report has been developed by OFRI to synthesize the current information on carbon sequestration and storage in Oregon's working forests and harvested wood products. Most Oregonians recognize that climate change is happening; that increasing levels of anthropogenic atmospheric carbon and other greenhouse gases are part of the cause; and that forests and harvested wood products can play a major role in keeping carbon out of the atmosphere.

The following conclusions have been shared in this chapter and those that follow:

Chapter 1 – Overview of carbon and forests

- Climate is changing.
- Climate change impacts forests.
- Forests sequester carbon.
- Oregon has both the highest net annual timber growth rate and the highest net volume of standing timber of any state in the country.
- Oregon forests are sequestering more carbon than any other state in the West, and our greenhouse gas emissions are comparatively very small.
- Wood products store carbon.
- As much as 52% of carbon removed from our forests in timber harvest is stored for the long term in wood products.
- Oregon's total net carbon flux is estimated to be between 41.1 and 49.5 MMT CO_2e/year, including the forest and harvested wood products pools.

Chapter 2 – Carbon sequestration and storage in Oregon's forests

- Oregon's total forest carbon stocks are estimated at 3,240 MMT C.
- The greatest forest carbon stock is found on USFS-managed land, and accounts for >50% of Oregon's forest carbon stock.
- The greatest forest carbon stocks are found in the Western Cascades and Coast Range ecoregions.
- The Douglas-fir forest type has the greatest concentration of carbon stocks, estimated at 47% of Oregon's forest carbon stock.
- Oregon's total forest net flux is estimated at 30.9 MMT CO_2e/year.
- Per acre, Oregon's forest lands are net sequestering an average 1.0 MT CO_2e/acre/year. This includes gross growth minus removals (harvest) and mortality (fire, insects and disease, or natural/other).
- Private corporate lands harvest the most per acre and have the least amount of mortality, while federal forests experience the most loss of carbon per acre due to mortality and have the lowest rate of harvest.

Chapter 3 – Managing forests to increase their carbon storage, productivity and resiliency

- Conversion of forest land to other uses is a source of carbon emission, and even with Oregon's strict land use laws, an estimated 2.5 MMT CO_2e/year are still being emitted due to forest conversion.
- Forest management that focuses on stand resilience can reduce carbon emissions from wildfire, disease and insects. This includes matching species and stocking to sites, retaining or increasing species diversity, and thinning to maintain forest vigor.

- Expanding forest area through afforestation/reforestation has the greatest potential globally and in the United States to increase carbon sequestration. Reforestation will have best climate outcomes on land that been previously forested. In Oregon, these include riparian buffers of farmland, pasture, understocked stands in non-fire prone areas, lands not naturally regenerating after high severity fire, and urban reforestation.
- Silvicultural strategies including lengthening rotations, genetic improvement, stocking control and fertilization have the potential to increase carbon in existing forests and products.

Chapter 4 – The role of wood products and biomass energy in carbon storage and emissions

- Oregon mills annually produce about 5.6 MMT of wood products, which contain one-half carbon by weight and thus store an estimated 2.8 MMT of carbon, equivalent to 10.2 MMT CO_2.
- Life cycle assessments (LCA) are data-based processes to quantify energy and raw material requirements and environmental releases during the manufacture of building products.
- Life cycle inventories (LCI) and life cycle impact assessments (LCIA) are developed during LCAs. The LCIA characterizes and assesses the raw material use and environmental releases identified in the LCI, sorting into impact categories such as global warming potential, acidification, eutrophication, ozone depletion and smog. According to the most recent LCAs of the five major solid-wood products produced in the PNW, softwood lumber has the least amount of Global Warming Potential (GWP) (61 kg CO_2e), followed by glulam (136 kg CO_2e), softwood plywood (176 kg CO_2e), laminated veneer lumber (LVL) (254 Kg CO_2e) and engineered I-joist (295 kg CO_2e).
- Wood can be measured against other materials by comparing individual components or building assemblies that perform the same function.
- Substituting a PNW wood stud component for a PNW steel stud component displaces 1.54 units of carbon emission for every unit of carbon used in the wood stud.
- Comparing a PNW wood stud and plywood wall assembly with a concrete block assembly results in a higher efficiency (3.94).
- A cradle-to-gate example of harvesting wood and producing 1 m^3 of softwood lumber shows that nearly 100% of the CO_2e contained in harvested logs was stored in lumber, long-term coproducts and the biofuel used for production.
- Oregon's primary wood product facilities produce around 5.7 MMT of dry residues. It is reported that less than 1% of the residues are not utilized, which means the residues are not considered waste and go to produce products such as pulp and paper (62%) and to on-site energy use.

Chapter 5 – Harvested wood products carbon accounting

- Methods are well-established to measure and monitor harvested wood product (HWP) carbon storage over time.
- The IPCC/EPA historical approach and the 100-year average are two established reporting systems, and they use the same data to create decay tables that track products in use and in landfills over 100 years.
- The state of Oregon has recently commissioned an Oregon Harvested Wood Products Carbon Inventory 1906-2017. This inventory calculates and reports Oregon data using the IPCC/EPA method. Our report will be updated to include this material when it is available.

Chapter 6 – Current and future markets for carbon and co-benefits from Oregon forests

- Market mechanisms currently employed across the United States to mitigate climate change include compliance emissions trading, voluntary emissions trading and incentive programs.
- Compliance carbon markets include the California Cap and Trade program and the Regional Greenhouse Gas Initiative (RGGI).
- There are a range of market mechanisms being operated by governments and the private sector, from international to local levels. International mechanisms include the UN Paris Agreement, the Clean Development Mechanism, the International Civil Aviation Organization, international shipping and cloud computing.
- States, through the U.S. Climate Alliance, are beginning to coordinate and increase actions that will create markets and incentivize actions to increase removal of carbon from the atmosphere and store it in forests and other natural and working landscapes.
- Carbon offset projects are one way carbon markets are accessed. Three types of forest projects qualify for offsets under the major carbon programs in the United States: reforestation, avoided conversion and improved forest management.
- There are active carbon offset projects in Oregon on city, tribal and private forestlands.

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Authors

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Advisory committee

- Andrew Yost (Oregon Department of Forestry)
- Katy Kavanagh (Oregon State University, College of Forestry)
- Taylor Lucey (USDA Forest Service)
- Jad Daley (American Forests)
- Cassie Phillips (Weyerhaeuser, retired)

1.7 Units of carbon measurement

Carbon is measured using different units in different types of literature. Scientific studies of forest carbon sequestration commonly use petagrams per hectare. Grey literature and public literature commonly use metric tons per acre. In order to make the information in this report meaningful to the largest audience, we are reporting our measurements in metric tons and metric tons per acre.

1.7.1 Metric tons carbon dioxide equivalent

Metric tons carbon dioxide equivalent (CO_2e) is used in this report, because it is the most common way atmospheric carbon is talked about.

To directly compare CO_2 emissions to atmospheric CO_2 levels, both sets of data can be converted to metric tons of CO_2. The CO_2 emissions data is commonly expressed in billion metric tons carbon (BMTC). This means only the carbon element of the carbon dioxide molecule has been included.

1.7.2 Carbon dioxide equivalents

One ton of carbon equals 3.667 tons of carbon dioxide. The atomic mass of carbon is 12, while the atomic mass of CO_2 is 44. Therefore, to convert from metric tons of carbon to metric tons of carbon dioxide, you simply multiply by 44/12. In other words, 1 metric ton of carbon equals 3.667 metric tons of carbon dioxide.

Other commonly used terms include:

- Petagrams = 1016 grams = 1 billion metric tons = 109 metric tons = 1 Gigatonne
- Teragram = 1013 grams = 1 million metric tons = 106 metric tons
- MT = metric tons
- MMT = million metric tons
- BMT = billion metric tons

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CHAPTER 2: Carbon Sequestration and Storage in Oregon's Forests

Glenn Christensen, USDA Forest Service, PNW Research Station, Portland, Oregon

2.0 Introduction – background

The USDA Forest Service's Forest Inventory and Analysis (FIA) program at the Pacific Northwest (PNW) Research Station recently completed a comprehensive analysis of Oregon's forest carbon stocks and flux, in partnership with the Oregon Department of Forestry and the Governor's Carbon Policy Office (Christensen et al. 2019). The report represents FIA plot measurements taken from 2001 through 2016, and can be found online at https://www.oregon.gov/ODF/ForestBenefits/Pages/ForestCarbonStudy.aspx. Results and discussion presented here are a summary of key findings taken from this most recent analysis of carbon found in Oregon's forest ecosystem. Carbon stocks transferred from the forest into other products, such as harvested wood products, are not included in this overview of Oregon's forest carbon.

2.1 Overview of FIA forest inventory sampling design, and how carbon storage and flux estimates are calculated by pool

2.1.1 The base FIA plot grid

In 2001 FIA established a nationally standardized "annual inventory." The sampling frame for this area was determined by a national layer of hexagons, each approximately 6,000 acres in size. Plot sample locations were identified within each hexagon in a manner sometimes referred to as "randomized systematic." In addition, in 2001 Region 6 National Forests began installing the annualized FIA inventory using the same procedures on their earlier Current Vegetation Survey (CVS) inventory plot locations, based on a square grid of plots – one for every 1,875 acres outside wilderness (Max et al. 1996). FIA has included this sample and the data collected for it in their databases, estimates and reports since 2001. Additional details of FIA's sampling methodology can be found in the above-referenced forest carbon report for Oregon. More information about the Forest Service's FIA program can be found on our homepage: https://www.fia.fs.fed.us/.

Using FIA's national annualized inventory design, the FIA's Pacific Northwest regional program, based out of the PNW Research Station in Portland, began a new inventory of *forestland* for Oregon in 2001. A complete sample of the state was established by installing 10% of the full set of 15,082 plots each year. This equates to a complete sample of all inventory plots in Oregon every 10 years. FIA completed the first full annualized inventory of Oregon forests in 2010. In 2011, FIA began re-measuring the same plot locations established in 2001, and as of 2016 had re-measured 60% of the initially installed plots.

All inventory estimates are based on the grid of plots, along with their classifications and measurements taken on them. The precision of the estimates is improved, however, by incorporating information from independent, ancillary data sets in a process referred to as "post-stratification" (MacLean 1972, Bechtold and Patterson 2005). Post-stratification is used in calculating sampling errors. These errors describe the uncertainty associated with sampling the forest (i.e., with plots) instead of measuring the entire population. Additional details on inventory design and estimation methods are provided in Bechtold and Patterson (2005) and Palmer et al. (2018). The latest PNW-FIA database, including documentation of the field plot protocol, can be found online at: https://www.fs.usda.gov/pnw/tools/pnw-fiadb-forest-inventory-and-analysis-database.

2.1.2 FIA inventory measurements as used for nationwide forest carbon reporting

The U.S. Environmental Protection Agency (US EPA) coordinates and compiles summaries and analyses by multiple agencies to produce the National Greenhouse Gas Inventory (NGHGI). The most recent published report provides national estimates of stocks and flux of greenhouse gases for 1990-2017 (US EPA 2019) (Table 2.1). Because FIA's inventory is based on empirical field measurements of carbon pools and uses algometric models that complement the field measurements, the NGHGI uses FIA's inventory as the core data set for forest carbon pools and follows IPCC guidance as closely as possible with available data sets.

Table 2.1: Carbon flux, stocks and pool defined.

Carbon flux – Flux describes the net change in carbon in one or more pools over a specific period of time, expressed as either a total or a rate (to distinguish change from carbon stocks), with a negative flux meaning a loss of carbon from the pool. Often expressed as an exchange with the atmosphere, not all carbon exchanges occur with the atmosphere (e.g., live trees convert to dead wood when they die).
Carbon stocks – The amount of physical carbon mass in one or more pools (categories) at one point in time.
Carbon pool – A specific component of the forest containing carbon (as carbon mass or CO_2e); e.g., live trees or down woody material.

Estimates compiled by FIA for the ODF report on Oregon's forest carbon stocks and flux differs from the NGHGI analysis in that some of the fluxes can be estimated from measurements available in Oregon, rather than models designed for national estimation, not attempting to model results back to 1990 for all lands. This report also uses regionally developed biomass equations instead of national models, and adjustments for decay and fragmentation of snags that differ from those used in the NGHGI.

2.1.3 How carbon stock estimates are calculated and pools are included

The amount of carbon mass physically present in Oregon's forests is estimated by the pool within which it is located; for example, carbon present in live trees. Total forest carbon is the summed total of all carbon pools. Estimating the amount of carbon present by pool uses measurements taken in the field by FIA crews whenever possible. If using measured values is not possible, estimates are derived using nationally accepted models as employed by the FIA program, such as estimating carbon in belowground roots. Specific forest carbon pools estimated for Oregon from FIA inventory measurements include:

- Live trees
- Standing dead trees (i.e., snags)
- Belowground live and dead roots

- Dead and down woody material on the forest floor (i.e., fallen branches and logs)
- Above- and belowground understory vegetation (i.e., shrub vegetation including roots)
- Forest floor (i.e., forest duff and litter)
- Soil carbon

Summarized from Christensen et al. 2019, Table 2.2 provides additional details for each carbon stock estimate by pool, as calculated from FIA field measurements.

Table 2.2: Detailed definition by forest carbon pool (Christensen et al. 2019)**.**

Aboveground live tree – Estimates of aboveground live-tree woody carbon were based on regional FIA equations of the sum of the bole, bark and branch biomass in metric tons for each tree measurement, multiplied by 0.5 (the carbon fraction of biomass) (Burrill et al. 2018). Bole biomass (ground to tip) was calculated from regional species-specific volume equations documented in Zhou and Hemstrom (2010) and species-specific wood density values documented in Burrill et al. (2018). Bark and branch biomass were calculated from regional species-specific equations selected from Means et al. (1994) and documented in Zhou and Hemstrom (2010), except that the red alder branch equation (Eqn. 16) used Snell and Little (1983), and Douglas-fir and red alder bark equations (Eqn. 8 and 20) used Means et al. (1994) equations 5 and 275, respectively. Most equations use both diameter at breast height (dbh) and height data, whereas a few bark and branch equations use diameter only. Foliage biomass was calculated using the Jenkins et al. (2003) ratios to total tree biomass as implemented in Woodall et al. (2011) and added to aboveground wood biomass before calculating aboveground live tree carbon. In contrast, the NGHGI estimates of live tree biomass are based on the "component ratio method" equations in Woodall et al. (2011). An expansion factor derived from the fixed-area plot size was used to convert individual tree carbon to an area basis (e.g., metric tons per acre).
Aboveground standing dead tree – Estimates of aboveground standing dead tree carbon followed the same procedures as for aboveground live trees, but with the following modifications. Gross volume from ground to tip was adjusted for broken tops by calculating the gross volume (to an intact "total" height estimated in the field or modeled using Barrett (2006) and the net volume to the broken "actual" height with a Flewelling (1994) taper equation for Douglas-fir. The proportion of net to gross volume from the Flewelling equation was applied to reduce the gross volume calculated for each tree. In addition, the biomass of all components (bole, bark and branch) was reduced for decay using the hardwood/softwood parameters in Harmon et al. (2011), Table 6. Standing dead biomass was further reduced to account for the tendency of bark and branches to be dropped from snags sooner than bole biomass; component reductions described in Harmon et al. (2011) were applied to further reduce bark and branch biomass. Biomass calculations in metric tons were multiplied by 0.5 to calculate carbon. In contrast, the NGHGI estimates of standing dead tree biomass are based on the equations in Woodall et al. (2011) and the species-specific decay-reduction factors in the table REF_SPECIES in Burrill et al. (2018). The species-level decay factors appear to be based on small data sets and are highly variable among similar species; the hardwood/softwood parameters seemed more reliable. Stumps are not included, and it is unlikely that they can be included in future inventories without substantial additional effort.

Belowground live and standing dead tree (i.e., roots) – Estimates of belowground biomass (i.e., coarse roots > 2 mm diameter) were based on the ratios for species-groups developed in Jenkins et al. (2003) as implemented in Woodall et al. (2011); i.e., adjusting the estimate by the ratio of the FIA volume-based estimate of bole biomass to the Jenkins equation-based estimate. Decay classes of standing dead trees were used to reduce belowground calculations using the species- and decay class-specific parameters in the REF_SPECIES table (Burrill et al. 2018); biomass calculations in metric tons were multiplied by 0.5 to calculate carbon.
Aboveground down wood – Estimates of carbon in down wood were based on the transect-intercept measurements of coarse wood (≥ 3 inches intersect diameter) and counts of fine wood (≥ 0.25 to < 3 inches diameter). Piles were not included, as the field estimates of pile density in the initial years of the inventory were unreliable. Biomass of coarse wood was calculated using the equations in Woodall and Monleon (2008) with wood density and decay-class reduction factors from the REF_SPECIES table (Burrill et al. 2018). For the smaller size classes of down wood ("fine wood") we followed the procedures in Woodall and Monleon (2008), where the fine wood piece counts in each size class are multiplied by a quadratic mean diameter (QMD) to calculate volume, and a wood density factor to calculate biomass, which is multiplied by 0.5 to calculate carbon. Parameters are specific to forest type group and available in REF_FOREST_TYPE_GROUP in the FIA database (FIADB) (Burrill et al. 2018).
Aboveground and belowground understory vegetation – Estimates of above- and belowground biomass and carbon of understory vegetation (which includes live trees < 1 inch in diameter) are based on the calculations from the U.S. Forest Carbon Budget Model (FORCARB2) (Smith et al. 2006), as populated in the FIADB. Calculations are based on FORCARB estimates of live-tree biomass, (calculated from forest type and stand age), and are highest at low levels of live tree biomass and decline slightly at higher levels. Dead understory vegetation is not included in estimates for this pool.
Forest floor – Estimates for carbon in the forest floor (i.e., duff and litter) use the same model used in the NGHGI, which was based on FIA Phase 3 data and predictor variables of location, elevation, forest type group, live tree carbon and some climate variables (Domke et al. 2016).
Soil – We estimated soil organic carbon stocks to a depth of 1 meter using the modeled estimates from Domke et al. (2017) as implemented in the latest NGHGI report. This model incorporated data from soil cores on FIA plots, with other national data sets and values comparing favorably to those calculated from FIA cores in Oregon.

2.1.4 How carbon flux estimates are calculated by pool

Unlike carbon stock calculations that estimate the mass of carbon physically present by pool in the forest, carbon flux estimates the amount and rate of gaseous carbon being emitted or sequestered by the forest. Estimates of carbon flux are reported in metric tons (MT) of carbon dioxide equivalent (CO_2e). Net changes in individual carbon pools are also shown in units of CO_2e, and are referred to as flux to provide insight into the components of change, even if there isn't a direct flux with the atmosphere (e.g., tree mortality, which is a conversion from live to dead wood that initially stays in the ecosystem). Carbon in wood can be converted to CO_2e by multiplying by 3.667.

Negative values indicate a loss from the pool (i.e., carbon transferred out of a pool exceeds inputs for the 10-year measurement period). Ranges in the text (i.e., ±) represent a 95% confidence interval (CI), while estimates in the tables report the sampling error (SE; CI = 1.96*SE).

Estimates of carbon stocks and net flux from the Oregon Forest Ecosystem Carbon Report as summarized in this report that are based on modeled attributes (e.g., belowground roots, soils), or estimates based on measured values but summarized for a small area or filtered set of specific criteria (e.g., carbon stocks for a single ownership and a small forested region), must be interpreted with caution. An estimate of error (SE and 95% CI) is provided as an interpretation aid and as a measure of confidence in each summarized result. The sampling error for modeled attributes does not account for a potentially much larger amount of error associated with the model itself. Additionally, modeled attributes are developed by estimating total carbon stocks, and not carbon change.

The growth, removals and mortality (i.e., GRM) approach, as defined nationally by FIA, was used to calculate the change and magnitude of carbon flux in the live tree pool by comparing measurements taken on the same set of plots and trees 10 years apart (Bechtold and Patterson 2005). This approach to calculate net annual live tree flux starts with gross tree growth and deducts total mortality and removals (i.e., harvest) in the time since the plots were initially measured 10 years earlier. All flux calculations were summarized based on plot classifications at time of initial measurement (e.g., owner, forest type, etc.), and are detailed by pool in Table 2.3.

Table 2.3. Flux by forest carbon pool (Christensen et al. 2019)**.**

Live trees – For live trees that died or were cut between measurements, growth equations were used to estimate tree diameter and height at the midpoint of the measurement interval and to calculate carbon at the time of death (Bechtold and Patterson 2005). New trees that grew into the sapling size class (≥ 1-inch diameter) between estimates were considered ingrowth (a component of growth). Live tree carbon was allocated into the components of change based on initial and re-measurement tree status, namely: growth, removals and mortality.
Standing dead trees – Change in carbon for standing dead trees was based on the difference in calculated carbon at each time period, and would include live tree carbon entering this pool through mortality as well as dead tree carbon leaving this pool through decay, transition to other pools or combustion; trees that fell over or were cut were assigned zero for the second measurement.
Belowground live and standing dead tree (i.e., roots) – Changes in belowground live and dead tree carbon (i.e., roots) were based on modeled estimates from each measurement.
Downed woody material – Changes in down wood carbon were estimated at the plot level. Changes in this pool include tree carbon entering this pool from live or standing dead pools, and carbon leaving this pool through decay, transition to other pools or combustion.
Understory vegetation – Changes in understory vegetation, above- and belowground, were based on modeled estimates (from live tree biomass) from each measurement.

Forest floor and soil – Flux was also calculated for forest floor and mineral soil carbon, based on the difference in modeled estimates for each plot at each measurement. While there is some confidence in the estimates of carbon stocks with the models used, their accuracy in estimating carbon flux in Oregon is unknown.

2.2 Carbon currently stored in Oregon's forests: 2007-16

Based on FIA-compiled inventory estimates from the 2007-16 reporting period, there are approximately 30 million acres of forestland across all ownerships in Oregon. Approximately 64% (19.0 million acres) of these forests are managed by federal agencies and state/local governments. This leaves 36% in private ownerships, divided between corporate forestlands of approximately 6.6 million acres and private individuals (including tribal ownerships) owning 4.1 million acres.

For the same 10-year reporting cycle (2007-16), FIA estimates there are 3.2 ± 0.03 billion metric tons of carbon stocks stored on forestland in all pools, including forest floor and forest soils, across all ownerships in Oregon. When comparing total stored carbon by ownership, there is a close relationship between the proportion of forestland area by ownership and total stored carbon. Differences in this relationship between ownerships are a reflection of current management priorities, forest policy, recent disturbances and the inherent productive ability of the land base. For example, the national forests are storing over half the carbon stocks (52%) and constitute just under half of the forestland base (47%) (Figure 2.1), while private ownerships store 30% of the carbon stocks and manage 36% of forestland. State and local governments store 4.5% of the carbon stocks and manage 3.9% of forestland.

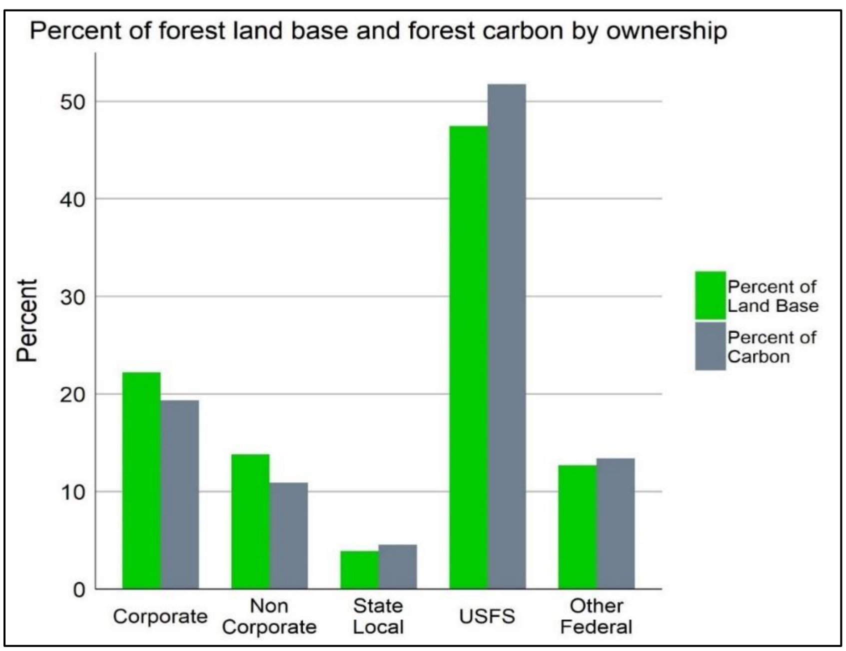

Figure 2.1: Oregon statewide percentage of forestland base and carbon stocks by ownership group, 2007-16 (Christensen et al. 2019).

FIA estimates that just under half of all Oregon's stored forest carbon is found belowground in organic soils (49%), and about a third is found aboveground in the live tree pool (32%) (Figure 2.2, Table 2.4). The remaining stored carbon is distributed among the dead trees (2%), roots (7%), down wood (5%), forest floor (4%) and understory vegetation pools (1%). By land status, approximately 82% of the forest carbon stores are found on unreserved timberland, with about 12% found within areas reserved from timber harvest (Figure 2.3). Less productive unreserved forest land accounts for the remaining 6% of carbon stores.

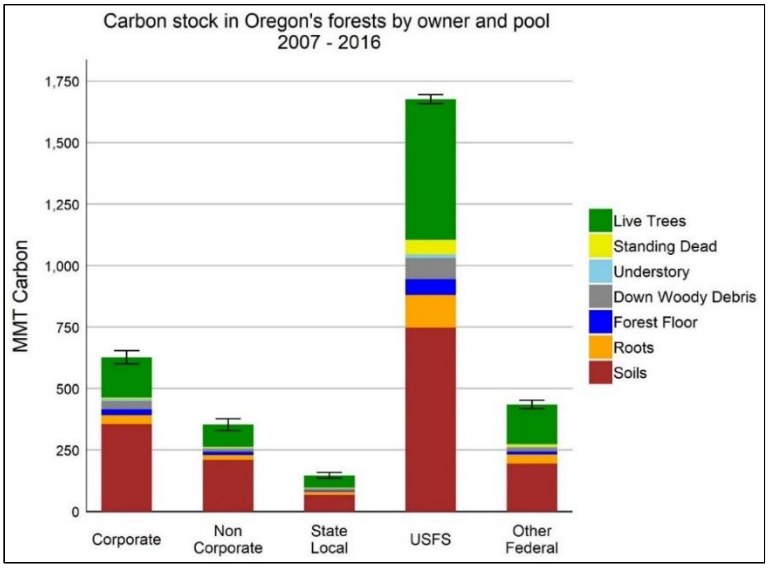

Figure 2.2: Oregon statewide average forest carbon stock by pool and ownership, 2007-16 (MMT). Error bars represent a 95% confidence interval of estimated total stock for each ownership (Christensen et al. 2019).

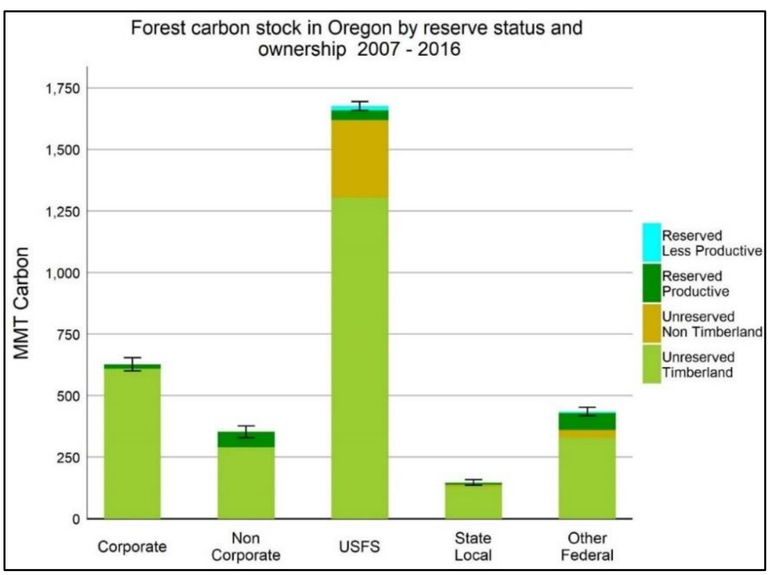

Figure 2.3: Oregon statewide average forest carbon stock by reserve status and ownership, 2007-16 (MMT). Error bars represent 95% confidence interval of estimated total stock for each ownership (Christensen et al. 2019).

Table 2.4: Oregon statewide forest carbon stocks by pool, 2007-16.

Forest carbon pool		**Carbon stock**	
		Total	**SE**
		million metric tons carbon (MMT C)	
Live trees	Aboveground	1,039.20	9.63
	Belowground (roots)	212.83	2.07
Dead trees	Aboveground	79.10	1.56
	Belowground (roots)	21.58	0.42
Understory vegetation	Aboveground	33.95	0.21
	Belowground (roots)	3.77	0.02
Down woody material		156.83	1.93
Forest floor		117.19	0.55
Soil organic carbon		1,575.27	7.55
TOTAL FOREST CARBON STOCKS		**3,239.72**	**16.73**

By geographic region, the greatest proportion of Oregon's forest carbon stocks is found in the forests of the western ecological regions (ecoregions). Together the Western Cascades and Oregon Coast Range ecoregions account for over half of Oregon's forest carbon stocks (52%) (Figure 2.4). Of these two regions, the Oregon Coast Range has the greatest proportion of total carbon stocks managed by private ownerships (46%). However, within these two regions, publicly managed carbon stocks in all pools tend to carry a greater density of carbon per acre compared to privately managed ownerships. For example, in the Oregon Coast Range, public forests have on average 168.4 metric tons of carbon stocks per acre. Within this same region, the privately managed forests have 111.8 metric tons of carbon stocks per acre.

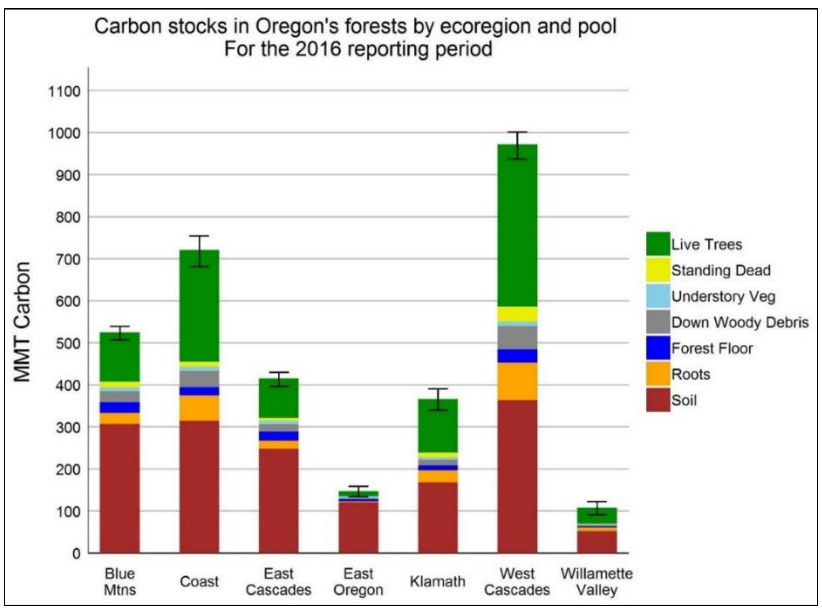

Figure 2.4: Average carbon stock (MMT C) by pool and ecological region, 2007-16. Error bars represent a 95% confidence interval of estimated total stock for each region (Christensen et al. 2019).

In Oregon's forests, the Douglas-fir forest type has the greatest concentration of carbon stocks compared to all other major forest types. Forests of this type are estimated to be storing 1,511.1 ± 42.0 MMT of carbon, about 47% of Oregon's total forest carbon stocks (Figure 2.5). The next most abundant forest types are divided between the fir/spruce/mountain hemlock forests and the ponderosa pine forest types. Of the hardwood forest types, the alder/maple forests are currently storing the most total forest carbon, at 122.7 ± 15.5 MMT of carbon.

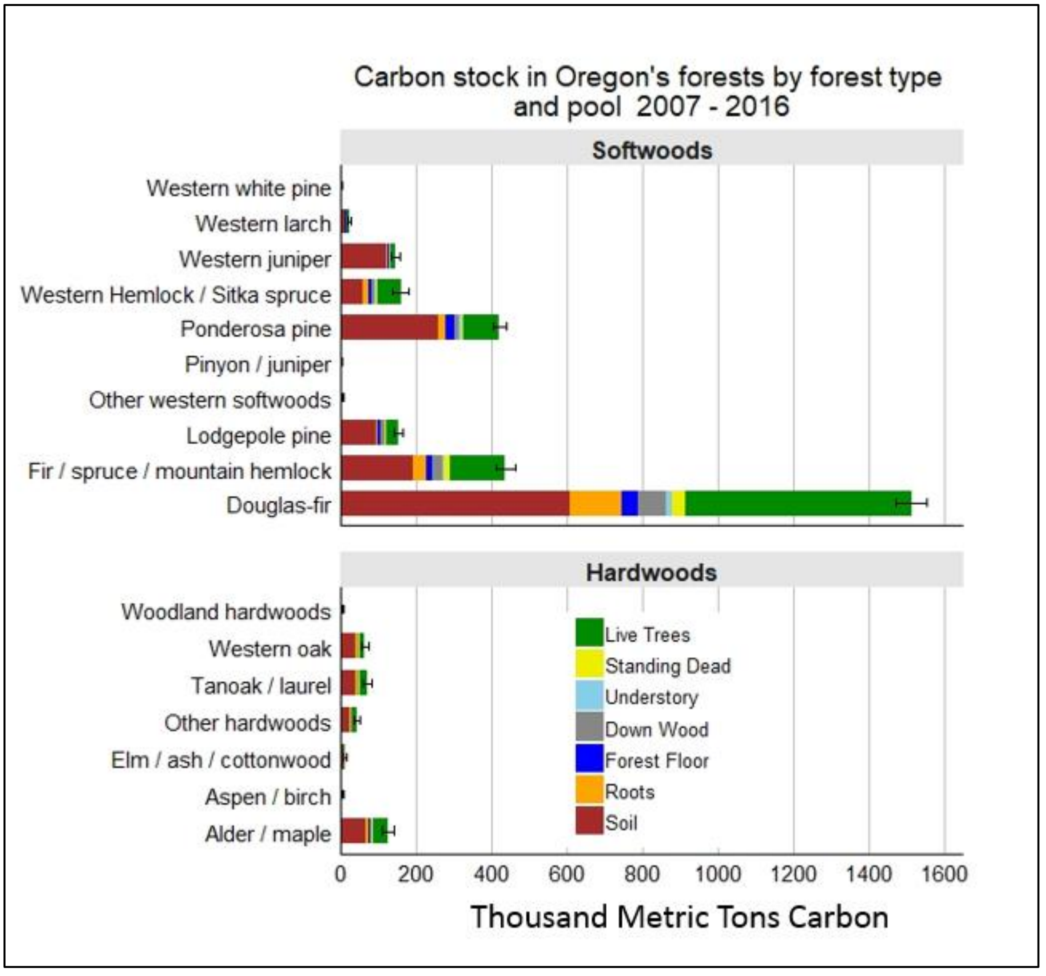

Figure 2.5: Oregon statewide average carbon stock by pool and forest type, 2007-16 (thousand metric tons C). Error bars represent a 95% confidence interval of total stock for each forest type (Christensen et al. 2019).

2.3 Carbon sequestration in Oregon forests: Ten-year change from 2001-06 through 2011-16

FIA estimates of average annual net carbon sequestration are based on a 10-year average, from plots and trees initially measured between 2001 and 2006 and then re-measured 10 years later between 2011 and 2016. Remeasuring permanently located inventory plots has the advantage of being able to fully evaluate and monitor changes on each plot in all carbon pools, especially changes in tree growth, removals and mortality across all ownerships and forested areas of the state. Most of the results focus on the net change in forest ecosystem carbon for forestland remaining forested at both measurement intervals. Net change accounts for effects on CO_2 flux from growth, harvest and mortality from any disturbances such as wildfire. Unlike carbon stock estimates that estimate the amount of carbon physically stored in each pool, in this report estimates of change in each pool are provided as the annual rate of flux and expressed as carbon dioxide equivalent (CO_2e), an approximation of equivalent gaseous carbon as measured in the atmosphere.

From FIA measurements taken on remeasured plots, Oregon's statewide rate of carbon sequestration from all forest ecosystem pools and across all ownerships is 30.9 ± 7.3 MMT CO_2e/year, excluding net CO_2e contributions from other sources such as harvested wood products, land moving to and from a forested condition, and non-CO_2 greenhouse gas emissions from wildfire (Table 2.5). After accounting for forestland use conversions and non-CO_2 greenhouse gas emissions from wildfire, the 2016 statewide rate of carbon sequestration on all forestland is 31.4 ± 7.2 MMT CO_2e/year.

The rate of annual growth in Oregon's live forest vegetation carbon pools exceeds annual losses from these pools (Table 2.5). Annual growth of live vegetation is sequestering carbon at a rate of about 37.9 ± 5.8 MMT CO_2e/year. Dead vegetation, including standing dead trees, dead roots and down wood as fallen logs or other decaying woody material, is losing CO_2e to the atmosphere or other forest ecosystem pools at a rate of 7.3 ± 2.1 MMT CO_2e/year. This does not account for the CO_2e partially offset in harvested trees. Carbon in wood products manufactured from a portion of the wood volume in these harvested trees is not immediately emitted in the atmosphere as CO_2, but is stored as sequestered carbon.

Table 2.5: Statewide average annual net CO_2e flux from forest pools in forestland remaining forestland, based on plots initially measured between 2001 and 2006 and re-measured between 2011 and 2016 (Christensen et al. 2019).

	Net flux	
	Total	**SE**
	million metric tons CO_2 equivalent	
CARBON POOL		
Aboveground live[1]	31.6	3.0
Aboveground dead[2]	-7.0	1.0
Belowground live[3]	6.3	0.7
Belowground dead[4]	-0.3	0.2
NET VEGETATION FLUX	***30.5***	***3.7***
Forest floor	0.6	0.1
Soil organic C	-0.2	0.3
TOTAL FOREST NET FLUX	***30.9***	***3.8***

[1]includes live trees, foliage and understory veg
[2]includes standing and down dead wood
[3]includes live tree and live understory veg roots
[4]includes dead tree and dead understory veg roots

Annual growth in Oregon's federally managed forests accounts for the largest share of the state's total net annual CO_2e sequestration. Most of this growth is on national forests, which account for over half (54%) the annual net growth in live trees (Figure 2.6). Combined with forestland managed by other federal agencies such as the BLM, this contribution from federal forests equals 82% of the state's annual carbon sequestration. Tree growth on private ownerships, including both corporate and private individual owners, has a net contribution of 15% to the overall rate of sequestration in live trees after accounting for removals due to harvest and mortality. State- and local government-managed forests contribute about 3%.

Oregon's national forests are sequestering carbon at a rate of 19.1 ± 2.0 MMT CO_2e/year (Figure 2.6). Of the forestland managed by private owners, those managed by private individuals are sequestering carbon at a rate of 3.6 ± 2.3 MMT CO_2e/year. Although the estimate for net annual change on private corporate forest lands is negative (-2.4 ± 6.2 MMT CO_2e/year), the variation in the estimate of current annual growth when accounting for trees removed through management activities is too large to determine if the average net annual rate of carbon sequestration is statistically different from zero. Forests managed by state agencies such as the Oregon Department of Forestry, and including local governments such as county forestland, are sequestering carbon at a rate of 1.1 ± 2.2 MMT CO_2e/year. The estimate of annual CO_2e flux on these public forests that manage a smaller share of Oregon's forest has a large variation that includes zero. The additional uncertainty in the estimated annual CO_2e flux is partially due to fewer FIA plots on this smaller area of forestland, including fewer plots having been remeasured by 2016, the most current inventory year represented in the sample.

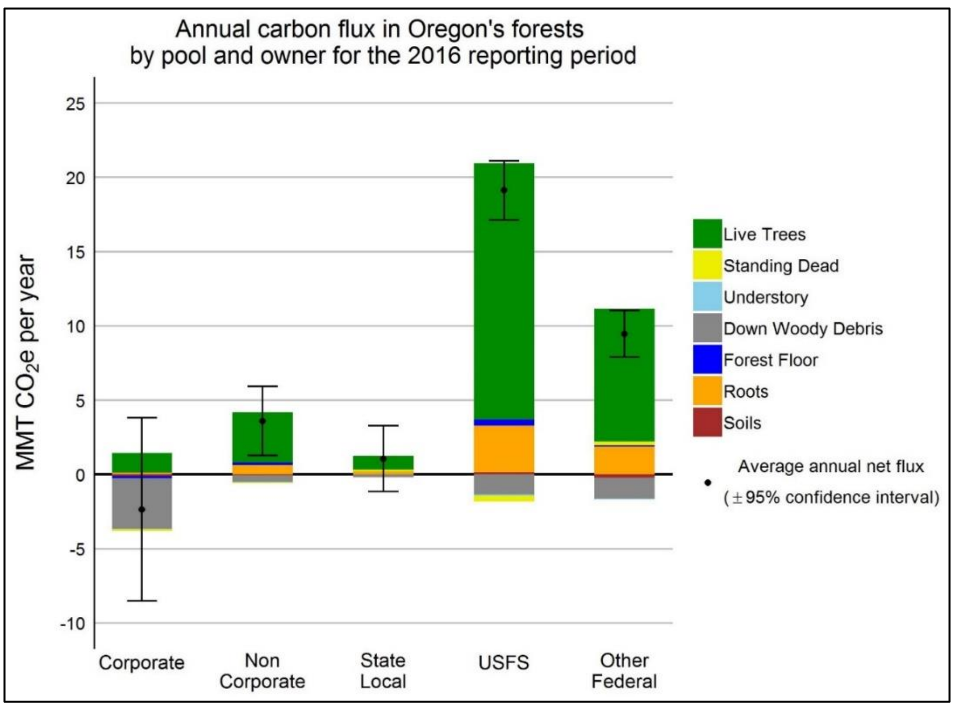

Figure 2.6: Oregon statewide estimate of average annual carbon flux (MMT CO_2e/year) by pool and ownership, 2001-06 to 2011-16. Estimates exclude emissions from land-use changes and non-CO_2 greenhouse gases. Roots includes belowground live and dead tree roots. Understory includes aboveground and belowground pools. Error bars represent 95% confidence intervals around point estimates for net flux (Christensen et al. 2019).

Carbon sequestration as a function of gross annual tree growth per acre is highest on forestlands managed by state and local governments (4.5 ± 0.5 MT CO_2e/acre/year), and private corporate owners (4.1 ± 0.2 MT CO_2e/acre/year) (Figure 2.7, Table 2.6). Annual timber harvest has also been highest from these forests, and is expected to contribute proportionally more to carbon sequestering as harvested wood products as compared to contributions from the other ownerships, including forests managed by private noncorporate individuals, national forests managed by the USDA Forest Service, or other federal forestlands.

After accounting for reductions in the rate of gross growth from harvest and tree mortality, forestland managed by other federal owners such as the BLM currently has the highest average annual net rate of carbon flux per acre. FIA estimates that 2.3 ± 0.3 MT of CO_2e is sequestered annually per acre on average for these forests. Statewide, after accounting for timber harvest and tree mortality, Oregon's forests are sequestering CO_2e at an average annual rate of 1.0 ± 0.4 MT per acre across all ownerships (Table 2.6).

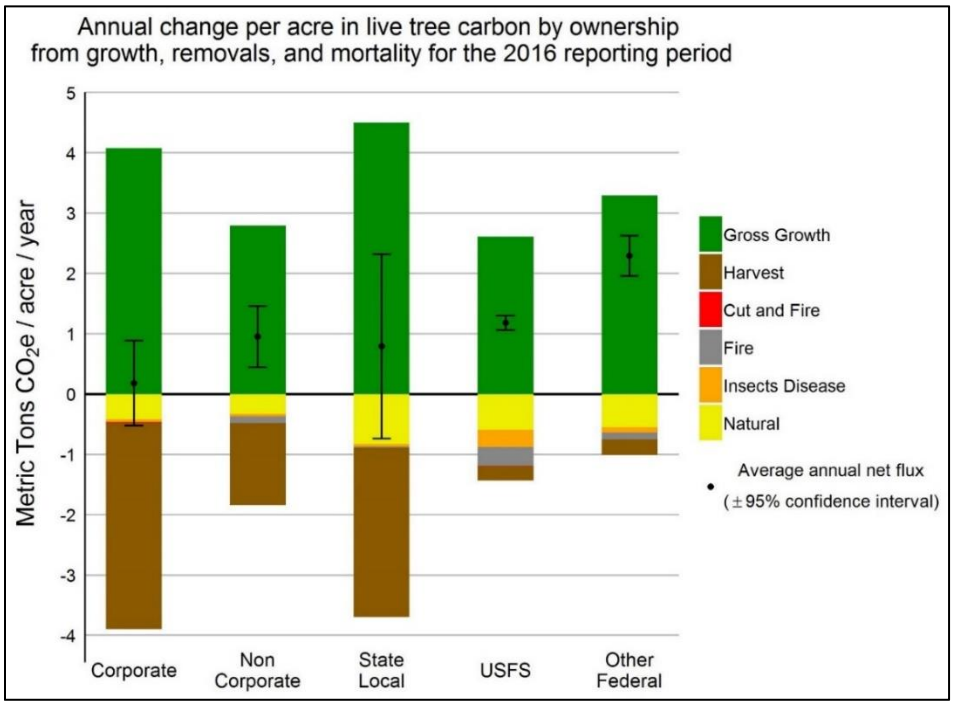

Figure 2.7: Average annual net change per acre in aboveground live tree carbon (MT/CO_2e/acre) by ownership in Oregon's forests, 2001-06 to 2011-16. The error bars represent a 95% confidence interval of net change (Christensen et al. 2019).

Table 2.6: Forest land average annual growth, mortality, harvest and net change per acre in aboveground live tree carbon (CO_2e) pool by ownership of Oregon's forests, 2001-06 to 2011-16 (Christensen et al. 2019).

	Private – Corporate	Private – Noncorporate	Other Federal	State and Local Gov.	National Forests	All Ownerships
			Metric tons CO_2e/acre/year			
Gross tree growth	4.08	2.79	3.29	4.50	2.61	3.14
Removals – harvest	-3.42	-1.36	-0.26	-2.81	-0.28	-1.21
Mortality – fire-killed	-0.01	-0.11	-0.11	-0.02	-0.22	-0.18
Mortality – cut and fire[1]	-0.01	0.00	--	--	-0.01	-0.01
Mortality – insects and disease	-0.04	-0.04	-0.09	-0.04	-0.26	-0.17
Mortality – natural/other	-0.42	-0.33	-0.53	-0.76	-0.57	-0.52
Net change (± 95% CI)	**0.18 (0.70)**	**0.95 (0.52)**	**2.29 (0.33)**	**0.79 (1.52)**	**1.17 (0.12)**	**1.04 (0.20)**

[1]Mortality – cut and fire: Plots where tree mortality has occurred due to both harvest and fire.

The Cascades mountain range generally divides Oregon's forests into two distinct moisture regimes, and current forest carbon pools tend to reflect distinct differences based on which side of the Cascade divide they occur. Forests grown west of the Cascade divide generally receive abundant annual rainfall compared to forests found east of the divide. Exceptions include forests found at higher elevations of the Blue Mountains ecological region that tend to receive more annual rainfall compared to other forests found east of the Cascade Mountains (Figure 2.8b). The other exception is forests found in the Klamath Mountains ecological region, which tend to have a mix of both wet and dry forest characteristics.

Current estimated annual average net flux by forest carbon pool and ecological region is similarly impacted by these geographic differences found across Oregon. Forests on the western and less moisture-restricted side of the Cascades are growing trees faster (live tree gross growth) and tend to have proportionally less tree mortality as standing dead trees, resulting in a higher average annual net flux rate. For example, the Western Cascades and Oregon Coast Range ecological regions, both located west of the Cascade divide, account for over half the annual CO_2e sequestration in statewide live tree gross growth (Figures 2.8b and 2.9). The Western Cascades region accounts for 31% of the state's total annual net CO_2e flux in live trees, at 9.4 ± 3.0 MMT/year, slightly more than the live tree net flux of 8.1 ± 4.3 MMT CO_2e sequestered annually from the Oregon Coast Range (Figure 2.9). The Blue Mountains and East Cascades ecological regions have the highest annual live tree growth rates of regions east of the Cascades, and together account for about 21% of the state's total annual net CO_2e sequestration in statewide live tree gross growth. After accounting for tree mortality from all causes and carbon removed through timber harvest, no single ecological region is currently losing more CO_2e annually than is being sequestered through live tree growth (Figure 2.9).

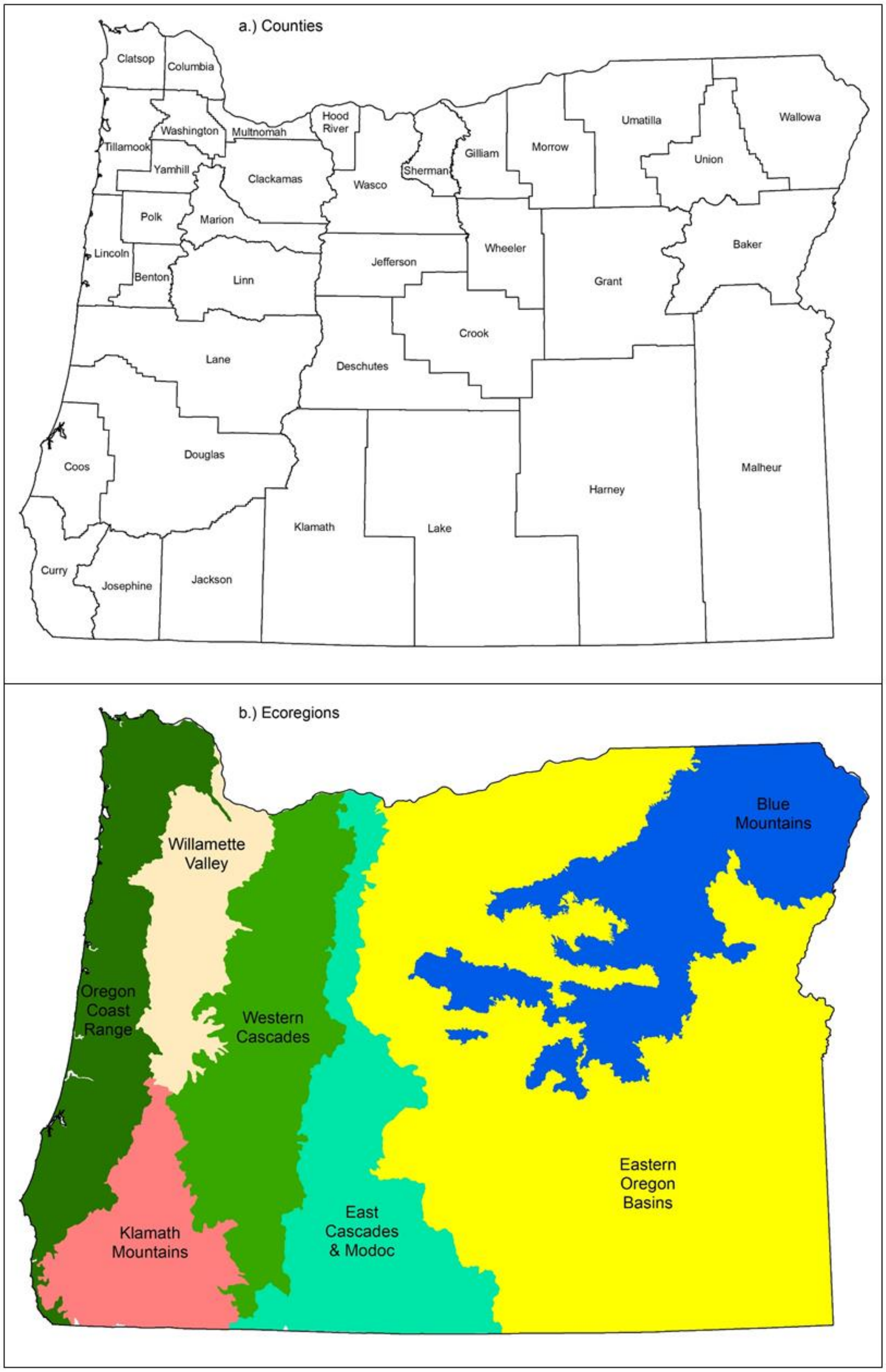

Figure 2.8: Oregon a.) counties and b.) ecoregions, based on ecological sections as described by Cleland et al. (2007) (Christensen et al. 2019).

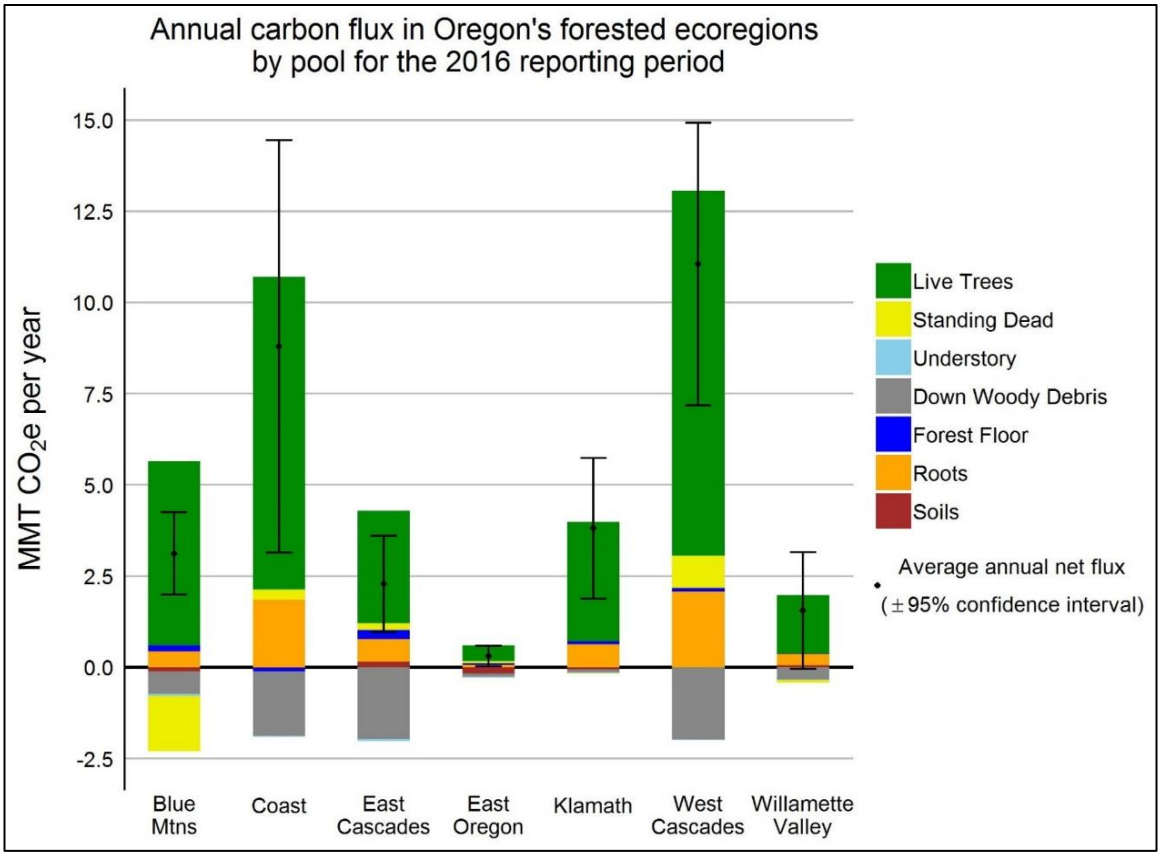

Figure 2.9: Average annual carbon flux in Oregon forested ecological regions by pool ($MMT/CO_2e/acre$), 2001-06 to 2011-16. The error bars represent a 95% confidence interval of net change (Christensen et al. 2019).

Annual change by forest carbon pool varies with management, disturbance and ownership. In forests that experienced harvesting, the loss of live trees on National Forest lands was slightly more than growth when also accounting for natural mortality (-0.87 ± 0.5 MMT CO_2e/year), since on average growth was roughly proportional to harvest in those stands. In contrast, on private corporate lands the net change in live trees on cut stands was -16.1 ± 3.7 MMT CO_2e/year, reflecting greater proportional removals of live trees in stands under that ownership compared to others. Accounting for additional losses of dead wood resulted in a net removal of -29.0 ± 5.3 MMT CO_2e/year in stands where harvesting occurred across all ownerships in Oregon. Of the estimated 34.8 ± 4.6 MMT CO_2e/year of live trees cut within the forest, live tree growth annually exceeded harvest and mortality.

The total net change in carbon in stands that experienced fire in Oregon was -2.3 ± 0.8 MMT CO_2e/year. Most of that loss occurred on National Forest lands. Although live tree mortality was nearly twice that amount on national forests (-4.3 ± 1.2 MMT CO_2e/year), live tree growth and the increase in standing dead trees was significant. In contrast to stands experiencing fire and/or cutting, stands affected by weather disturbances or insect and disease accumulated carbon in the live and dead tree pools. Overall, in spite of annual statewide losses due to fire and/or cutting across Oregon, carbon sequestration in stands experiencing other disturbances, plus undisturbed stands, resulted in a net overall accumulation of nearly 30.1 ± 5.7 MMT CO_2e/year, reflecting the state's high annual tree growth rate across all forest ownerships.

2.4 Summary

FIA's forest inventory provides Oregon with statistically valid and unbiased current estimates of forest carbon stocks and flux across all forests and ownerships. Forest carbon stock estimates by pool are based on a 10-year running average, and are updated with each year's plot measurements. For this report, estimates of change in these carbon pools are based on remeasurement of 60% of the original plots installed 10 years earlier. As with forest carbon stocks, the proportion of remeasured plots used to calculate change by pool and net flux increases 10% each year. Following completion of the 2020 field season, all FIA plots will have been remeasured at least once. Completing the remeasurement of all plots is important, because it will reduce the overall statistical error associated with carbon change estimates, improving our confidence in interpreting these statistics.

The possibility of increasing the intensity of the FIA inventory has been raised, as a way to get more precise information on conditions and changes in Oregon's forestland. Concerns revolve around getting more precise estimates of the timing and causes of changes to forests, and getting more precise estimates of the changes on specific ownerships or vegetation types. The options to improve inventory precision include doubling the number of plots in the state (spatial intensification) and cutting the time between measurements on the same plot in half (temporal intensification). As an initial effort to increase the number of sampled FIA plots, FIA has partnered with the Oregon Department of Forestry to install a spatial intensification on forestland managed by ODF. Similar spatial intensification of FIA plots is being done on national forests and BLM-managed forestland. These efforts will lead to better forest inventory information and forest carbon statistics, enabling state forest managers to have a more detailed and nuanced view of the complex forest carbon dynamics of these forests – critical to Oregon's overall efforts toward mitigating greenhouse gas emissions.

2.5 Appendix 1: Glossary of terms used and FIA-specific definitions

Forestland – Under the FIA definition, land that has at least 10% crown cover by live tally trees of any size, or has had at least 10% canopy cover of live tally species in the past, based on the presence of stumps, snags or other evidence. To qualify, the area must be at least 1.0 acre in size and 120 feet wide. Forestland includes transition zones, such as areas between forest and non-forest lands that meet the minimal tree stocking/cover requirement, and forest areas adjacent to urban and built-up lands. Roadside, streamside and shelter-belt strips of trees must have a width of at least 120 feet and a continuous length of at least 363 feet to qualify as forestland. Unimproved roads, trails and meadows less than 120 feet wide or less than an acre in size, and streams less than 30 feet wide in forest areas, are classified as forest. Tree-covered areas in agricultural production settings, such as fruit orchards or tree-covered areas in urban settings subjected to regular mowing, such as city parks, are not considered forestland. Per this definition, chaparral is not included in the definition for forestland unless it also meets the minimum stocking or crown cover requirements to qualify as forestland.
Forestland status – Refers to the different FIA categories of forestland (i.e., productive forestland, timberland, other forestland), including the reserve categories (i.e., reserved or unreserved), defined below.
Flux – Flux describes the net change in carbon in one or more pools over a specific period of time, expressed as either a total or a rate (to distinguish change from carbon stocks), with a negative flux meaning a loss of carbon from the pool. Often expressed as an exchange with the atmosphere, not all carbon exchanges occur with the atmosphere (e.g., live trees convert to dead wood when they die).
Gross growth – The increase in wood volume or biomass between the previous and current measurements, based on trees that were alive at the previous measurement.
IPCC – The Intergovernmental Panel on Climate Change is a United Nations-sponsored panel of scientists that develops guidance on the conduct of carbon emissions assessments, among other things.
Land status – Refers to the FIA distinction between forestland and non-forestland (e.g., crops, improved pasture, residential areas, city parks, etc.) or other area (e.g., water). Also includes forestland status categories.
Mortality – The wood volume or biomass of live trees that died between the previous and current measurements.
Net growth – The net change in live tree wood volume or biomass between the previous and current measurements, equivalent to gross growth minus mortality.
Other forestland – Forested lands not capable of producing at least 20 cubic feet of wood per acre at the culmination of a mean annual increment.
Pool – A category containing carbon mass – e.g., live trees, down wood or harvested wood products.
Productive capacity – Ability for land to grow commercial tree species.

Productive forestland – Forested lands capable of producing at least 20 cubic feet of wood per acre per year at the culmination of a mean annual increment.
Reserved status – Lands where management for producing wood products is precluded permanently by law, including wildernesses, national parks, national recreation areas and state parks. In some cases, timber harvest can occur for various resource objectives (e.g., restoration, salvage, etc.).
Sequestration – A net increase in carbon stores in one or more pools (categories) over a specific period of time.
Stocks – The amount of carbon in one or more pools (categories) at one point in time (synonym: stores).
Stores – The amount of carbon in one or more pools (categories) at one point in time (synonym: stocks).
Timberland – Forestland that is potentially capable of producing at least 20 cubic feet/acre/year at culmination in fully stocked, natural stands of continuous crops of trees to industrial roundwood size and quality. Industrial roundwood requires species that grow to size and quality adequate to produce lumber and other manufactured products (excluding fence posts and fuel wood, which are not considered manufactured). Timberland is characterized by no severe limitations on artificial or natural restocking with species capable of producing industrial roundwood.
Unreserved – Land not otherwise classified by FIA as reserved (see reserved status, defined above).

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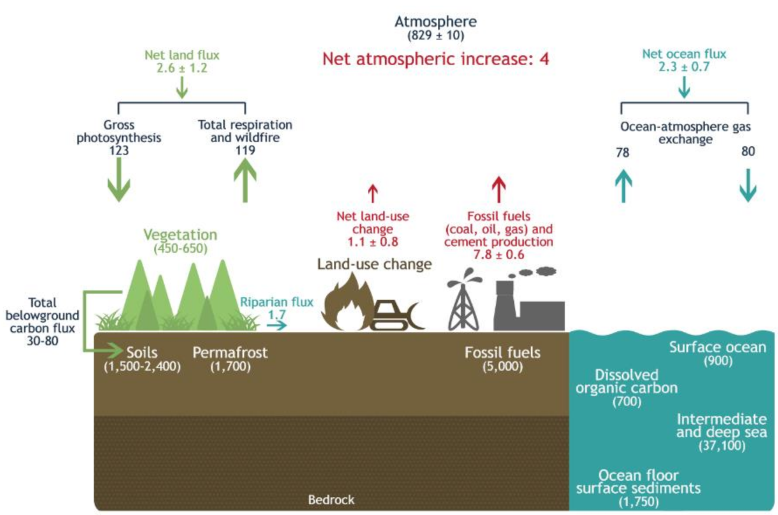
CHAPTER 3: Managing Forests to Increase Their Carbon Storage, Productivity and Resiliency

Edie Sonne Hall, Three Trees Consulting

3.0 Introduction

As described in Chapter 1, photosynthesis enables trees to sequester large amounts of carbon from the atmosphere, storing 450-650 and 1,500-2,400 billion metric tons of carbon (BMT C) in the earth's forests and soils, respectively. While vegetation removes carbon dioxide from the atmosphere during growth (photosynthesis), carbon dioxide is released back into the atmosphere through respiration, combustion from fire, and decay. The net flux of the exchange between the land and atmosphere is influenced by both anthropogenic and natural drivers, making it hard to separate into distinct drivers (IPCC 2019, section 3.1). The forest sector also influences the flux between the fossil fuel pool and atmosphere when wood products are substituted for more emissions-intensive materials or fossil fuel energy (IPCC 2019,



There are four major carbon pools on earth: fossil fuels, the ocean, the terrestrial biosphere and the atmosphere. Exchange between pools is termed "flux." The ocean and terrestrial biosphere can exchange carbon with the atmosphere in both directions, storing and releasing. Except on geologic time scales, fossil fuels represent a one-way exchange, meaning they only move from their pool to the atmosphere. The ocean-atmosphere exchange results from diffusion; CO_2 will move from the area of higher concentration to lower concentration in order to reach equilibrium. The ocean is currently a net sink, because the atmosphere has a higher CO_2 concentration.

The terrestrial biosphere is more complicated, because uptake and release are based on a combination of variables. Currently, the ocean and the terrestrial biosphere are net sinks (~2.3 and 1.5 BMT CO_2e, respectively), but not enough to offset fossil fuel emissions to the atmosphere (Janowiak et al. 2017).

Box 3.1- Overview of global carbon pools

section 5.3).[2] Finally, climate change may impact both growth and emissions if growing seasons shift or the prevalence of disease and/or fire increases.

International research communities have long discussed the role forests can play in mitigating climate change. Detailed summaries of the latest research and recommendations are compiled by the Intergovernmental Panel on Climate Change (IPCC). Each of the first five assessment reports on mitigation recognize the role sustainable forest management can play in enhancing carbon sinks on land and produced wood products. The most recent IPCC special report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems emphasizes the importance of understanding the interaction between land management, value chain management and climate adaptation management (IPCC 2019, Table 6.6). The report summarizes key integrated land management strategies, including 1) reduced deforestation and degradation; 2) fire and natural disturbance management; 3) afforestation; and 4) improved forest management, to "enhance the carbon stocks in biomass, dead organic matter, and soil – while providing wood-based products to reduce emissions in other sectors through material and energy substitution." (IPCC 2019). The Food and Agriculture Organization of the United Nations lists similar strategies in the report *Forestry for a Low Carbon Future,* though it adds two more strategies highlighting improvements that can be made with the use of forest products (Figure 3.1). These include substituting wood products for more energy-intensive materials and substituting biomass energy for fossil fuels (FAO 2016). These last two pathways will be discussed in Chapter 4.

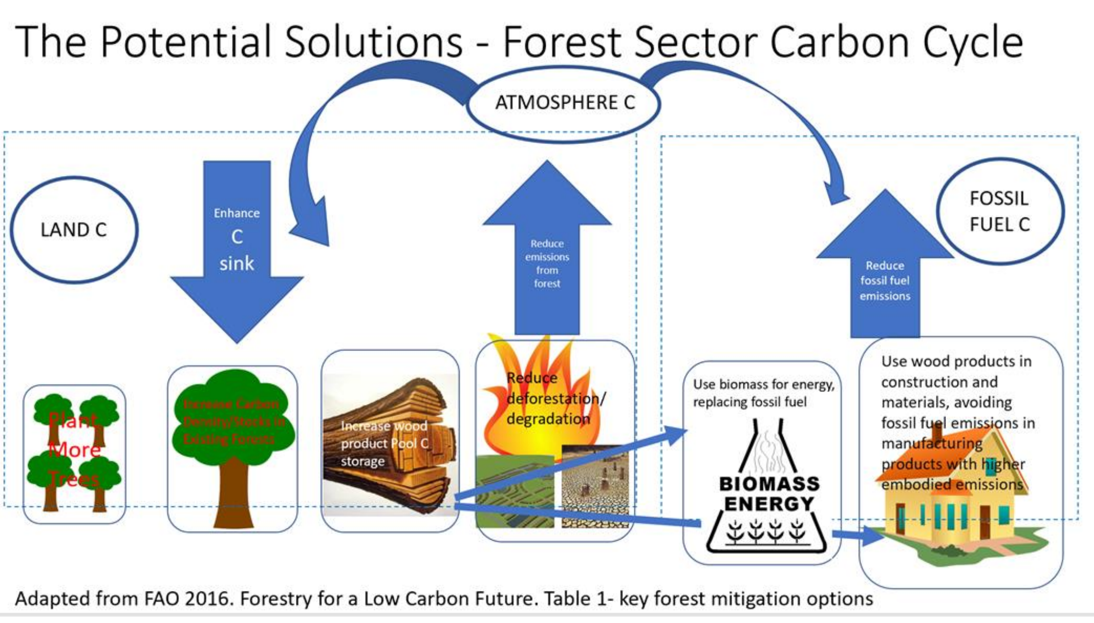


Figure 3.1: Forest sector strategies, adapted from FAO 2016: Forestry for a Low Carbon Future.

[2] IPCC 2019, Section 5.3. "Sustainable forest management can maintain or enhance forest carbon stocks, and can maintain forest carbon sinks, including by transferring carbon to wood products, thus addressing the issue of sink saturation."

The forest sector strategies can be separated into two broad categories: 1) Reduce emissions; e.g., put less carbon dioxide (either biogenic or fossil fuel) into the atmosphere, and 2) Increase sequestration; e.g., take more carbon dioxide out of the atmosphere.

Given the capacity of forests to capture and store carbon in the ecosystem and in wood products, the forest sector is frequently discussed as a critical component to reducing atmospheric carbon. Blessed with climate and soils particularly suited for high tree productivity, Oregon is well situated to contribute. Douglas-fir, the most dominant tree species in the state, is valued for its strength as a building material, and Oregon plays a significant role as the state with the largest production of sawtimber in the United States, which as a country leads the world in sawtimber production.

Placed in this context, there are several ways Oregon's managed forests can help reduce atmospheric carbon. The first two focus on reducing biogenic emissions from existing forests – first by reducing land conversion to other uses, and second by reducing the risk of high-severity fires or uncharacteristic mortality due to pests and pathogens. Strategies associated with these two pathways specific to Oregon are discussed in sections 3.1 and 3.2 of this chapter. Oregon's managed forests can also take more carbon dioxide out of the atmosphere by harnessing the photosynthetic capabilities of trees and other plants. The two principal strategies are to increase the amount of area in forest by planting more trees, and increasing carbon storage in existing forests and products. These pathways are discussed in sections 3.3 and 3.4 of this chapter.

3.1 Land strategy 1: Avoid emissions by reducing forest conversion

As explained in Chapter 3 of the 2006 OFRI report, the global impact of land conversion away from forests began with clearing for agriculture thousands of years ago. In the United States, land-based carbon emissions were dominated by clearing for agriculture and fuelwood through the turn of the 20th century. Around this time, abandoned farms in the northeast United States started converting back to forests, and trees were replanted across the southeastern and northwestern United States.

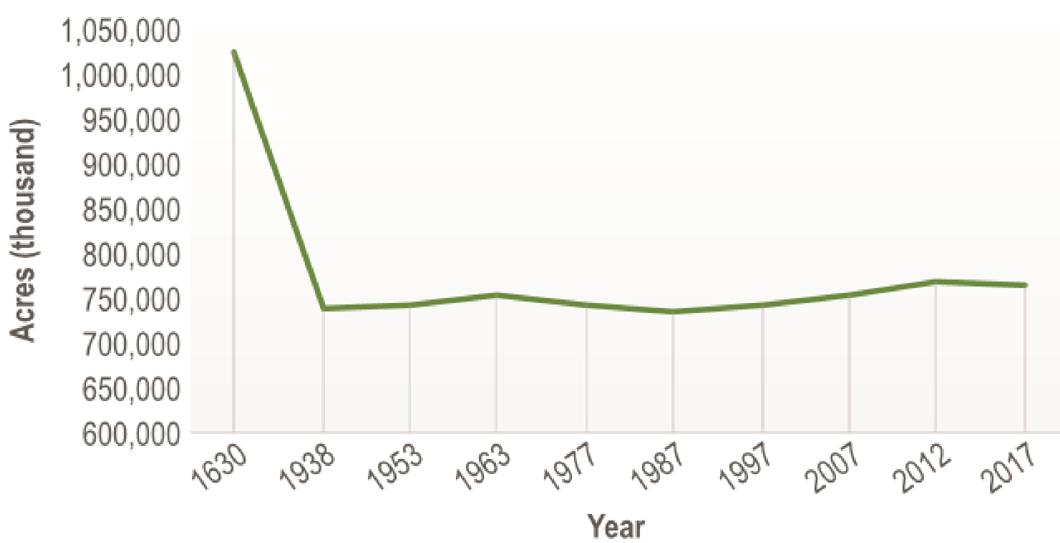


Figure 3.2: Forestland area in the United States, 1630-2017 (Oswalt et al. 2019).

Forestland area has been stable and slightly increasing since the 1940s (Figure 3.2), a figure cited and celebrated widely. The most recent release of Forest Resources of the United States (Oswalt et al. 2019), however, shows a plateau in forest cover and evidence that this trend will reverse. By 2060, between 16 and 30 million acres of forestland across the United States are predicted to be converted to other uses, with the largest conversion rate occurring in the U.S. South (Figure 3.3) (USFS 2012). Fargione et al. (2018) estimate that reducing forest conversion could save 39 MMT CO_2e/year. IPCC has identified a potential of 0.41-0.58 BMT CO_2e/year in emissions reduction by lessening deforestation and degradation (IPCC 2019, Table 6.14).

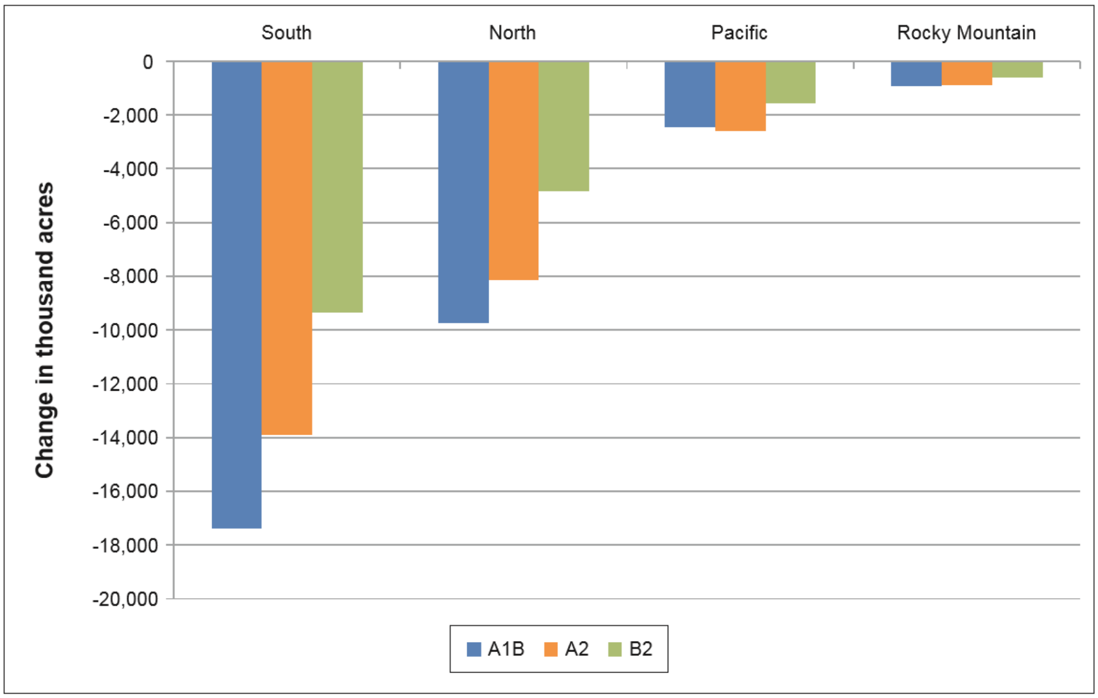


Figure 3.3: Change in conterminous U.S. nonfederal forest area from 2010-60 by RPA assessment region and RPA scenario (thousand acres) (USFS 2012).

Oregon's Conservation and Development Act of 1973 set in motion strategies for reducing loss of forest to development.[3] This act required all counties to develop comprehensive land-use plans, which resulted in zoning lands as either resource use (e.g., forest, farm and range land) or as developable zones for either urban or low-density residential (Lettman et al. 2018). Though conversion is allowed in resource lands, it is difficult, and as of 2014, 97% of lands zoned as resource in 1974 remained in these uses. Of the 704,000 acres that were converted to low-density or urban uses, 247,000 were from wildland forest, with more than three-quarters of the conversion occurring in western Oregon (Lettman et al. 2018). According to the most recent Oregon State GHG Inventory Report, 2.5 MMT CO_2e/year were emitted from forestland conversion between 2001-06 and 2011-16, though an additional 3.4 metric tons CO_2e were added in conversion of non-forest to forest resulting in a net increase of 923,000 metric tons CO_2e (Christiansen et al. 2019).

[3] See Chapter 6 of OFRI 2006 for a more thorough overview of Oregon's land-use laws and conversion impacts.

Population increases put pressure on resource lands. Oregon's population grew by 1.69 million people between 1974 and 2014 (Lettman et al. 2018), and by another 200,000 people between 2015 and 2018 (Oregon Office of Economic Analysis). A study adapted from Wear et al. (1999) shows that as population grows, the probability of active forest management lessens. As of 2009, 21% of areas categorized as wildland forest were within one mile of more developed land. The number of structures on private land classified as wildland forest have increased from 0.7 per square mile in 1974 to 1.8 per square mile in 2009, corresponding to potential population densities of 5.0 per square mile (Lettman et al. 2011).

The carbon outcomes when population increases near wildland forest can be mixed. If trees are valued for recreation or aesthetics, carbon sequestration and storage can continue to occur. However, lack of income from harvest activities can increase pressure for landowners to convert to other uses. In Oregon, most conversions from wildland forest to low-density residential have occurred on non-industrial private lands, as opposed to industrial (commercial forestry) or other public entities (Lettman et al. 2018).

Although Oregon's zoning laws roughly determine the pathway for development, as of 2009, 460,000 (31%) acres of all lands zoned as developable were still in either forest, range or agricultural range uses, continuing to store carbon. The percentage of these lands within 0.25 miles of low-density residential or urban uses increased from 39% in 1974 to 66% in 2009, with an average of 30.2 structures per square mile – in contrast to 3.2 structures per square mile for non-developable land in resource land uses (Lettman 2011). This corresponds to a population density of roughly 70 people per square mile, making the chances for active forest management only 25%, according to Wear (1999).

While Oregon's land-use laws have resulted in a robust framework for stemming land conversion, strategies and incentives for avoiding forest conversion can help with remaining developable forestland. The most notable strategies Oregon implements for avoiding land conversion are summarized below.

Preferential tax programs – All states have some program to reduce property taxes on private forest and farm landowners. There is usually a penalty if a landowner disenrolls from the program, but there is no guarantee of permanent protection. In Oregon there are two options for private forestland owners. The Forestland Program enrolls productive forestland of two or more acres and assesses property tax at a rate (the specially assessed value), based on land values for forestry, not development or other uses. The Small Tract Forestland Program is for landowners with >10 and <5000 acres, and annual property tax is only 20% of the forestland special assessment value. A tax per thousand board feet (MBF) (in 2019, $4.65/MBF for eastern Oregon and $5.98/MBF for western Oregon) is paid upon timber harvest.

Voluntary incentives – Though relief from property taxes provides some incentive against conversion, in some cases land values rise high enough that the penalty is much less than the market value of the land. Voluntary incentives can provide an important stop-gap measure. Conservation easements, offered by local land trusts or the federal government through the USDA NRCS Healthy Forests Reserve Program, usually allow lands to continue to be managed for forestry in exchange for permanent protection from conversion for development. A Transfer of Development Rights (TDR) is a program that specifically targets conversion. Oregon has a TDR program for Measure 49 properties, as well as a pilot program.[4]

[4] https://www.oregon.gov/lcd/FF/Pages/Transfer-of-Development-Rights.aspx.

Finally, NRCS cost-share programs such as EQIP and the Conservation Stewardship Program help fund forest management and conservation projects and lessen the financial burden of stewardship, especially on marginal lands, helping reduce the need to develop land for financial reasons.

3.2 Land strategy 2: Prevent emissions by reducing risk of fire, disease and mortality

Disturbances including extreme weather events, drought, fire, tornadoes, heat waves and ice storms are a natural part of the forest cycle. Though weather events vary across time and space, many are predicted to increase in frequency and intensity as a result of climate change, as seen in Figure 3.4 (IPCC 2019, Figure 2.3).

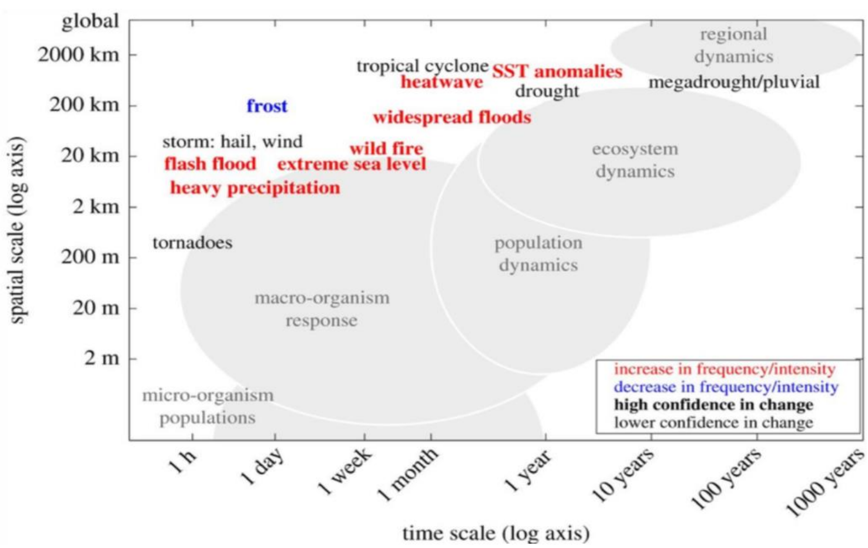


Figure 3.4: Spatial and temporal scales of typical extreme weather and climate events and the biological systems they impact (IPCC 2019).

In Oregon, other than timber harvest the biggest disturbances impacting forests are fire, insects and drought. There is evidence that these disturbances are increasing in frequency and intensity relative to historic levels (Littell et al. 2009, Van Mantgem et al. 2009, Joyce et al. 2014). Diminished growth potential resulting from forest disturbances reduces carbon sequestration rates, and disturbances such as fire also can diminish pools of stored carbon. Both are detrimental to relative atmospheric carbon. Management strategies that focus on creating healthy, resilient forests that withstand increasing risk of disturbances are an important component to reducing terrestrial carbon emissions.

3.2.1 Reduction of uncharacteristic fires

Fire is a natural phenomenon, recurring with a frequency that varies by geography (Hessburg et al. 2019). Fire frequency is likely to increase in many parts of the country, due to changes in precipitation patterns (e.g., more winter precipitation falling as rain than snow, or longer dry seasons) and higher temperatures (Littell et al. 2009, Wimberly and Liu 2014). A history of fire suppression coupled with increasing fire frequency is resulting in larger-than-average fires in certain ecosystems (Hurteau et al. 2019). Combinations of forest type, predicted fire return intervals, and past and current forest management histories can be used to determine a fire risk profile and associated carbon management strategy.

Oregon overlaps with six different climatic ecoregions, labeled (see Figure 3.5): Pacific Northwest Coastal Mountain Forests (2), Willamette Valley Mixed-wood Forests (7), Western Cascade Mountains (6), Middle Rocky Mountains-Blue Mountains (8), Eastern Cascade Mountains-Modoc Plateau (10) and Klamath Mountains (13) (Hessburg et al. 2019). Each of these regions has distinct fire return intervals, forest types and management histories.

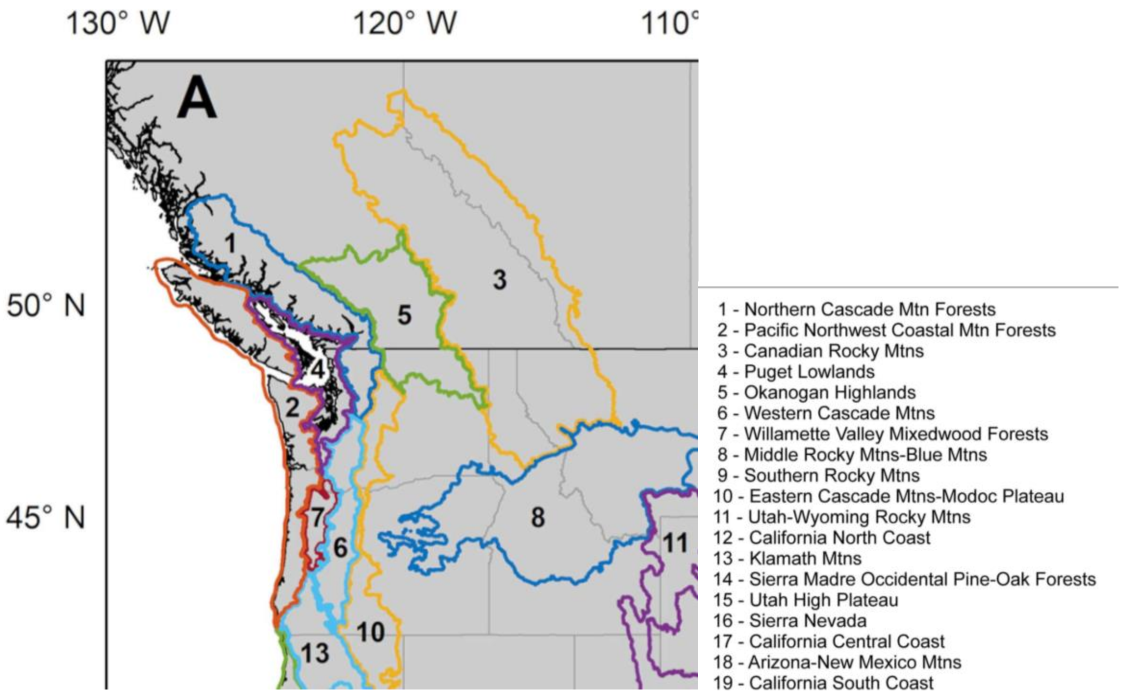


Figure 3.5: Climatic ecoregions in the Pacific Northwest (Hessburg et al. 2019).

In the eastern part of Oregon (Middle Rocky Mountains-Blue Mountains, Eastern Cascade Mountains-Modoc Plateau), natural fire intervals vary according to a temperature/elevation gradient, with dry ponderosa pine forests experiencing low to moderate fire severity every five to 25 years; more moist forests (western larch, ponderosa pine, Douglas-fir and grand fir) with a longer fire return interval (25 to 50 years), and cold subalpine forests (Engelmann spruce, lodgepole pine and subalpine fir mixes) with 75- to 150-year fire return intervals. Fire suppression and a lack of harvesting in this region have increased fuel loads such that current fires have a higher percentage of high severity than historic burns (Reilly et al. 2017).

In western Oregon (including Western Cascade Mountains, Klamath and Southern Cascades), fire regimes are determined primarily by topography. In contrast to eastern Oregon, climate change may not increase fire frequency in this area, though this could change with a long period of extreme drought (Hessburg et al. 2019). These geographic differences are important when designing strategies for reducing emissions from fire. Mitchell et al. (2009) found that long-term carbon savings for thinning to reduce fire risk depend on forest locations. The reduction in stand carbon from thinning in Western Cascade western hemlock/Douglas-fir forests and Coast Range western hemlock/Sitka spruce forests is higher than what is expected to be avoided from fire emissions. However, thinning in the more fire-prone and overstocked eastern Cascade ponderosa pine stands has a higher probability of creating more emissions savings than the reduction in on-site carbon from the thinning itself.

Globally, IPCC estimates 0.48-8.1 BMT CO_2e/year in emissions savings from better fire management for resiliency (IPCC 2019, Table 6.16). Across the United States, Fargione et al. (2018) estimate significant carbon savings (~18 MMT CO_2e/year) through removal of small-diameter trees and/or prescribed burning in overstocked forests with high fire frequency. This strategy reduces fuel loads, decreasing risk that a fire will get hot enough to burn all the trees in the stand. In the short term, thinning alone results in lower carbon, even if including wood products and biomass substitution (Hanson et al. 2009, Harmon et al. 2009). Over the long term, when the risk of predicted fire emissions is included, carbon stabilization strategies are found to result in lower carbon emissions in applicable ecosystems (Hurteau et al. 2019). In Oregon, Nature4Climate estimates that natural climate solution pathways could deliver 1.82 MMT CO_2e /year in savings in areas at risk of high-intensity fire (with a natural fire return interval of 40 years or less) (Nature4climate 2019).

Stephens et al. (2012) found that in dry, coniferous forests of the Western Umited States that once burned frequently, the strategy of reducing carbon in the short term through thinning and prescribed fire results in more stable forest carbon in the long term. They examined different fuel treatments and estimated wildfire carbon loss from fire-prone forests in Montana, Oregon, California and Arizona (including the Blue Mountains in Oregon and Southern Cascades in the Klamath National Forest), and found potential carbon savings in emissions with a relatively small reduction in short-term forest carbon. A combination of mechanical thinning and prescribed burning was found to be most effective in both the Blue Mountains and Southern Cascades, reducing total carbon emissions from 30 Mg/ha to less than 10 Mg/ha in both cases. Krofcheck et al. (2018) found that prioritizing treatments based on the probability of a crown fire can achieve the same carbon stability (e.g., an increase in fire resiliency) with the least amount of carbon removals. Practically speaking, this means thinning with mechanical treatments, followed by regular prescribed burning only in places that have the highest risk of crown fire.

Several fuels-reduction and cost-share programs are currently available in Oregon. Oregon State University Extension published a comprehensive manual for ecology and management of eastern Oregon forests (Oester et al. 2018), and Strong and Bevis (2016) outlined a practical guide for fuel management. The Oregon Department of Forestry offers cost-share assistance for pre-commercial thinning and slash treatment designed to mitigate insect and disease problems and create defensible space through fuels reduction around home sites in fire-prone areas. In addition, NRCS (Natural Resources Conservation Service) and EQIP (Environmental Quality Incentives Program) programs offer cost-share elements, OWEB (Oregon Watershed Enhancement Board) grants, USDA Joint Chiefs funding and FEMA pre-hazard mitigation sources. ODF also has Western states funding (depending on county) and state/private funding (USDA). There is also funding through SWCD (Soil & Water Conservation Districts) and Watershed Councils, depending on location throughout the state.

Fire carbon management benefits from spatial prioritization in areas that are most at risk and when matched with techniques most suited to the landscape. Generally, dry forests will benefit most from restoring fire to the understory (through thinning and prescribed burning) (Allen et al. 2019).

3.2.2 Managing for increased risk of pests and disease

As with fire, insects and disease are natural phenomena that can cause large-scale transformations in species composition, forest productivity and carbon stocks. Climate change can exacerbate impacts of pests and disease, by increasing the likelihood of pest survival with warmer winters and the reduced tree resistance resulting from drought-induced stress. The USFS predicts that 81 million acres of U.S. forests are at risk of losing at least 25% of their basal area in the next 15 years due to insects or disease without management intervention (Krist et al. 2014). This equates to a reduction of 21 MMT of carbon (77 MMT CO_2e) per year in live biomass in next 15 years (Williams et al. 2016).

In Oregon the highest risks by region include western spruce budworm and balsam wooly adelgid (see Figure 3.6, Zone 3); root disease, western spruce budworm and Douglas-fir beetle (Zone 4); and mountain pine beetle and western pine beetle (Zone 5), covering 18% of Oregon's forests (Krist 2014).

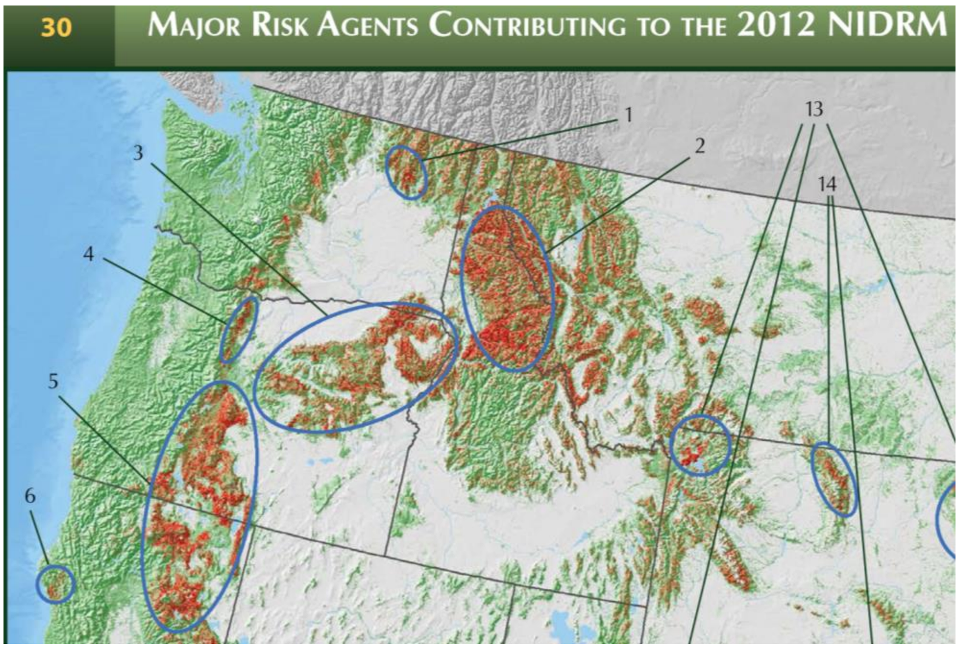


Figure 3.6: Major risk agents contributing to the 2012 National Insect and Disease Forest Risk Assessment (Krist 2014).

Swiss needle cast disease (SNC), caused by the pathogen *Phaeocryptopus gaeumannii,* impacts Douglas-fir foliage and has been shown to slow growth by 23% to 50%, leading to a significant impact on carbon sequestration rates (Macguire et al. 2002, Manter et al. 2003). As of 2015, 588,000 acres of coastal Oregon timberlands had shown visible signs of symptoms, up from 130,000 acres in 1996. Warming temperatures and changes in precipitation regimes may shift the range and deepen the impact of SNC (Agne et al. 2018, Stone et al. 2008).

Tree stress caused by warmer and drier conditions may also increase the prevalence of Armillaria root disease (Agne et al. 2018), which currently is found in grand fir and Douglas-fir in northeastern Oregon and southeastern Washington. The 2013-2027 National Insect and Disease Forest Risk Assessment predicts there will be increased mortality in future climates, relative to historical mortality (Krist et al. 2014).

Forest thinning that keeps the most vigorous stems, retains diversity and is well-timed is a key tool to reducing forest-health-related carbon emissions from forests. While thinning may result in a short-term reduction in carbon storage, minimizing the risk of loss due to forest health issues offsets this impact. In addition, by increasing forest stand resilience by matching species and stocking to each site, managing for diversity and avoiding overstocking, forests are better able to withstand initial insect and disease attacks.

3.3 Land strategy 3: Increase forest area

Globally, increasing forest area has the most potential to increase the contribution from the global biosphere pool, ranging from 0.5 to 10.1 BMT CO_2e per year (IPCC 2019, Table 6.14). U.S. reforestation potential is also the largest pathway, with estimates of 300 MMT CO_2e, though activity cost per ton of CO_2 is predicted to be high if fully implemented (Fargione et al. 2018).

Planting trees indiscriminately does not necessarily help mitigate global warming, and in fact could do the opposite if, for example, planted trees replace natural peatlands or other areas that are currently treeless and should be. Reforestation has the most potential for co-benefits (biodiversity, water filtration, flood control, enhanced soil fertility) on lands that have been previously forested (IPCC 2019, Chapter 1, Box 2). In Oregon, these include riparian buffers of farmland, pasture, understocked stands in non-fire-prone areas, lands not naturally regenerating after high-severity fire, and urban reforestation.

There is a growing body of research identifying the carbon opportunity of reforestation after high-severity fires, especially in areas where there is little natural regeneration. In the West, studies have already documented increasing annual moisture deficits, resulting in greater difficulty for natural regeneration. Stevens-Rumann et al. (2018) conducted a meta-analysis of 52 wildfires in the U.S. Rockies between 1988 and 2011, and found that satisfactory seedling recruitment decreased from 70% to 46% and the percentage of sites experiencing no post-fire tree regeneration nearly doubled from 19% to 32%. Welch et al. (2016) found no regeneration on 43% of sites crossing 14 fires and 10 national forests in California. Even when disturbances are less severe or extensive, reforestation can enhance carbon sequestration rates, in both stand and soil, compared to waiting for natural regeneration (Nave et al. 2018). In another study, Sample (2017) identified 19.8 million acres of non-stocked forestland after recent natural or human disturbances, which could sequester an additional 46 MMT CO_2e per year if replanted. When reforestation occurs on land that had previously been converted to another use, such as in riparian buffers in farmland or pasture, there is not only a significant multi-decade boost in biomass sequestration, but also a significant enhancement to soil carbon (Nave et al. 2019).

Urban reforestation can also serve as an important carbon sink (Nowak 2013), and can help reduce emissions through energy savings (Nowak 2017). Oregon's urban areas currently store 8.1 MMT of carbon and sequester 710,600 metric tons CO_2e/year (Nowak 2013). These trees provide shade that result in 257,900 MWh and 1,212,100 MMBtu in energy savings, valued at $41.3 million/year (Nowak 2017).

Oregon has several mechanisms already in place to fund reforestation efforts. For reforestation after natural disaster, the Emergency Forest Restoration Program (EFRP) provides payments to nonindustrial private landowners to conduct restoration efforts, including tree planting, after a natural disaster. It pays 75% of the cost, including debris removal, site preparation, planting materials and labor, road restoration, fuel breaks, fencing and wildlife enhancement. For example, it was used in Wasco and Hood

River counties in Oregon to address 2018 wildfire damage, and in Douglas County to address 2018 drought and 2019 snow damages. Funding for the program must be approved annually by Congress, and each natural disaster is evaluated by the USDA's county or state Farm Services Agency committees.[5]

Oregon's Conservation Reserve Enhancement Program (CREP) incentivizes tree planting in agricultural riparian buffers. It is a cooperative venture between USDA Farm Service Agency and the state of Oregon, with support from local soil and water conservation districts, watershed councils and other regional partnership organizations. CREP pays landowners to plant trees and shrubs in riparian areas, install livestock fencing and implement other conservation measures.[6]

3.4 Land strategy 4: Increase carbon in existing forests and products through silviculture

Globally, improved forest management has the potential to mitigate 0.4 to 2.1 BMT CO_2e per year (IPCC 2019, Table 6.14). Fargione et al. (2018) estimate that improved forest management in the United States can sequester up to an additional 260 MMT CO_2e per year. Unlike the previously discussed strategies, increasing carbon storage in existing forests has the potential to either enhance or decrease harvest, which can impact fossil fuel emissions through material and energy substitution such as described in Figure 3.1 (IPCC 2019, Table 6.6; Smyth et al. 2014). For example, the Fargione et al. estimate assumes a national reduction in harvest of 10% (Fargione et al. 2018).

A lot of attention has been given to increasing carbon in existing forests and harvested wood products in the state of Oregon. Oregon's productive soils and climate accommodate trees species that are long-lived and can accumulate large amounts of biomass per acre. The main dominant species, Douglas-fir, is also valued as a building material and plays a globally significant role in providing long-lived wood products.

The most straightforward way to increase carbon stocks is to increase rotation age (Hudiburg et al. 2009; Law and Waring 2015; IPCC 2019) or decrease harvest intensity (Harmon et al. 2009). Older forests store more carbon than their younger counterparts, and if there is little risk of disturbance these can be considered relatively stable carbon pools. The age and maximum amount of carbon stored depends on species and site index (Gray et al. 2016). The rate of carbon sequestration also varies with age, with the largest amount of carbon accumulating during the mid-successional stages.

Maximizing production of both wood products and carbon stocks is done when the age of trees approaches the culmination of mean annual increment (CMAI), which is calculated by dividing the total stand volume by the age of the stand. CMAI varies by species and management intensity. For example, intensively managed loblolly pine trees can reach CMAI within 25 years, while mountain hemlock in the Rocky Mountains may take 125 years. CMAI for Douglas-fir in the Pacific Northwest is approximately 95 years, though intensive management can reduce CMAI to 55 years (Smith et al. 2006).

[5] https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2017/emergency_forest_restoration_program_oct2017.pdf

[6] http://library.state.or.us/repository/2010/201001201433493/OWEB_MONITOR_docs_2013_CREP_Annual_Report.pdf

Strategies that focus on maintaining or increasing soil carbon can result in better tree productivity, and vice versa. Nitrogen fertilization often increases soil carbon as well as tree growth, though the amount is dependent on soil origin and texture (Adams et al. 2005). Frey et al. (2014) found that U.S. soils typically have a high C:N ratio, resulting in high carbon accumulation with nitrogen additions, and almost the same amount of carbon increases in soil as in vegetation. Fertilization emits nitrous oxide (a potent GHG), but in Douglas-fir forests the emissions are more than offset by the increase in growth (Shrestha et al. 2014). However, the type of fertilizer, the timing of fertilization and the soil type can all influence the relative amount of nitrous oxide to carbon intake. Shrestha et al. (2014) found coated urea fertilizer had slightly less nitrous oxide emissions than urea, and emissions were less when soil was drier and cooler.

Other silvicultural practices, such as planting with improved seedlings bred for growth and other desired characteristics, or chemical site preparation, release from competing vegetation, fertilization and stocking control (e.g., initial-planting spacing and thinning) have been found to increase productivity in Douglas-fir forests by up to 43% (Vance et al. 2010). Similar to fertilization, site preparation, herbicide use and stocking control have embodied emissions associated with chemical manufacturing or emissions associated with the actual practice. These emissions are small compared to stand growth (Sonne 2006; Oneil and Puettmann 2017).

Developing strategies for increasing carbon stocks depends on initial site conditions, site productivity, risk of disturbance, product end-uses and substitution factors (Nabuurs et al. 2017; Pingoud et al. 2018; Smyth et al. 2014; Valade et al. 2017; Werner et al. 2010). Many studies have attempted to quantify mitigation strategies by looking at different scenarios of wood harvest, bioenergy use and product use. For example, Smyth et al. (2014) examined forest sector strategies for Canada and found they could achieve a cumulative mitigation of 254 MMT CO_2e in 2030 and 1.18 BMT CO_2e in 2050 through a combination of strategies including better utilization (more products per harvest through use of slash and more efficient harvest). They also found that the best strategy for short-term mitigation, which can be reducing harvest, reduced the ability of the forest sector to contribute to long-term mitigation, which can be producing wood products in a sustainable manner. Pingoud et al. (2018) found that in Finland carbon stocks could be increased while maintaining current harvest levels, by extending rotation ages and using less-intensive but more efficient thinning compared to current practices. Valade et al. (2017) found that European forest-sector sequestration efficiency was sensitive to harvest intensity, rotation length, fraction of harvest residues left on site, substitution efficiency and the impact of climate change itself. In the Pacific Northwest, Diaz et al. (2018) found that increasing carbon storage by expanding riparian buffers and increasing rotation length can increase total carbon storage, but reduces net present value to the landowner.

Carbon should be looked at as one of many other ecosystem services provided by forests, including biodiversity, clean water and timber. Werner et al. (2010) concluded that “the maximum possible, sustained increment should be generated in the forest, taking into account biodiversity conservation as well as the long-term preservation of soil quality and growth performance.”

3.5 Summary

Oregon's forests are well poised to help reduce the concentration of atmospheric CO_2 by concomitantly reducing the net flux of carbon dioxide to the atmosphere and increasing sequestration and storage of carbon in forests and long-lived wood products.

Oregon's land-use laws position the state at less risk of forest conversion relative to the rest of the country, though 2.5 MMT CO_2e is still lost every year through forest conversion. Favorable resource land property tax laws, incentive programs such as conservation easements and TDRs, and general forest management education and cost-share programs can help reduce forestland conversion rates.

Dry coniferous forests in the eastern part of Oregon are also at increasing risk of fire with climate change. Targeted thinning of smaller trees in combination with prescribed fire can increase forest resiliency. Cost-share programs are available through federal (NRSC and EQIP) and state (ODF, OWEB and SWDC) agencies, as well as education through Extension services and ODF. As with fire, insects and disease are also predicted to increase tree mortality with warmer winters and drought stressed forests. Almost 20% of Oregon's forests are at risk of losing up to 25% of their basal area in the next 15 years, due to insects such as spruce budworm and western pine beetle and root disease such as root rot. The best defense against mortality is to maintain healthy, vigorous forests by matching species and stock to sites, retaining or increasing diversity, and using well-timed thinning to select for the most vigorous stems.

Targeted reforestation can increase forest area, thereby increasing carbon sequestration and storage in both trees and soil. Oregon's opportunities include riparian buffers in current non-forestland, lands not naturally regenerating after high-severity fire, and urban reforestation. There are many cost-share programs in place to help with reforestation efforts, including the Emergency Forest Restoration Program (EFRP) and CREP, though all could be enhanced.

Potential avenues for increasing carbon sequestration and storage in Oregon's existing forests and products include increasing productivity through more intensive silviculture, and increasing rotation length or decreasing harvest intensity. In the latter pathway, careful attention should be given to trade-offs between overall wood product production and forest sequestration.

Given the breadth of forest management options listed above, it is clear that no one strategy is suited to every acre. Carbon should be managed along with the multitude of ecosystem services provided by forests, including clean water, biodiversity, air filtration and flood control, as well as timber and other non-timber forest products. A goal of creating healthy, resilient and productive forests will usually result in less emissions to the atmosphere and more sequestration in forests and products.

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CHAPTER 4: The Role of Wood Products and Biomass Energy in Carbon Stores and Emissions

Maureen Puettmann, Woodlife Environmental Consultants, and Bruce Lippke, University of Washington, retired

4.0 Introduction

Producing all materials, renewable and non-renewable, has environmental impacts. The environmental consequences, beginning with raw-material extraction and product production such as softwood lumber, are carried forward in the life cycle of a product through use, re-use and, ultimately, final disposal. All wood products and their production are not equal when it comes to environmental impacts. Some require whole logs, while others utilize the residues produced from other production processes such as lumber or plywood production. When wood products arise from sustainably managed forests, they can store more carbon in the final product for decades than is released during their manufacturing. References in this chapter to wood from sustainably managed forests means a forest where harvest rates do not exceed growth.

Life cycle assessment (LCA) standardized methodologies provide us a tool for determining the impacts of products (Figure 4.1). The key component is the life cycle inventory (LCI), which is an objective, data-based process of quantifying energy and raw material use as well as air emissions, waterborne effluents, solid waste and other environmental releases occurring within a system boundary. The life cycle impact assessment (LCIA) step characterizes and assesses the raw material use and environmental releases identified in the LCI, dividing them into impact categories such as global warming potential; acidification; eutrophication; ozone depletion; smog; primary energy and water consumption; and waste.

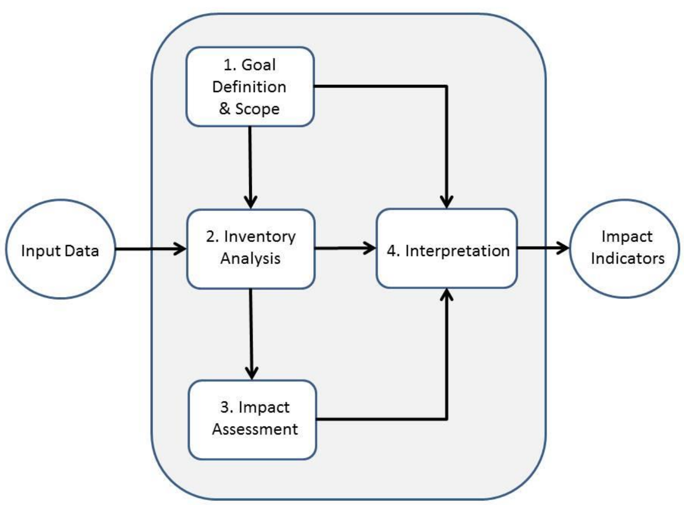

Figure 4.1: Life cycle assessment framework and the relationships between components. Adapted from ISO 14044 (ISO 2016).

The environmental impacts and benefits of wood use have been well documented using LCA over the past two decades. CORRIM, the Consortium for Research on Renewable Industrial Materials (www.corrim.org) has been reporting on the environmental impacts of producing wood products (Bergman and Alanya-Rosenbaum 2017a-b, Bowers et al. 2017, Milota and Puettmann 2017, Oneil and Puettmann 2017, CORRIM 2017, Chen et al. 2019, Salazar and Meil 2009). Due to its low embodied carbon and energy, wood has been shown to be the material of choice for building structures when enhanced sustainability is a goal. As sustainability goals become more important, products and processes that use less energy become correspondingly more important. Therefore, the focus of this chapter is how to produce and use wood to achieve this goal.

Embodied Carbon

Embodied carbon refers to the sum of all greenhouse emissions released during in the context of the LCA system boundary, which could include extraction, manufacture, transport, construction and end-of-life emission of building materials. Embodied carbon is expressed as CO_2e.

Nearly a decade ago, Lippke and Wilson (CORRIM 2010) stated, ‘‘The emphasis on carbon as an important metric for judging sustainability will likely have a profound effect on our future and provides many opportunities for research as well as investment in improved performance.’’ This prediction seems to be proving true. Since CORRIM's first publications (CORRIM 2005), there has been a steady increase in the demand for credible information on the environmental performance of materials, and more transparency within the LCA reports (CORRIM 2010, 2012, 2017). Architects and the wood products industry are playing an increased role in developing more environmental product declaration (EPDs) (http://www.carbonleadershipforum.org/projects/ec3/), international standards related to the sustainability of buildings (ISO 2017), and guidelines for developing EPDs for North American wood products (FPInnovations 2015, UL 2019).

LCAs will become increasingly more important as they're used by all industries to inform product and process design, as well as building system development, to minimize energy needs and carbon releases. Going forward, the need for credible, scientific, LCA-based information will be greater than ever. We cannot assume wood products will continue to enjoy environmental superiority without continued advancement in environmental and product performance, from cradle to grave. This chapter will provide information on the environmental impacts of wood products and biofuels, looking first at the role long-lived wood products have on carbon storage. We will then discuss the environmental impacts of wood building products; energy sources and how they drive embodied carbon and energy; and finally, opportunities for improved uses of wood to mitigate carbon emissions.

4.1 The role of wood products in carbon storage

Sustaining a volume of carbon stored in the forest through sustainable management while increasing carbon stored in harvested wood products provides an important climate change mitigation opportunity (Perez-Garcia et al. 2005a, Johnston and Radeloff 2019). Buildings provide an opportunity to displace nonrenewable materials with various wood products, thereby reducing dependence on more fossil-fuel-intensive materials.

Timber framing and "post-and-beam" construction are traditional methods of constructing buildings. Historically this type of construction has been limited to low-rise buildings such as single-family homes, smaller apartment buildings and nonresidential structures. More recently, there has been a shift in the fundamental assumptions surrounding building with wood. A new class of wood products (mass timber) has emerged, allowing wood buildings to be much taller; e.g., eight to 18 stories (MTCC 2018). Mass timber building materials thus provide an even greater opportunity for displacing steel and concrete building materials, which have inherently higher embodied carbon and energy (Buchanan et al. 2013, Malij et al. 2017, Meil et al. 2004, Perez-Garcia et al. 2005b, Pierobon et al. 2019, Robertson et al. 2012, Salazar and Puettmann 2019, Upton et al. 2007).

For example, a 186 m^2 single-family home built using light frame construction can use approximately 25.2 m^3 of softwood lumber, 6.7 m^3 of plywood or oriented strandboard (OSB) and 2.6 m^3 of nonstructural panels such as particleboard, totaling 16.7 tons of wood[7] (adapted from McKeever and Phelps 1994). From cradle to gate, the wood products used store 8.3 MT of carbon[8] or 30.4 MT of CO_2[9] (cradle to construction) (no use/maintenance or end-of-life scenarios included). The estimated[10] embodied carbon from cradle to construction is 11.9 MT carbon dioxide equivalents (CO_2e), with biogenic carbon emissions included (CORRIM 2017, Puettmann and Salazar 2018a). When the CO_2 stored in the wood is deducted as an offset, the resulting **net negative** is 18.6 MT CO_2e emissions—i.e., much more carbon is stored than emitted. The additional benefit of substituting wood for steel or concrete – i.e., displacing the emissions from producing them – can be even greater than storing more carbon, as will be detailed later in this chapter.

There are two dimensions to the dynamics of carbon stored in housing stock (adapted from Wilson 2006): 1) carbon flux, the carbon flow into and out of the stock on an annual basis, because every pool of carbon has a rate of carbon input and a rate of carbon output, and flux is the difference between the two; and 2) carbon storage, the total carbon pool for all housing stock (U.S.). Figure 4.2 illustrates single-unit new housing starts for the past 40 years in the entire United States and in the U.S. West. Total Western housing starts (Figure 4.2: orange line) ranged from 117,000 total units in 2009 to 525,000 in 2005 (U.S. Census 2019).

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[7] Plywood is represented in the mass of the house and the GWP impact

[8] Assumes a 50% carbon content of wood

[9] To convert from mass of wood to CO_2 = Mass of wood x 50/100 x 44/12

[10] Estimated construction impacts from Meil et al. 2004. https://corrim.org/wp-content/uploads/2018/03/environmental-impacts-single-family-building-shell-harvest-to-construction.pdf

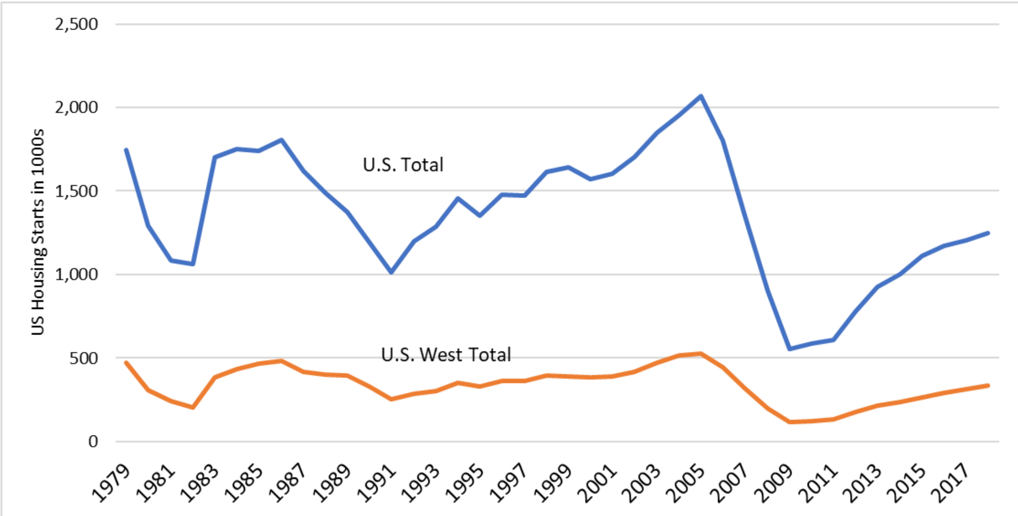


Figure 4.2: Total unit housing starts in the the United States (blue line) and in the western United States (orange line) (U.S. Census 2019).

Figure 4.3 shows the estimated annual new carbon storage based on new housing units. Calculations for assessing the amount of carbon going into new housing starts used the mass for a single-family home of 16.7 tons (adapted from McKeever and Phelps 1994). The carbon associated with the total single housing starts annually ranged from 3.6 to 14.6 MMT (1979-2018) (Figure 4.3). The carbon estimates in Figure 4.3 represents softwood lumber, plywood and particleboard; it does not include windows, doors, floors, cabinetry, millwork or furniture.

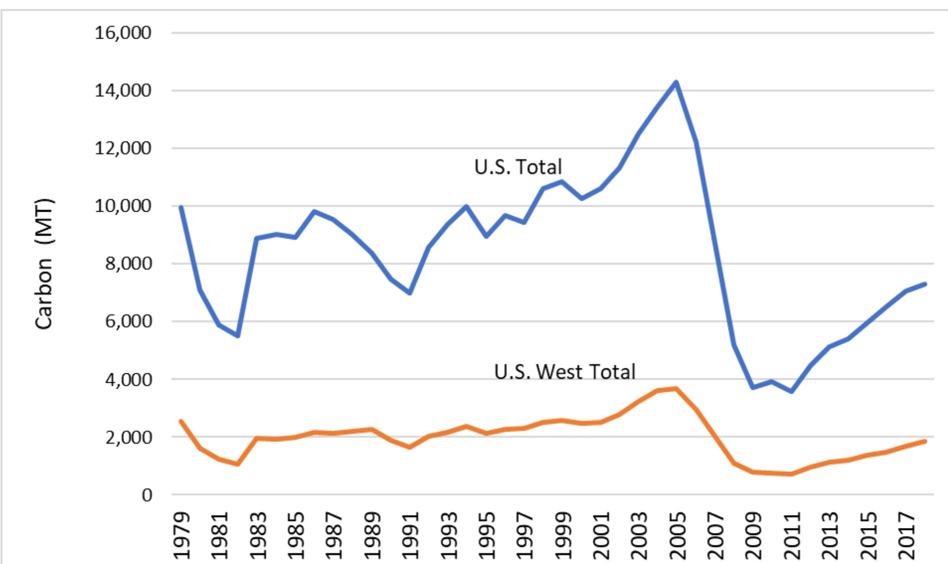


Figure 4.3: Annual new carbon storage in the United States (blue line) and in the western United States (orange line) for single-family housing stock (U.S. Census 2019).

The estimates of carbon stock are based on the U.S. housing inventory for 2018, estimated at 138 million single units (HUD 2019). Using the same average house size of 186 m^2 and an average carbon storage of 8.3 MT per house, the total carbon store of the U.S. housing inventory is 1,150 MMT. This amount is equivalent to 4,218 MMT of CO_2. The flux would be the annual change in total carbon store (i.e., the change in housing inventory). If wood use increases over time, displacing the use of steel and concrete designs and their subsequent emissions, the carbon store and overall global carbon mitigation would likely increase. The stock in harvested wood products in use in the Pacific Northwest has been reported to be 70 MMT (Butler et al. 2014).

The main product from softwood sawmills is lumber. Other products (coproducts) are also made when logs, which are round in cross-section, are processed into lumber, which is rectangular in cross-section (Figure 4.4). These coproducts could include chips for pulp, and sawdust and shavings for panels, paper or fuel. In the Pacific Northwest, logs arrive at the mill with much of the tree's bark intact (Figure 4.4). Lumber represents about 44% of the log mass. Coproducts, which include bark, chips, sawdust and shavings, represent the remaining 56%. Roughly 30% of the chips are sold to pulp to paper. Another product of the mill is hogged fuel, which can be bark or a mix of bark and wood, depending on how individual mills classify it. The hogged fuel (22%) goes to on-site boilers or energy systems and is used for drying lumber. On-site energy for PNW lumber production covers nearly 100% of the on-site energy demand.

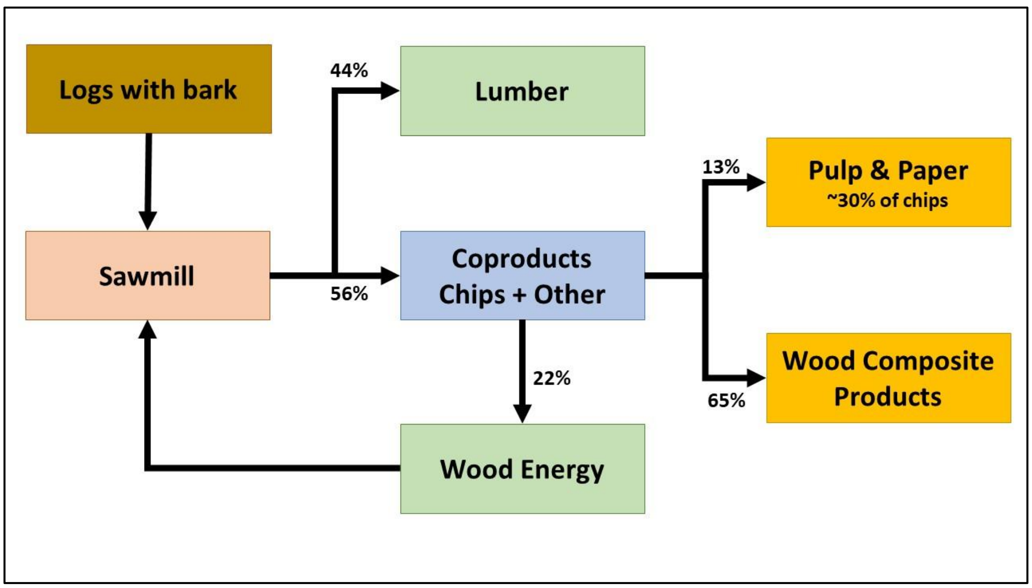


Figure 4.4: Flow material in an average PNW softwood lumber production facility (data is based on surveys of manufacturers located in Oregon and Washington in 2012; Milota 2015, Puettmann 2019).

Oregon plays a major role in providing a wood resource for manufacturing the many different products used in residential construction and mass timber buildings. Nearly 88% of Oregon's timber harvest is processed into lumber and plywood at wood manufacturing facilities in the state (Simmons et al. 2016). Lumber and plywood manufacturing facilities combined represent 89% of Oregon's wood products manufacturing sector. Using the total lumber and plywood produced in Oregon in 2017 at an estimated mass of 5.6 MMT (OFRI 2019), and assuming an average house size of 186 m^2 with a mass of 14.9 MT of wood products, the state provides enough lumber to make 374,000 single-family homes. Therefore, the **carbon storage potential** of Oregon-produced lumber and plywood is approximately 2.8 MMT (10.2 MMT CO_2e).

4.2 LCA of wood products

Wood-based materials have been shown to outperform steel and concrete assemblies across several environmental impact indicators including GWP, embodied energy and solid waste. Perez-Garcia et al. (2005b) reported that wood floor assemblies of a single-family house used 67% less energy, emitted 157% fewer carbon emissions and had 312% less water consumption from cradle to grave than an equivalent steel assembly. Over the past 20 years there has been extensive documentation on the environmental impacts of producing wood products from cradle to gate. (www.corrim.org). Based on LCA studies, many key environmental attributes of wood products, such as lower embodied energy and lower embodied carbon, compared to equivalent use of non-renewable materials, have been extensively documented (Perez-Garcia et al. 2005b, Lippke et al. 2019, Meil et al. 2004, Sathre and O'Connor 2010, Upton et al. 2007). Although wood is the primary building material in single-family residential construction, it has previously had limited application in mid-rise and commercial buildings. However, with the introduction of mass timber products such as cross-laminated timber (CLT) and mass plywood panels (MPP) (Ortiz 2018), the dynamics of the building industry are changing. Environmental attributes of mass timber are discussed later in this section.

Global Warming Potential (GWP)

GWP is a measure of how much heat a greenhouse gas traps in the atmosphere up to a specific time horizon relative to CO_2 *(source: Wikipedia).*

What is an EPD?

An environmental product declaration, or EPD, is a standardized report of environmental impacts linked to a product or service. An EPD is similar to a nutritional label on food. It communicates the environmental performance of a product to consumers.

EPD "Nutritional" Label – Wood Product

Amount per Unit – cubic meter

LCA Impact Assessment	Unit	Total	Forestry Operations	Wood Production
Global Warming Potential	kg CO_2 eq.	143	11	132
Acidification Potential	SO_2 eq.	1.60	0.15	1.45
Eutrophication	kg N eq.	0.06	0.01	0.05
Smog	kg O3 eq.	25	5	20
Total Energy	MJ	7,425	165	7,260
Non-Renewable Resources	kg	6	0.01	6
Renewable Resources	kg	640	0.00	640
Water Use	L	1,061	11	1,050

Historically, a preferred environmental building product was one that was made from renewable or recycled resources. Today, building materials are held to a higher standard of transparency that goes beyond their natural attributes. Builders, designers, politicians and the general public are asking for the full suite of a material's environmental impacts to meet "green building" standards and state and national emission reduction benchmarks, to name a few. Building materials that have low embodied carbon and energy are sought out, and other functional aspects such as structural performance, ease of installation and product durability are also desired. Users of building materials are increasingly relying on science-based quantitative LCA studies and EPDs that offer assurance that the material has the environmental attributes they seek.

4.2.1 Importance of standards in LCAs

According to the International Organization for Standardization (ISO 2006), LCAs are performed under a predetermined system boundary. For example, the LCA might only include activities on-site at a production facility, which would classify the LCA as a gate-to-gate. A cradle-to-gate would include all activities from resource extraction through the production gate or construction gate. A cradle-to-grave LCA would include extraction, production, use/maintenance and final disposal. It is important to understand the system boundaries LCA results represent. Inaccurate descriptions or misinterpretations of system boundaries could lead to false claims and comparisons with other materials. A generic cradle-to-grave system boundary for a wood product is shown in Figure 4.5. This system boundary shows the potential of recycling or reusing the wood product, and the opportunity for capturing energy at the end of life.

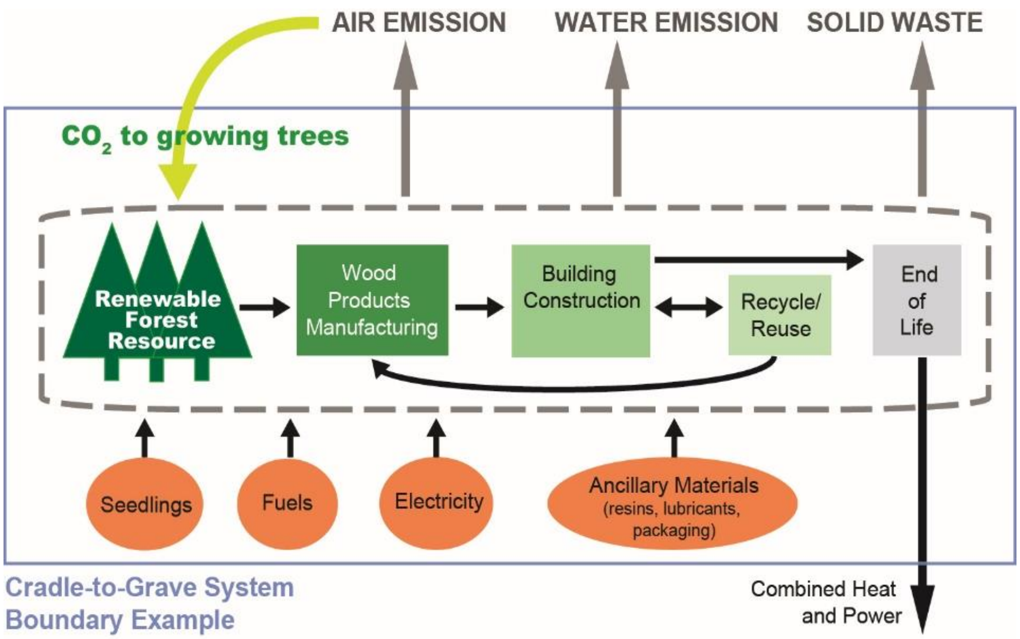
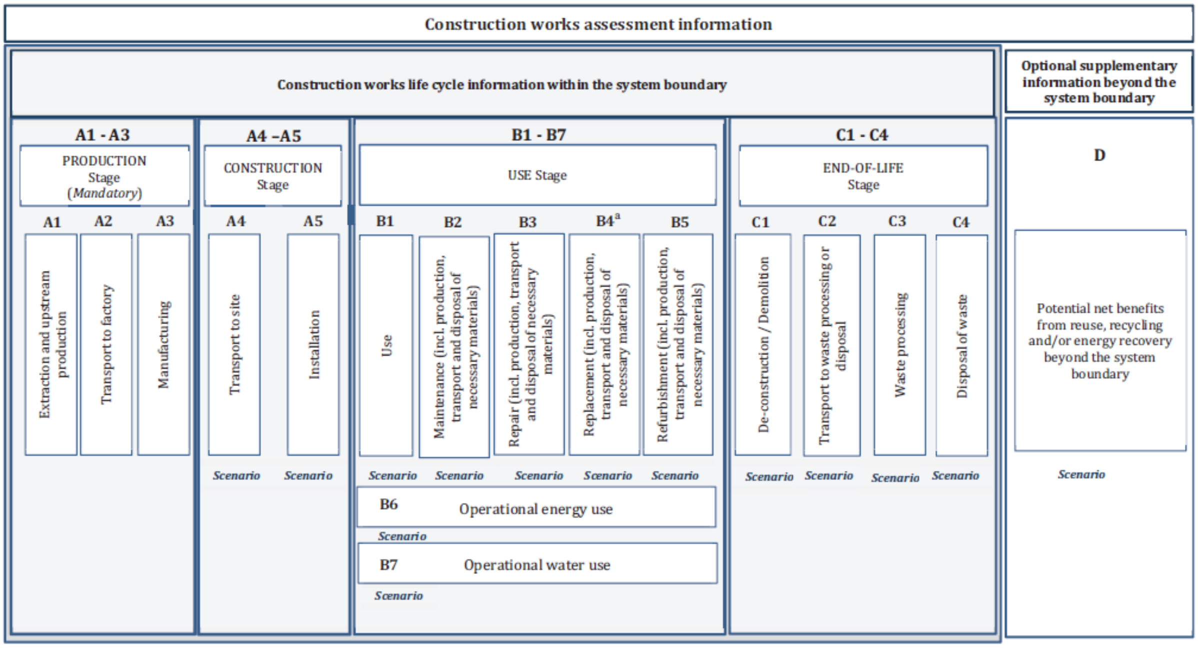


Figure 4.5: Cradle-to-grave system boundary example of a wood product.

The core document for wood product LCAs and subsequent EPD development is the ISO 21930 standard *Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services* (ISO 2017). The standard serves as the main reference guideline to the *Product Category Rule Guidance for Building-Related Products and Services Part B Structural and Architectural Wood Products EPD Requirements* (UL 2019) (hereafter referred to as "PCR"). ISO 21930 provides the essential guidance to maintain uniformity in the means and methods for reporting LCAs and EPDs across products. The standard defines the rules and core elements that must be included. The standard also requires the clear definition of included life stages, in the form of modules (Figure 4.6). Depending on the system boundary defined as described earlier, the life cycle of a wood product, defined by ISO 21930, is divided into four life cycle stages. All life cycle stages (modules) are not required, only those that fall within the defined system boundary. A cradle-to-gate LCA would include the mandatory modules A1-A3, with an option for A4-A5 (cradle to installation).



[a] Replacement information module (B4) not applicable at the product level.

Figure 4.6: Life cycle stages and associated modules for construction products from ISO 21930 (ISO 2017).

LCA results for wood products are expressed on a declared unit of cubic meter (m^3) for most products, and a lineal meter for other products such as I-joists and molding. For the purposes of comparison and inclusion, LCAs on products are presented in this chapter on a declared unit of one cubic meter. Later in the chapter results are presented on a square meter of a wall or floor area; in these cases, a functional unit of a square meter is used. Table 4.1 shows recent cradle-to-gate (A1-A3) LCA results for several wood building materials produced in the Pacific Northwest (PNW). A small subset of the reporting indicators required by ISO 21930 and the PCR is presented here. For a complete list all mandatory reporting requirements, see reports available at www.corrim.org.

Engineered wood products (EWP) such as laminated veneer lumber (LVL) and I-joists result in higher energy use and environmental impact potentials, due to the additional processing required and the addition of resin. For example, when plywood is produced, veneer is also produced and sold as a coproduct to LVL manufacturers. The veneer enters the LVL system boundary as a resource input, bringing with it some of the upstream impacts associated with producing veneer (CORRIM 2017). This is also the case for I-joists, which have a low on-site impact for assembly, but inherit the upstream impacts of plywood, OSB, LVL and lumber production (CORRIM 2017).

Table 4.1: Cradle-to-gate (A1-A3) impact indicators for wood products produced in the Pacific Northwest, per cubic meter of each product.

Selected indicators as described in ISO 21930		**Softwood lumber**	**Softwood plywood**	**Glulam**	**LVL**	**Engineered I-joist**
Indicator	**Unit**	**Values (A1-A3) / per cubic meter**				
Global warming potential, fossil	kg CO_2e	61	176	136	254	294
Ozone depletion potential	kg CFC11e	<0.00	<0.00	<0.00	<0.00	<0.00
Acidification potential	kg SO2e	0.52	0.95	11.80	2.40	4.19
Eutrophication potential	kg Ne	0.22	0.78	1.16	1.89	1.14
Smog potential	kg O3e	15	24	411	61	133
Nonrenewable energy	MJ	865	3,088	4,743	4,352	6,372
Renewable energy	MJ	2,488	4,915	3,176	4,540	3,282
Total energy	MJ	3,353	8,003	7,920	8,892	9,654
Freshwater use	L	369	1,059	543	1,175	1,707
Solid waste	kg	6	44	12	52	46

4.2.2 Reporting biogenic carbon removals and emissions of wood products

Tracking carbon can be complicated, especially when wood product manufacturing processes vary significantly between products. Every manufacturing process emits carbon, and these processes are linked through complex interactions, leaving every impact dependent on a long list of other impacts. We need to look closely at the effectiveness of using all wood products, in terms of how best to mitigate carbon emissions and avoid unintended consequences. For example, the wood residues produced during lumber manufacturing can have many uses, such as pulp and paper, wood composite panels and biofuels. Some of these uses are more effective in displacing carbon emissions than others, and some have a direct substitution effect with fossil products. Proper accounting of the biogenic pathways in a wood product's life cycle is critical to fully evaluate the carbon benefits. Evaluating cradle-to-gate (A1-A3) life cycle stages provides vital information regarding differences between products, taking these evaluations all the way through to end of life (C4-C5) and possible reuse (D), would provide the best understanding. Unfortunately, much of this information is unavailable or based on many subjective assumptions.

Wood is a bio-based material and thus contains biogenic carbon. The accounting of biogenic carbon follows the requirements set out in the UL 2018 PCR Part A, which follows requirements in ISO 29130 (ISO 2017).[11] Per these standards, biogenic carbon enters the product system via removal from the forest as a primary material. Under the guidelines for sustainable forest management in ISO 21930, the carbon removal is considered a negative emission, and is characterized with a factor of -1 kg CO_2e/kg CO_2.[12] The biogenic carbon that leaves the system as a product or coproduct(s), and/or is directly

[11] PCR Specific Part B (§3.10): Treatment of Biogenic Carbon: Accounting for the uptake and release of biogenic carbon throughout the product life cycle shall follow Section 7.2.7 of ISO 21930:2017.

[12] From ISO 21930 "Note that for wood entering the product system, biogenic carbon may only use the negative characterization factor when the wood originates from sustainably managed forests."

emitted to the atmosphere when combusted, is characterized with a factor of +1 kg CO_2e/kg CO_2 of biogenic carbon in calculating the GWP. These mass flows of biogenic carbon from and to nature are listed in the LCI and expressed in kg CO_2. Emissions other than CO_2 associated with biomass combustion (e.g., methane or nitrogen oxides) are characterized by their specific radiative forcing factors in calculating the GWP (Table 4.1).

An example of using reporting requirements[13] is described for PNW softwood lumber production (Milota 2020) in Table 4.2. Using the method described above, when the log was removed from the forest 1.98 MT CO_2e (A1-resource extraction) was removed (-1.98 MT CO_2e). When 1 m^3 of lumber was produced, it stored 0.23 MT of carbon or +0.85 MT of CO_2e (C3/C4). As lumber is produced, several coproducts are also being produced (Figure 4.4), and these account for an additional +0.90 MT CO_2e (A3). Together the product and coproduct(s) represent a total "emission" of wood products leaving the system boundary of +1.75 MT CO_2e. Transportation does not have biogenic carbon emissions associated with it; therefore, there are not values in that column in Table 4.2. Packaging contributes a small amount to both the removal and the emission (Table 4.2). In accordance with ISO 21930, emission from packaging is reported in A5 and emission from main product is reported in C3/C4. The system boundary for this LCA data only includes module A1-A3; Table 4.2 is only a reporting requirement of results that occurred within the A1-A3 system boundary. This example shows that 90% of CO_2e harvested in the logs ends up in the final product, the coproducts and the biofuel used on-site for energy.

Table 4.2: A1-A3 reporting requirements for removals and emissions of all biogenic carbon parameters as per ISO 21930 and UL 2018 Part A (data is from softwood lumber; Milota 2020).

A1 A3 (cradle-to-gate) biogenic carbon parameters for PNW softwood lumber	**A1- Resource extraction**	**A2- Transportation**	**A3- Manufacturing**	**A5 – Construction**	**C3/C4 – End-of-life scenario**	**Total**
	MT CO_2e/m^3					
Biogenic carbon removal from product	(1.984)					(1.984)
Biogenic carbon emission from product + coproducts			0.902		0.853	1.754
Biogenic carbon removal from packaging			(0.002)			(0.002)
Biogenic carbon emission from packaging				0.001		0.001
Biogenic carbon emission from combustion of waste from renewable sources used in production	0.024		0.207			0.231

[13] PCR Specific Part A (§4.2): Accounting for Biogenic Carbon Uptake and Emissions: See ISO 21930, section 7.2.7, for requirements on accounting for the biogenic carbon removal(s) and emissions of the product system in the form of mass flows to and from nature. The amount of biogenic carbon contained within the packaging material shall be included in the scenario information for module A5. The amount of biogenic carbon removed via the declared unit of product shall be documented in the scenario information at end of life. In both instances, biogenic carbon shall be expressed as kg CO_2.

Building off the biogenic carbon removals and emissions reported in Table 4.2, these are reported as GWP biogenic in Table 4.3. Taking the sum of the biogenic and fossil GWP, the net result is the value of the GWP fossil alone.

Table 4.3: Mandatory reporting requirements for A1-A3 global warming potential (GWP) as per ISO 21930 and UL 2018 Part A (data is from softwood lumber; Milota 2020).

Selected mandatory indicators as described in ISO 21930	**A1**	**A2**	**A3**	**Total**
PNW softwood lumber	**MT CO_2e/m^3**			
Global warming potential, total	(1.97)	0.102	2,021.10	60.97[14]
Global warming potential, biogenic	(1.98)	0.00	1,983.94	0.00
Global warming potential, fossil	0.014	0.102	37.17	60.97[15]

4.2.3 Carbon impacts for building components and assemblies

So far, the LCA results presented in this chapter have been on a declared unit basis of 1 cubic meter. When LCA results are presented as a functional unit, it's possible to make comparisons between alternative building materials. For example, on a functional unit basis we can compare two wall assemblies serving the same function using different materials (e.g., steel, wood, concrete block). Figure 4.7 shows GWP results for different structural components that make up a wall (no hardware, insulation, gypsum, etc.) when wood products are used, compared to non-wood alternatives. EWPs have higher GWP results per square meter over the solid wood stud, due to the energy requirements and chemical production of the resin. Recent published LCAs indicate the resin impact on GWP can increase the total A1-A3 from 23% to 28% (www.corrim.org/latest-reports/). Developing renewable-based resins could have significant positive environmental attributes to EWP. The type of fuel used is usually correlated directly with the GWP of a product. During the production of wood products, renewable wood fuel is used for generating the heat and steam used for drying wood and veneer, and for pressing wood and resin together (Table 4.1). The combustion of renewable biomass fuel releases the biogenic CO_2e emissions shown in green in Figure 4.7. The GWP biogenic emission shown in Figure 4.7 includes carbon emissions from slash burning, a management practice that allows for more effective forest regeneration. Later in this chapter, we will present the parameters for biogenic carbon reporting in LCAs.

[14] See Table 4.1 softwood lumber of this chapter.

[15] See Table 4.1 softwood lumber of this chapter.

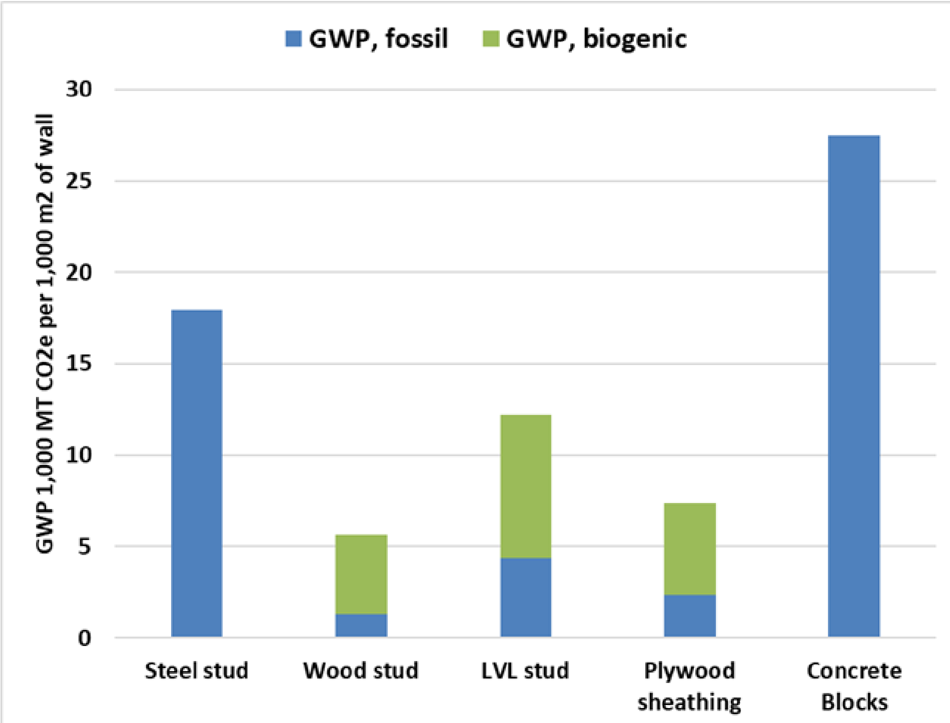


Figure 4.7: Cradle-to-gate (A1-A3) GWP for different structural components in a 1,000-square-meter wall. No hardware, insulation, gypsum, etc., is included. GWP biogenic emission includes carbon emissions from slash burning for more effective forest regeneration. (Lippke et al. 2019).

When we introduce the methodology described above on carbon store, the wall becomes the "inventory." The result is a value for net carbon emission, as expressed as GWP (total carbon emission minus carbon store). To illustrate this, Figure 4.8 shows 1 square meter (m^2) of floor area for wood product assemblies and alternatives. The orange bars show total GWP for all assemblies. The blue bars are the carbon stored (as CO_2e) in the wood component as part of the total floor assembly. The green bars are the net carbon emission. All assemblies that contain some wood will store carbon. The all-wood assemblies will store more carbon in the floor than is released during production (A1-A3), resulting in a net negative GWP.

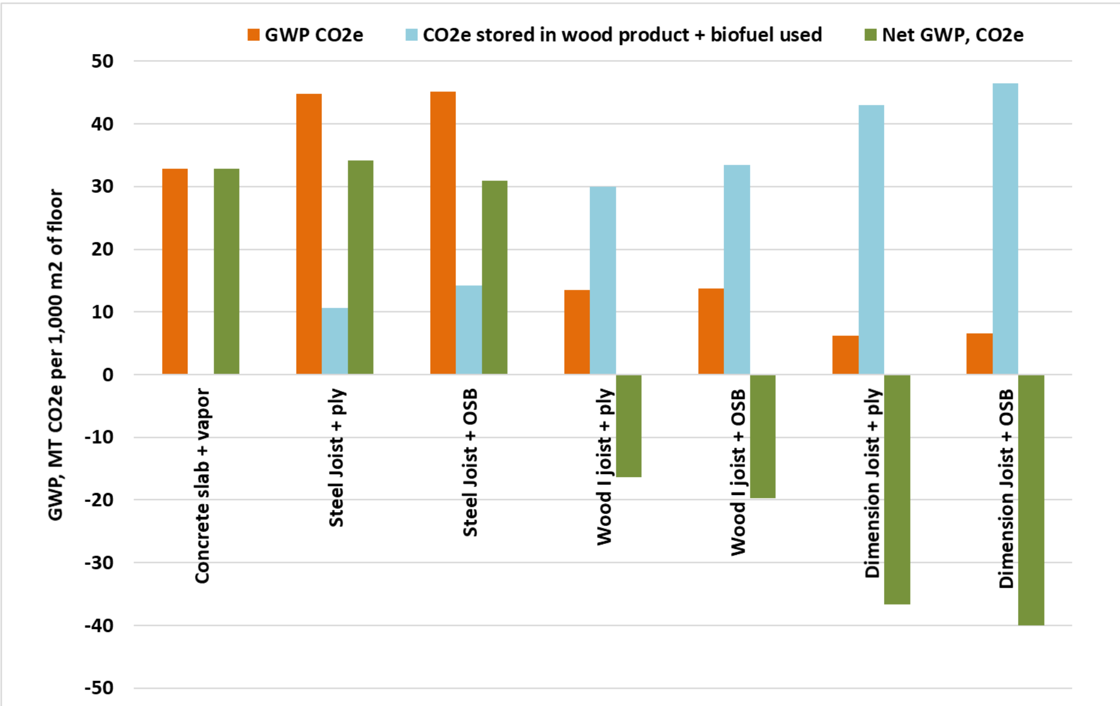


Figure 4.8: Cradle-to-gate (A1-A3) GWP for different structural assemblies in 1,000 square meters of floor area (Lippke et al. 2019).

4.2.4 Emission displacement information to improve carbon mitigation and avoid unintended impacts

Estimating carbon displacement has been a primary focus of recent research. It requires measurements across every stage of processing from forest regeneration to harvesting, through the creation of biofuels used in production and a wide range of high-volume wood products, plus analysis of different end uses and final disposal. There is a wide range of efficiencies with each possible use of wood, with an equal range to displace alternative materials. Carbon efficiency in terms of carbon stored and displaced per unit of carbon in the wood used is expressed in Equation 1. By applying this equation to wall and floor components and assemblies, a hierarchy of carbon efficiencies can be established (Tables 4.4 and 4.5).

Equation 1:

$$Displacement\ Efficiency = \frac{[(Alt\ GWP - Alt\ C\ in\ product) - (Wood\ GWP - Wood\ C\ in\ product)]}{(Wood\ fiber\ used)}$$

- *Alt GWP = GWP result for non-wood alternative*
- *Alt C in product = Carbon stored in non-wood alternative as* CO_2
- *Wood GWP =* GWP_{fossil} *result for wood product*
- *Wood C in product = Carbon stored in wood product as* CO_2
- *Wood fiber used = Carbon stored in total wood fiber used as* CO_2 *for non-wood alternative and wood product*
- *All units in mass of* CO_2e

For wall components, substituting a PNW wood stud component for a PNW steel stud component displaces 1.54 units of carbon emission for every unit of carbon in the wood stud, including the biofuel used for processing (Table 4.4). The efficiency per unit of carbon in the wood stud only is 1.93. The efficiency based on the wood stud is only important when the biofuel feedstock (wood residues) may be of high enough quality to be used in wood composite panels – therefore increasing the overall efficiency more than using it as an energy fuel.

CLT is more like a wall assembly than a component of a wall. A CLT wall design contains much more wood than traditional light-frame wood construction. The low efficiencies seen in Table 4.4 are a result of the high denominator (mass of the CLT) in Equation 1. In addition, CLT inherits the upstream carbon emissions and subsequent energy use from lumber production; in one study by Puettmann et al. (2019), lumber production represented 27% of the total energy for producing CLT.

The potential for higher displacement efficiency of CLT will be in comparisons of whole building designs, where CLT has the opportunity to displace concrete and steel in high-rise buildings and subsequently store more carbon. Factoring this in, Table 4.4 still shows a positive displacement of 1 unit of carbon emission for every unit of carbon in the wood used for CLT, when substituted directly for a concrete block wall. What Table 4.4 does indicate is that using CLT in low-rise buildings results in lower efficiencies (1.02) than for traditional light-frame wood construction (1.93). The high potential to reuse CLT after the end of building life and efficiently reprocess it into new products will substantially increase efficiency over a longer time frame (A1-D).

Table 4.4: Displacement efficiencies of various wall and floor components when wood components are substituted for alternatives (net CO_2 emissions displaced per wood fiber used [A1-A3]; values calculated using Equation 1).

WALL COMPONENTS[16]	**Displacement efficiency**	**Displacement efficiency w/biofuel**
Steel stud vs. wood stud	1.93	1.54
Concrete blocks vs. wood stud	2.46	1.97
Concrete blocks vs. CLT Oregon	1.02	0.84
FLOOR COMPONENTS		
Steel joist vs. wood dimension joist	2.24	1.79
Steel joist vs. wood I-joist	2.95	1.77
Concrete slab vs. wood I-joist	2.36	1.77
Concrete slab vs. wood dimension joist	1.89	1.51
Wood I-joist vs. wood dimension joist	0.48	0.38

[16] Non-wood materials' environmental impacts were calculated using the Athena Sustainable Materials Institute (ATHENA) 2019 Impact Estimator for buildings: https://calculatelca.com/software/impact-estimator/. (Accessed Sept. 2019).

Floors are much different than walls, as they require greater stiffness to prevent bending and bounce; hence a higher gauge of steel and larger wood dimensions are required. The range of floor component efficiencies is displayed in Table 4.4. The PNW wood dimension joist (Figure 4.9A) component displacing a PNW steel joist component represents 1.79 units of carbon for every 1 unit of carbon in the wood joist, including the biofuel used in producing it (Table 4.4). The efficiency per unit of carbon in the dimension wood joist only is 2.24. While the wood I-joist (Figure 4.9B) uses 27% less wood fiber than a dimension joist, it also stores less carbon in the product, offsetting some of the efficiency benefits of using wood. By using less wood, it increases the amount of wood available for other uses, a resource efficiency improvement that is not captured in Equation 1.

Figure 4.9: A) A standard wood dimension joist can range in size from 2 inches thick to 4 to 12 inches wide (photo credit Lampert lumber); **B) Wood I-joists are manufactured on a linear basis, with no measurements for height and width.** On average, an I-joist has a height of 11.75 inches and a width of 1.88 inches (photo credit APA – The Engineered Wood Association).

While steel joists and wood I-joists are close functional substitutes, floors and walls generally require consideration of a sheathing material, which adds to both the carbon emission and the carbon stored in the product (Table 4.6). Adding a common component like a floor covering or wall sheathing results in the same increase of output carbon and input carbon to both the wood design and alternative design. It also lowers the efficiency, while still providing leverage to reduce emissions by substituting wood for non-wood assemblies. Every product and construction assembly impacts carbon differently, resulting in an enormous array of alternatives that affect carbon mitigation (Table 4.6).

Table 4.5: Displacement efficiencies of various wall and floor assemblies when wood components are substituted for alternative (net CO_2 emissions displaced per wood fiber used [A1-A3]; values calculated using Equation 1).

WALL ASSEMBLIES	**Displacement efficiency**
Steel stud + OSB vs. wood stud + OSB	1.04
Steel stud + plywood vs. wood stud + plywood	1.17
Concrete blocks + gypsum vs. wood stud + OSB	3.60
Concrete blocks + gypsum vs. wood stud + plywood	3.94

FLOOR ASSEMBLIES	Displacement efficiency
Steel joist + OSB vs. dimension joist + OSB	1.52
Steel joist + OSB vs. I-joist + OSB	1.51
Steel joist + plywood vs. dimension joist + plywood	1.65
Steel joist + plywood vs. wood I-joist + plywood	1.69
Concrete slab + vapor barrier vs. dimension joist + plywood	1.62
Concrete slab + vapor barrier vs. dimension joist + OSB	1.57
Concrete slab + vapor barrier vs. wood I-joist + plywood	1.65
Concrete slab + vapor barrier vs. wood I-joist + OSB	1.57

4.2.5 The impact of transportation (A2)

Where products are produced, how far they travel and the mode of transportation used are some of the product information details users seek. As mentioned earlier, 88% of Oregon's timber harvest is processed into wood products by Oregon manufacturers. Global warming potential (GWP) impacts from the transportation stage (A2) ranged from 5% to 17% for GWP and 4% to 15% for nonrenewable fuel consumption, depending on the type of wood product (Table 4.6). The transportation module A2 includes logs from the forest to sawmills and plywood facilities; resin transport from manufacturers to wood product facilities; veneer from plywood producers and logs to LVL sites; lumber to glulam facilities; and plywood, lumber, LVL and OSB to I-joist assembly facilities. For more detailed information on the transportation impacts of various wood products, visit www.corrim.org/latest-reports/.

Table 4.6: Transportation (A2) as a percent contribution of the total A1-A3 on GWP and nonrenewable energy use for various wood products produced in the PNW (products such as lumber and glulam that have low GWP and energy from cradle to gate [A1-A3] will show a higher percent contribution for transportation because their total [A1-A3] GWP value is less than GWP results for EWPs).

Cradle-to-gate A2 impacts	Softwood lumber	Softwood plywood	Glulam	LVL	Engineered I-joist
	Transportation (A2) as a percent of total (A1-A3) GWP				
GWP	17%	7%	16%	5%	8%
Nonrenewable energy	15%	5%	6%	4%	5%

Recent surveys show that the average log haul distance from the forest to lumber production facilities was 108 km, and 104 km for logs to plywood facilities (CORRIM 2017, Puettmann et al. 2016a). But if harvesting restrictions were imposed in the PNW, what would be the impact of longer haul distances on selected indicators for softwood lumber production? To answer this, log haul distances were set at 43%, 143%, 186% and 200% above the baseline of 108 km. Results from a sensitivity analysis showed that if the transportation distance of the log haul distanced were doubles (216 km or 134 miles), the result was a 90% increase in total (A1-A3) GWP (from 0.061 MT CO_2e to 0.116 MT CO_2e), and a 99% increase in nonrenewable fuel use (from 865 MJ to 1,655 MJ). This is a good example of an unintended consequence; in this case, reducing harvesting in a region with the intention of lowering carbon emission, with the assumption of maintaining the demand for wood products.

4.3 LCA of mass timber buildings

Mass timber construction can have a greater carbon displacement benefit, because it moves wood into building designs that traditionally have been dominated by steel and concrete materials. It is estimated that 200 million to 250 million board feet of softwood lumber was consumed in mass timber manufacturing in 2018 (Anderson et al. 2019), representing less than one-half of 1 percent (0.005%) of the total softwood lumber production in North America. To put this into perspective regarding sustainability, if the lumber demand for cross laminated timber (CLT) increased to 3 billion board feet, that would still only account for 5% of the total softwood lumber production. As it stands, there is very little threat to our forest systems from increasing wood production to support the movement of mass timber construction. On the contrary, mass timber construction can displace carbon emissions from building with steel and concrete by having lower embodied carbon, by storing carbon and by having the potential for re-use and recycling at the end of life.

The majority of North American mass timber production comes from facilities located in the Northwest (NW), representing western British Columbia, Washington, Oregon and Montana (Anderson et al. 2019). There are two mass timber producers in Oregon, one producing CLT and the second producing mass plywood panels (MPP) (www.frereslumber.com). In 2018, 53% of the mass timber production capacity was from the NW region, 33% from the northeast, 11% from the southeast and 3% from the mid-states. It is reported that the estimated annual North American mass timber production capacity for building materials is 285,000 m^3 for 2018 (Anderson et al. 2019). Since mills usually do not run at capacity, the estimated "practical" annual production is 186,000 m^3 (65% capacity). In the NW region, the new mass timber facilities planned in 2019 add an estimated practical capacity of 176,000 m^3. By 2020, the Northwest will be producing about 76% of U.S. CLT (Anderson et al. 2019).

Cross-laminated timber is at the forefront of the mass timber movement, which is enabling designers, engineers and other stakeholders to build taller wood buildings. Cross-laminated timber panels are made by laminating dimension lumber orthogonally in alternating layers. Among the environmental advantages of CLT are that it is a natural carbon store and that its use generates virtually no waste at a building site, as panels are generally prefabricated before delivery. Panels made from CLT are lightweight yet very strong, with good fire, seismic and thermal performance. The recently completed Brock Commons building in Vancouver, British Columbia, serves as just one of many testaments to the growing momentum of the mass timber movement. In a cradle-to-gate assessment of Canadian CLT (Structurlam 2013), net carbon impacts have been reported at -678 kg CO_2 eq/m^3, which can position CLT as having a high environmental advantage over non-wood materials.

Albina Yard

Albina Yard is a 4-story, 16,000 sq. ft commercial office building in Portland, Oregon. It is a mass timber building using both glulam beams and cross laminated timber manufactured in Oregon.

- Built in 2015
- 161,000 board feet (CLT + glulam)
- 19,550 wood panels
- Stores 80.5 MT carbon, the equivalent of offsetting 295 MT of CO_2 emissions.

Producing CLT currently uses much more fossil fuels with lumber mills not co-located, resulting in additional transportation impacts. Since CLT facilities currently purchase lumber from other locations, the transportation of lumber to the CLT plant is not optimal. Cross-laminated timber production and use is still in the early learning curve, and requires additional research to track how it responds over time in terms of lower embodied carbon from changes in production, as well as building design (Chen et al. 2019, Pierobon et al. 2019, Schmidt and Griffin 2013). From an optimistic perspective, CLT has the opportunity for easy reprocessing at end of life, and the potential for much higher carbon stores than conventional low-rise building products (Chen et al. 2019). However, using it in typical low-rise buildings is not as efficient as using conventional residential wood-frame walls (Glover et al. 2002, Hammond and Jones 2008).

We are just at the beginning of assessing the environmental impacts of mass timber components and their environmental performance in buildings. The carbon mitigation potential of mass timber buildings goes well beyond the embodied carbon from cradle to gate. Studies are underway to assess environmental performance and regional differences of mass timber buildings, compared to traditional buildings of concrete and steel ranging from 8 to 18 stories. When these results become public, we will have a better understanding of mass timber's environmental performance. We will not know the true carbon benefit until we assess the different applications for mass timber in high-rise buildings by displacing steel and concrete, the potential for a longer service life, and the opportunities for reuse and recycling. One can expect many innovations in how a mass timber wall or floor will be used, given that use is just at the beginning of a technology-driven learning curve.

There have been many studies on the mass timber of buildings, with some comparing it to traditional concrete and steel structures (Buchanan et al. 2013, Chen et al. 2019, Forterra 2018, Milaj et al. 2017, Pierobon et al. 2019, Robertson et al. 2012, Salazar and Puettmann 2019). These studies are stand-alone and not comparable, primarily due to the differences in the designs and life cycle stages included. In one case study of a mid-rise building (A1-A5, B2-B4, C1-C4) (Salazar and Puettmann 2019), total carbon emissions for a five-story mass timber building were dominated by the manufacturing stage (77%). Construction represented only 3.2% of the total GWP, and repair and replacement were 11%. The 60-year LCA result for GWP on the CLT building was 1,153 MT CO_2e, compared to 1,719 MT for a concrete building. The CLT building stored a total of 5,315 MT of CO_2e, resulting in a net negative -3,847 MT CO_2e emission. Carbon emissions for equivalent steel and concrete designs were +1,372 MT CO_2e and +1,718 MT CO_2e, respectively (Salazar and Puettmann 2019). In summary, in GWP the CLT building produced 33% fewer carbon emissions than the equivalent steel building, and 16% fewer carbon emissions than the concrete.

In another case study of a much smaller Northwest mid-rise building, the environmental benefit of using CLT compared to a concrete building was a 26.5% reduction in GWP and an 8% reduction in nonrenewable fuels (Pierobon et al. 2019). The hybrid CLT building stored 1,556 tons of CO_2, offsetting the emissions from product manufacturing and construction and resulting in a net negative emission of -1,222 MT of CO_2.

4.4 Energy use in wood products production

The main product of softwood sawmills is lumber (Figure 4.4). Other products (coproducts) are also generated when logs, which are round in cross-section, are processed into lumber, which is rectangular in cross-section. When the bark is removed, it is typically used for fuel or landscaping. Wood waste that has no other economic value at the mill is called hogged fuel. Hogged fuel typically goes to a boiler for on-site energy generation (Figure 4.10). A sawmill can typically be classified into four stages: 1) log yard operations; 2) sawmill (primary log breakdown); 3) drying operations; and 4) planing and finishing (Figure 4.10). Coproducts or residues can be generated at every step.

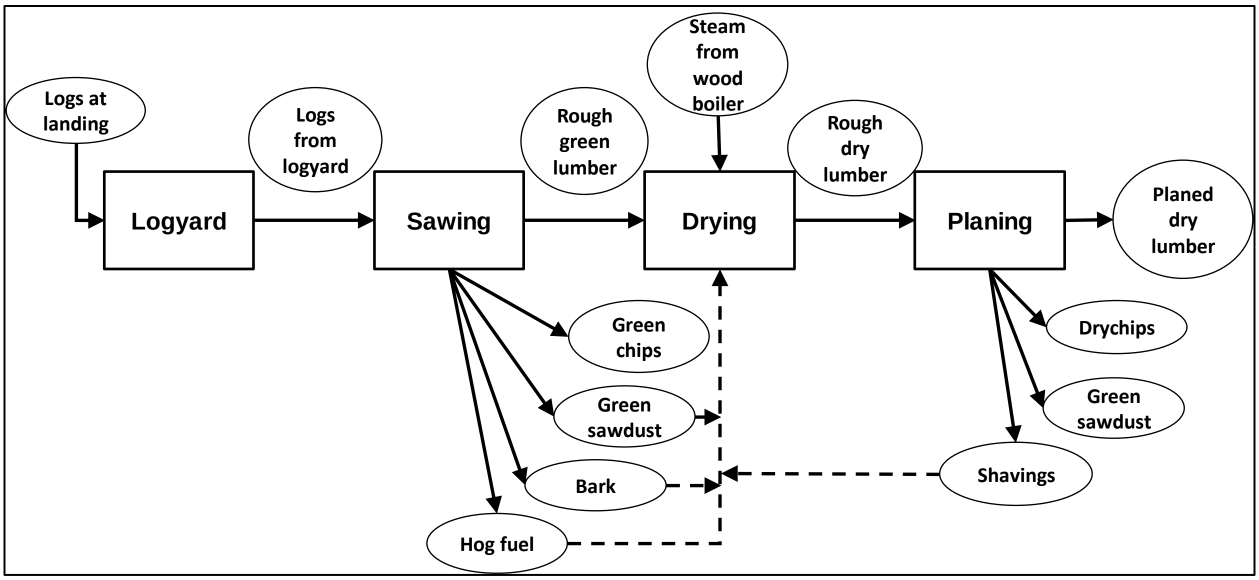


Figure 4.10: Diagram of the relationships between processes used to create PNW planed dry lumber from logs. Dotted line indicates that a portion of the product is burned at the dryer. (Milota 2015, 2020).

Residues with a higher commercial value can be sold as chips for pulp, bark for landscaping or sawdust for animal bedding, or in a variety of forms for use in wood composite panels such as particleboard and medium-density fiberboard (Puettmann and Salazar 2018a-b); however, wood residue is also used extensively in wood production processes, as an energy source to produce steam or to directly heat processes such as dryers (www.corrim.org/lcas-on-wood-products/). Steam is used to heat presses for panel products, wood dryers (kilns), power turbines (in some cases) and other mill operations (CORRIM 2017, Puettmann et al. 2016a).

Within the U.S. lumber industry, approximately 22 MMT of dry mill residues is produced annually (Puettmann 2019). Oregon's primary wood product facilities produced around 5.7 MMT of dry residues (Simmons et al. 2019). Simmons et al. (2019) reported that less than 1% of the residues were not utilized, which means the residues were not considered waste and went to produce products such as pulp and paper (62%) and on-site energy use. In recent surveys of PNW mills (Puettmann and Milota 2017), 22% of the residues produced during lumber manufacturing (A3) were used internally for energy (Figure 4.4, Figure 4.10), while PNW plywood mills in similar surveys reported utilizing 35% (A3) of their dry residues to produce heat energy for log conditioning, veneer drying and panel pressing (Puettmann et al. 2016a).

Lumber mills in western Oregon and Washington required 3,353 MJ/m^3 of total energy (A1-A3) to produce planed dry lumber, and 74% was sourced from renewable fuels (CORRIM 2017) (Figure 4.11). This includes heat and electrical energy needs. Of the total renewable fuels, nearly 100% was derived from wood residues generated at the facility for on-site energy (A3). Plywood mills in the PNW region required 8,003 MJ/m^3 total energy (A1-A3), with 61% coming from renewable fuel sources (Figure 4.11). To put this in perspective, energy from renewable wood residues used for both lumber and plywood combined for the entire PNW region is estimated at 43 billion MJ, which is equivalent to 1.24 billion liters (328 million gallons) of gasoline – which equates to 8.15 billion passenger miles.

Engineered wood products such as glulam beams, laminated veneer lumber (LVL) and I-joists all use more nonrenewable fuels than renewable fuels, mostly due to the unavailability of wood residues generated during their production. Each of these products utilizes materials such as lumber and veneer for glulam beams and LVL, or actual finished products in the case of I-joists; therefore, there is little wood residue generated (Figure 4.11).

A breakdown of the total cradle-to-gate (A1-A3) energy (heat, electrical and transportation) for producing a cubic meter of softwood lumber is shown in Figure 4.12. Renewable fuels represent 74%, leaving the remainder (26%) to be generated from nonrenewable (fossil and nuclear) energy. Renewable energy was from biomass, wind, solar, geothermal and hydro.

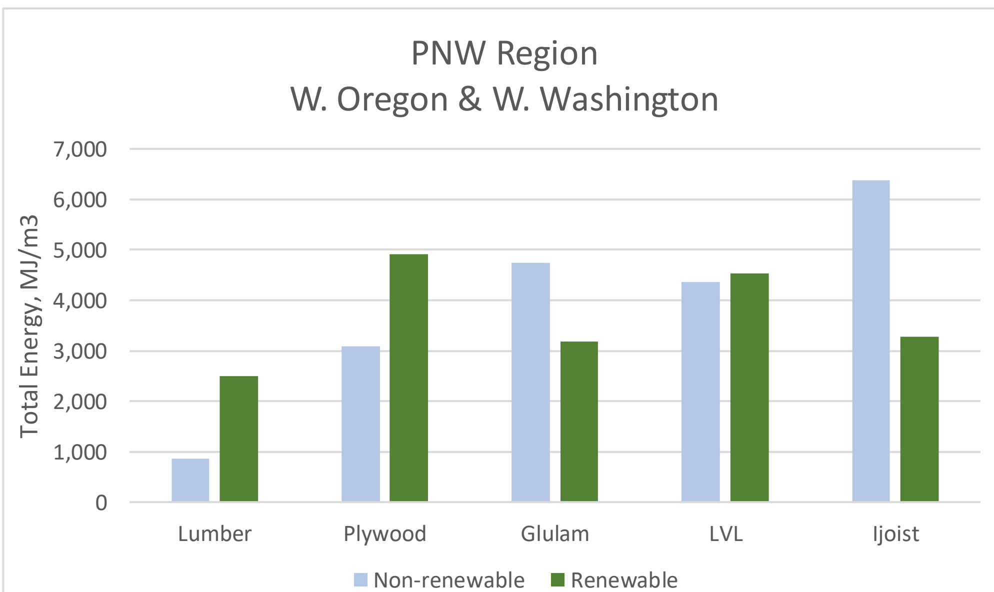


Figure 4.11: Total energy (A1-A3) use for selected wood products produced in the PNW (from 2012 production surveys: www.corrim.org/latest-reports/).

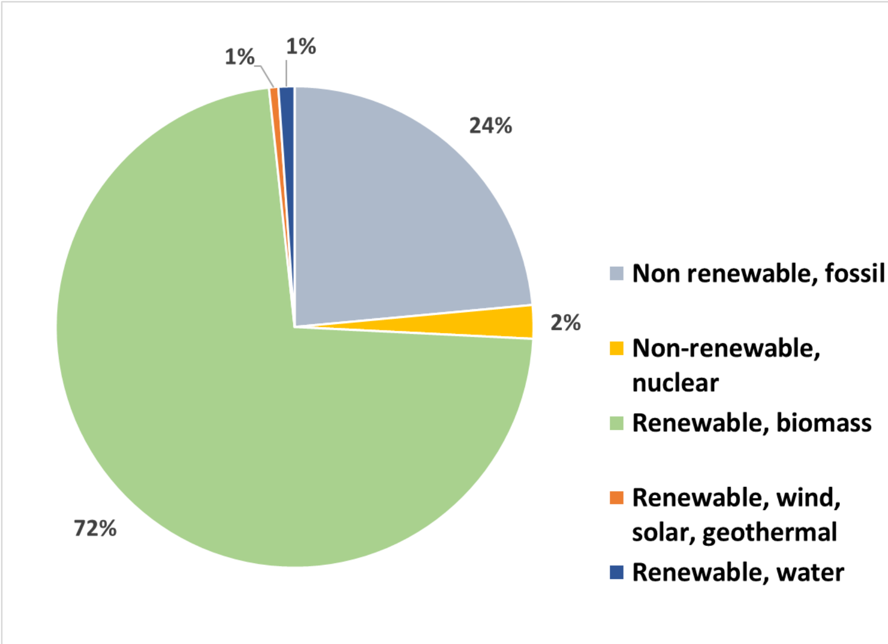


Figure 4.12: Average representation of fuel source for total energy demand for production of softwood lumber in the PNW (Milota 2015, 2020).

4.5 Substitution effects on carbon emission, and avoiding unintended consequences

Research on understanding the environmental impacts of fossil fuels and alternative renewable fuels has escalated since the early 1990s, with a heavy focus on seeking opportunities to reduce carbon emissions. Stricter standards for reducing particulate matter, along with public pressure to reduce the use of fossil fuels, has boosted interest in using clean wood residues from mills for energy and transportation fuels. But these uses may produce unintended consequences – such as greater carbon emissions than would occur if the wood residues were used in long-term products such as wood composite panels.

Historically, coproducts are sold as feedstock for pulp and paper, or for wood composite products (WCP) such as medium-density fiberboard (MDF), particleboard (PB) and hardboard. Recent LCA surveys of WCP industries estimate the softwood residue demand at 8.6 MMT per year (Puettmann and Salazar 2018a-b, Puettmann et al. 2016b-c). In addition, U.S. softwood lumber producers use about 3.8 MMT per year of coproduct for energy. Our findings found that it is 50% more efficient to use wood residues as a feedstock source to produce WCP than for use in ethanol production (Figure 4.13).

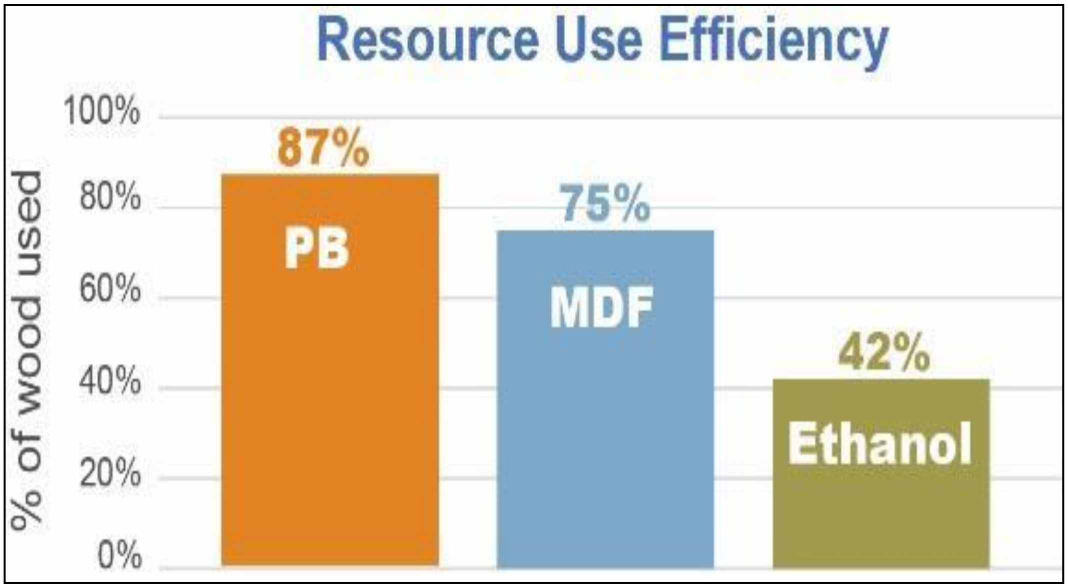


Figure 4.13: Percent wood used in final product, or resource use efficiency, for wood residues used for producing particleboard (PB), medium-density fiberboard (MDF) and ethanol.

Carbon emissions (GWP) were 64% and 39% lower when wood residues were used for producing PB and MDF, rather than ethanol (Figure 4.14). Using the displacement equation from above, there is a 7.8 and 5.15 displacement efficiency for PB and MDF over ethanol. Even though biofuels do not contribute to carbon storage, they do displace fossil-fuel emissions (0.43, or 43% efficiency) as the carbon absorbed through forest growth is returned to the atmosphere, constituting a bi-directional carbon exchange.

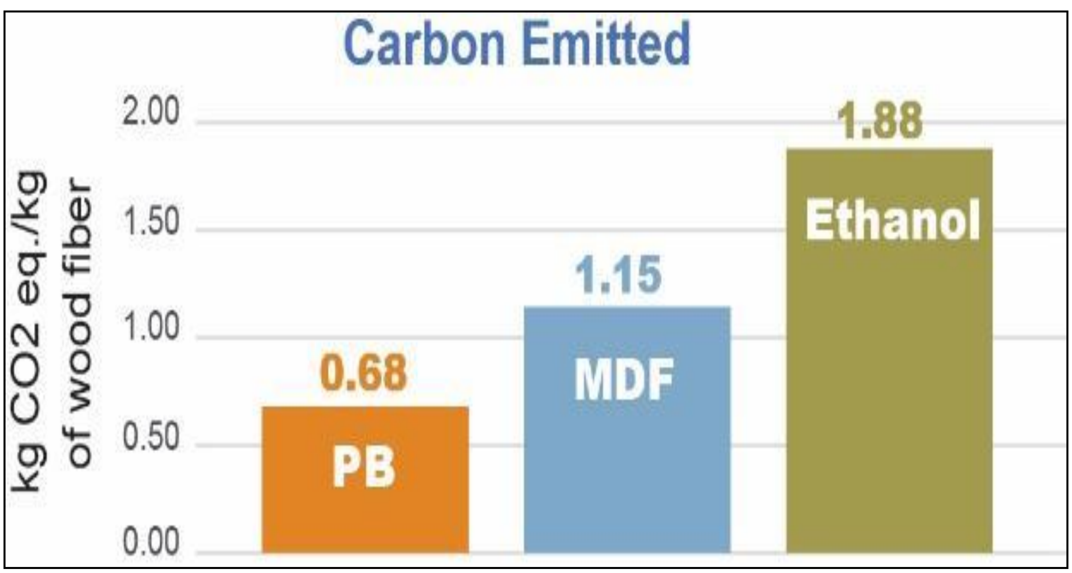


Figure 4.15: The trend in fossil energy use in selected PNW wood products production facilities covering two survey years, 2000 and 2012.

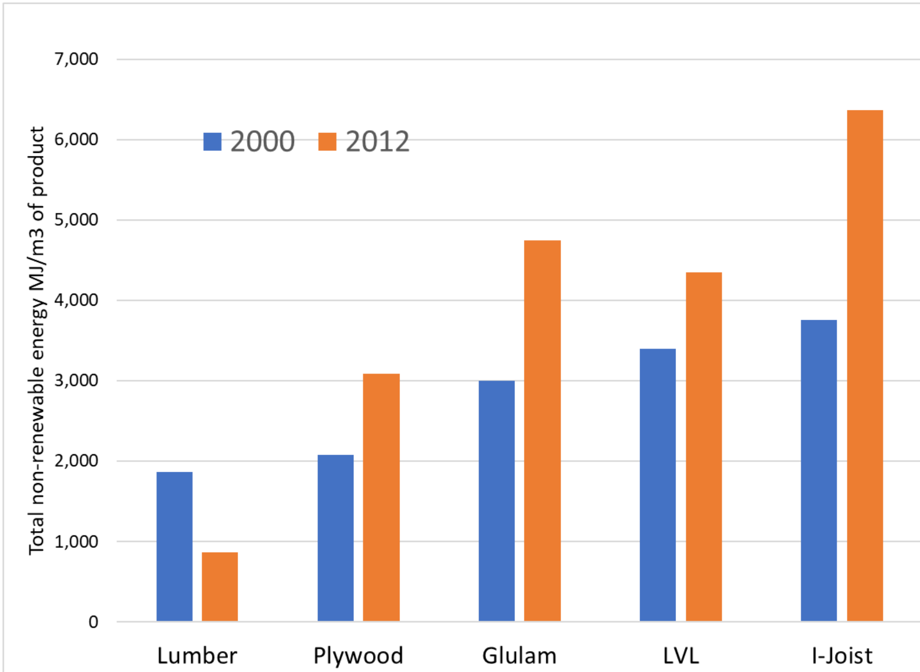


Figure 4.14: Carbon emissions as measure by GWP CO_2e for cradle-to-gate (A1-A3) particleboard (PB), medium-density fiberboard (MDF) and ethanol.

Energy use for producing several engineered wood composites (e.g., plywood, glulam, LVL, and I-joist) has increased over the years (Figure 4.15). Studies have shown that this increase in energy is not from the product production itself, but that the increased use in emission control devices (ECD) was the driver (In CORRIM Special Issue 2017). Normally powered by natural gas, ECDs are used to reduce emissions from wood boilers and dryers, and their use has increased since 2000 due to regulatory controls. This is an excellent example of an unintended consequence reducing one environmental impact, in this case volatile organic compounds or particulate matter, while increasing another. This is not uncommon, but wood producers and regulators need to be aware of the advantages and disadvantages of altering production processes in order to lower overall environmental footprints.

4.6 Summary: Opportunities to increase wood in building materials and fuels

There remain many opportunities to increase wood efficiencies than have been mentioned in this chapter. The adoption of new building codes internationally and locally for the use of wood in high-rise buildings is an excellent beginning toward highlighting the superior environmental performance attributes of wood building products. Twenty years of LCA research has shown that total carbon stored in wood products, combined with carbon emission reductions when wood is substituted for steel or concrete, far exceed the cradle-to-gate emissions from wood product manufacturing.

Manufacturing all building materials and constructing buildings makes up 11% of the global CO_2 emission by sector. Building use/operation represents 28%, industrial activities are 30%, and the transportation sector is 22% (UN 2017, EIA 2017). Wood-use opportunities for reducing global carbon emissions can be achieved by: growing more trees; intensively managing forests for yield and sustainably; using local wood sources and local wood products to reduce transportation impacts;

producing wood products for long service lives, reuse and recycling potential; using wood in buildings rather than more fossil-fuel-intensive materials; and using wood residues for long term product that have the highest efficiency for displacing fossil intensive products rather than low-efficiency biofuels, whenever possible.

Over the past decades, technological advances have provided numerous options for converting biomass to energy, such as electricity production, combined heat and power, pellet production for both residential and commercial heating, woody and agriculture feedstocks for liquid fuels, and steam generation for district heating systems and manufacturing operations. The challenge is to use wood resources sustainably while improving their economic competitiveness, yet without adverse effects on the environment. Using wood waste as an energy fuel can reduce our need for imported fossil fuels, resulting in many economic benefits and reducing carbon emissions – but may be lower in efficiency than producing composite products that store more carbon and replace more fossil-fuel-intensive product uses. As mentioned earlier, the PNW lumber industry meets nearly 100% of its manufacturing heat energy needs by using wood waste generated during production.

Using wood residues for nearly all heat demands was not always the case for PNW wood processing facilities. The use of residues for energy is unpredictable: 10 years ago, these same facilities reported in surveys that energy generated from residues produced on-site was only 46%, with the remainder coming from natural gas (Milota et al. 2005). Wood drying is the dominant use of energy in producing lumber, regardless of the geographical region in which the lumber is produced (www.corrim.org/latest-reports/). The lumber production industry also provides the best opportunity to look at alternate renewable fuel sources, such as forest residues, when markets or environmental regulations regulate fuels for energy.

The opportunities for improvement in using wood as a building material are endless, including materials choices, building designs, innovative products, building codes (such as the use of CLT for high-rise buildings that can store more carbon and displace fossil intensive alternatives) and better communication/education on how to improve the efficiency of wood uses and avoid unintended consequences. A plethora of data exists on the favorable environmental performance of wood as a building material and energy source, while many opportunities exist for research to improve on current practices.

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CHAPTER 5: Harvested Wood Products Carbon Accounting

Edie Sonne Hall, Three Trees Consulting, with input from Kenneth Skog, Research Forester Emeritus at U.S. Forest Service

5.0 Introduction

When trees are harvested and used to produce wood products, carbon remains stored in the product while in use and in landfills. The length of storage time varies by end-use and wood product. There is a long history of literature devoted to this subject, and well-established methods for measuring and monitoring harvest wood product (HWP) carbon storage over time. This chapter summarizes basic accounting principles and data from the U.S. Forest Service (USFS) that are used to estimate changes in yearly HWP carbon pools. It provides an overview of the IPCC/EPA National HWP reporting methods used by the United States, and presents options for smaller-scale assessments that include the IPCC method and the 100-year average "California Forest Project Protocol"(CFPP) approach as described in Hoover et al. (2014) and compared in Stockmann et al. (2012). It will also summarize the Oregon state HWP inventory report when it is published in 2020 (Morgan et al. 2020 *in press*).

5.1 Overview of HWP data inputs

Measuring the change in HWP carbon pools using true stock-change accounting would involve measuring the change wood stored in wood product pools (e.g., products in use, landfills) from time A to time B. In the forest, this type of accounting is accomplished with estimates researchers compile after measuring carbon in long-term plots scattered throughout the United States (i.e., the FIA program). An analogous wood product equivalent would be to annually sample the wood stock in buildings, furniture, railroad ties, landfills, etc., a feat that would be difficult to accomplish in the same manner as the FIA plots on forestland. The USFS solves this by estimating a derived inventory, using detailed statistics on the annual distribution of each type of wood product to various end-uses (e.g., how much harvested wood is converted to plywood and what percentage of plywood goes into single-family homes vs. multi-family homes vs. furniture, etc.) as well as decay functions indicating how quickly products move from each end use to solid waste disposal sites. It also tracks the landfill decay/emission rates.

	Half-life	Softwood lumber	Hardwood lumber	OSB	Plywood	Engineered wood
Single-family home	100 years (after 1980) 80 years (pre-1980)	33.2%	3.9%	57.8%	33.4%	13.0%
Multi-family home	70	3.1%	0.4%	4.7%	3.3%	1.9%
Commercial buildings	67	7.9%	2.8%	7.1%	9.0%	5.3%
Other products	20	23.3%	24.3%	13.1%	17.1%	32.4%

Repair and furniture	30	28%	32.2%	17.2%	33.9%	46.8%
Shipping	30	4.5%	36.4%	0.1%	3.3%	0.6%

Table 5.1: Distribution of product to end uses and use life of products in end uses (Smith et al. 2006). For official U.S. estimates published by the USEPA (2020) it is assumed that the percentages are the same for products used domestically and products exported.

The half-life values, end-use distributions and landfill decay rates are used to develop decay functions to estimate how much carbon is in each pool (product, land-use, burned for energy, or decay) by year since the harvest date, using a flow illustrated in the following schematic from Stockmann et al. (2012).

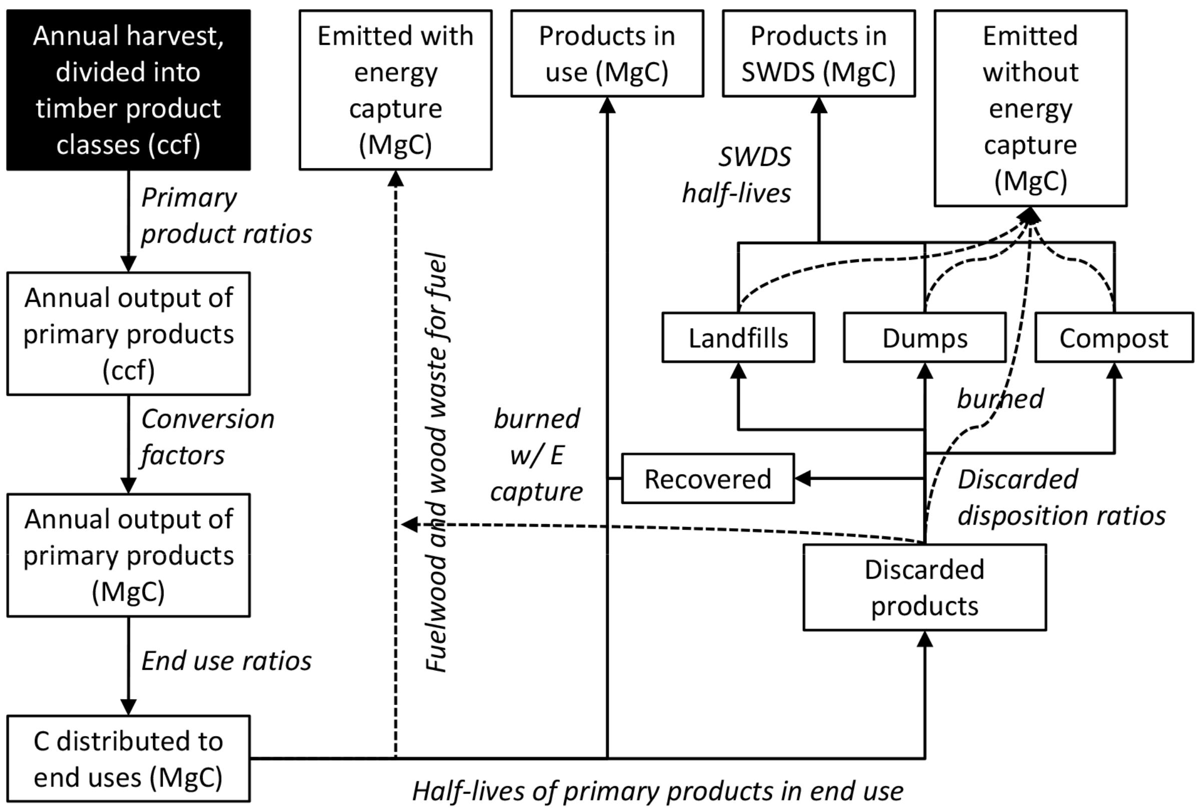

Figure 5.1: Schematic of the fate of carbon from harvest through manufacturing to end of use (Butler et al. 2014).

The data is compiled into Tables 5.2 and 5.3 below.

Table 5.2: Fraction of carbon in primary wood products remaining in end uses up to 100 years after production (Year 0 indicates fraction at time of production) (Hoover et al. 2014, Table 6-A-2).

Year after Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non-Structural Panels	Misc. Products	Paper
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	0.908	0.909	0.908	0.908	0.908	0.903	0.880
2	0.892	0.893	0.893	0.896	0.892	0.887	0.775
3	0.877	0.877	0.878	0.884	0.876	0.871	0.682
4	0.863	0.861	0.863	0.872	0.861	0.855	0.600
5	0.848	0.845	0.848	0.860	0.845	0.840	0.528
6	0.834	0.830	0.834	0.848	0.830	0.825	0.465
7	0.820	0.815	0.820	0.837	0.816	0.810	0.354
8	0.806	0.801	0.807	0.826	0.801	0.795	0.269
9	0.793	0.786	0.794	0.815	0.787	0.781	0.205
10	0.780	0.772	0.781	0.804	0.774	0.767	0.156
15	0.718	0.705	0.719	0.753	0.708	0.700	0.040
20	0.662	0.644	0.663	0.706	0.649	0.639	0.010
25	0.611	0.589	0.613	0.662	0.595	0.583	0.003
30	0.565	0.538	0.567	0.622	0.546	0.532	0.001
35	0.523	0.492	0.525	0.585	0.501	0.486	0.000
40	0.485	0.450	0.487	0.551	0.460	0.444	0.000
45	0.450	0.411	0.452	0.519	0.423	0.405	0.000
50	0.418	0.376	0.420	0.490	0.389	0.370	0.000
55	0.389	0.344	0.391	0.462	0.358	0.338	0.000
60	0.362	0.315	0.364	0.437	0.329	0.308	0.000
65	0.338	0.288	0.340	0.413	0.303	0.281	0.000
70	0.315	0.264	0.317	0.391	0.280	0.257	0.000
75	0.294	0.242	0.296	0.370	0.258	0.234	0.000
80	0.276	0.221	0.277	0.351	0.238	0.214	0.000
85	0.258	0.203	0.260	0.333	0.220	0.195	0.000
90	0.242	0.186	0.244	0.316	0.203	0.178	0.000
95	0.227	0.170	0.229	0.300	0.188	0.163	0.000
100	0.213	0.156	0.215	0.285	0.174	0.149	0.000
Average	**0.466**	**0.430**	**0.468**	**0.526**	**0.441**	**0.424**	**0.059**

Table 5.3: Fraction of carbon in primary wood products remaining in landfills up to 100 years after production (Year 0 indicates fraction at time of production) (Hoover et al. 2014, Table 6-A-3).

Year after Production	Softwood Lumber	Hardwood Lumber	Softwood Plywood	Oriented Strandboard	Non-Structural Panels	Misc. Products	Paper
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.061	0.060	0.061	0.061	0.061	0.064	0.040
2	0.071	0.070	0.071	0.068	0.071	0.074	0.073
3	0.080	0.080	0.080	0.076	0.081	0.084	0.102
4	0.089	0.090	0.089	0.083	0.090	0.094	0.127
5	0.098	0.099	0.097	0.090	0.099	0.103	0.147
6	0.106	0.109	0.106	0.097	0.108	0.112	0.164
7	0.114	0.117	0.114	0.103	0.117	0.121	0.197
8	0.122	0.126	0.122	0.110	0.125	0.129	0.220
9	0.130	0.134	0.130	0.116	0.134	0.138	0.236
10	0.138	0.143	0.137	0.122	0.142	0.146	0.247
15	0.173	0.181	0.172	0.151	0.179	0.184	0.256
20	0.203	0.214	0.202	0.176	0.211	0.217	0.241
25	0.230	0.243	0.229	0.199	0.239	0.246	0.223
30	0.253	0.269	0.252	0.220	0.265	0.272	0.207
35	0.274	0.292	0.273	0.238	0.287	0.296	0.195
40	0.293	0.313	0.292	0.255	0.307	0.316	0.185
45	0.310	0.332	0.308	0.271	0.325	0.335	0.177
50	0.325	0.348	0.324	0.285	0.341	0.352	0.171
55	0.338	0.363	0.337	0.298	0.356	0.367	0.166
60	0.351	0.377	0.349	0.310	0.369	0.380	0.163
65	0.362	0.389	0.361	0.321	0.381	0.393	0.160
70	0.372	0.400	0.371	0.331	0.391	0.404	0.158
75	0.381	0.410	0.380	0.341	0.401	0.414	0.156
80	0.390	0.419	0.389	0.350	0.410	0.423	0.154
85	0.398	0.427	0.397	0.359	0.418	0.431	0.153
90	0.405	0.435	0.404	0.366	0.426	0.439	0.153
95	0.412	0.442	0.411	0.374	0.432	0.446	0.152
100	0.418	0.448	0.417	0.381	0.438	0.452	0.151
Average	**0.297**	**0.317**	**0.296**	**0.264**	**0.311**	**0.321**	**0.178**

The decay tables above are based on data compiled on a national scale. Anderson et al. (2013) created an online model to allow input of customized data, which allows better regionalization. Model users can input: 1) annual timber harvest volume; 2) annual timber product ratios allocating harvest to different timber product classes; and 3) annual primary product ratios allocating timber products to various end uses.

The parameter values used for Oregon will be reported when the state HWP report is complete.

5.2 IPCC/EPA HWP reporting

The USFS uses the HWP data inputs and national-level data on wood and paper product production, imports and exports to report national-level estimates of carbon stored in HWP using guidelines from the IPCC. These estimates are reported annually by the US EPA to the United Nations as required under the United Nations Framework Convention on Climate Change (Skog 2008, US EPA 2020).

The data is tracked over time to estimate the annual change in carbon stored in wood products in each end-use pool. Table 5.4 is an illustration of how the proportions in the tables above are used to fill out a virtual inventory. Each row represents a single year's initial wood product contribution and the associated tracking of how much remains in use each year after production (the years labeled in the columns). The "Total" row is the sum of the amount of product that is still in use, from products manufactured in each year back to 1919. The "annual change" in the HWP carbon pool is the difference between two consecutive years' totals (for details, see Skog 2008).

Table 5.4: Illustration of the IPCC/EPA accounting methodology used to track changes in wood product carbon pools using past harvest.

		Amount remaining stored in each year after products are placed in end uses (using fractions from Table 5.2)					
Year products were placed in use	**Initial wood production (total of all wood products)**	**1919**	**1920**	**1921**	**....**	**2018**	**2019**
1919	10.2	9.2	9.1	9.0	....	3.5	3.4
1920	10.7		9.6	9.5	...	3.7	3.6
1921	11.2			10.1	....	3.9	3.9
....					...	x	x
2018	26.7				...	24.4	24.2
2019	27.3				....		24.7
Total		9.2	18.8	28.7	...	896.1	913.4
Change in carbon between 2018 and 2019							17.3

IPCC identifies three accounting approaches to report annual change in carbon stored in HWP on a national scale: production, stock change and atmosphere flow. The production approach tracks all the carbon in HWP made from timber harvested in a country (even products that are exported). The logs or products that are exported are assumed to follow the same disposition fate as the domestic stock. The stock-change approach[17] tracks all the carbon in HWP consumed in the United States, which includes imports and excludes exports. Atmospheric flow tracks the annual net change in carbon storage (additions to stocks) or net emissions (losses from stocks) held in the United States, so stock additions are recorded by the country where the wood is grown, and "emissions or losses" are recorded by the country in which the wood decays.

[17] Note in this instance that stock change is referring to changes in pools of product made in the production year (imports and consumption), not the pools of the products currently in use or in a landfill.

The United States officially reports to the IPCC using the production approach, though stock change and atmospheric flow are included in the annual inventory for comparison (USEPA 2020, appendix 3.13). The illustrative explanation of the difference between these three approaches is found in Table 5.5 below.

Table 5.5: Illustration of U.S. estimates of annual change in HWP carbon stored under the three IPCC accounting approaches, with sample numbers.

	Stock change or flow variable	**Metric ton CO_2e**
A	Domestic product stock change	212
B	Exported product stock change	3
C	Imported product stock change	36
D	Flow of imports	47
E	Flow of exports	25
	Approaches	
	Production (A+B)	215
	Stock change (A+C)	248
	Atmospheric flow (A+C-(D-E))	227

5.3 100-year-average accounting (California Forest Project Protocol – CFPP)

100-year-average accounting, like the IPCC method for national estimates, uses decay functions for tracking HWP carbon fate over 100 years. However, the IPCC method is used to track decay (loss from use) of products placed in use in the past, and to estimate current-year change in carbon stored. The 100-year-average accounting method is intended to estimate how long carbon in products placed in use today will remained stored in the future and serve as an offset to carbon emissions generally. The fraction of HWP carbon that is stored long-term (over 100 years) is estimated using weighted averaging of the fraction found in end use over each of the 100 years (see tables 5.2 and 5.3). This method approximates the reduction in radiative forcing (over 100 years) by temporary storage of carbon in wood products, which is what the atmosphere sees (Hoover et al., 2014, Section 6.5).[18] Ganguly et al. (2019) also confirmed that the 100-year-average method approximates the radiative forcing impact for storing carbon in wood products in end uses.

The 100-year-average accounting method was developed to be used by forest landowners, wood products producers or wood product users who currently produce and use wood products (e.g., reporting long-term wood product storage to the Carbon Disclosure Project) and for project-level accounting, such as in the California Forest Offset Protocol (Hoover et al. 2014; CARB 2015).

[18] Radiative forcing accounting can be helpful to calculate the climate benefit of a delayed release of a greenhouse gas, such as is the case of carbon stored in a wood product.

5.4 Comparison between IPCC/EPA method and 100-year average (CFPP)

The 100-year-average accounting estimates of carbon credit for current-year U.S. wood product production from U.S. timber differ notably from estimates of change in carbon stored in the United States using the IPCC methods and production-accounting approach. The 100-year method, when applied to U.S. wood products production each year, gives the future estimated climate impact of carbon storage in those products. The IPCC method, with production accounting, estimates change in carbon stored in a current year given the current-year additions, the dispositions of and emissions from past years' products from the products in use, and solid waste disposal pools.

Stockmann et al. (2012) compared estimates made by the two methods in a paper, *Estimates of carbon stored in harvested wood products from the United States forest service northern region, 1906-2010.* They calculated annual HWP contributions for the USFS Northern Region, which includes national forests in northern Idaho, Montana, South Dakota and eastern Washington, from 1900 to 2009, using both the IPCC method and the 100-year-average method, and their results are found in Table 5.6.

Table 5.6: Estimates made by applying the IPCC and CFPP methods to 1906-2010 (U.S. Forest Service, Northern Region harvest data, Stockmann et al. 2012).

Inventory year	IPCC change in HWP pool (MT C)	100-year avg. (MT C)
1910	104,116	73,547
1920	97.021	93,694
1930	75,712	75,819
1940	16,051	102,389
1950	298,029	180,923
1960	591,785	627,947
1970	966,125	897,496
1980	437,628	503,328
1990	481,517	613,675
1995	59,643	207,418
2000	-184,812	143,417
2005	-151,437	140,177
2006	-135,679	91,774
2007	-200,187	87,755
2008	-198,821	84,754
2009	-191,391	91,917
2010	-173,214	

The IPCC method following timber harvest in the Northern Region estimates large annual increases in the HWP pool based on many years of substantial harvest. Harvest levels increased to a peak in the 1960s. Harvest levels declined in this region during the 1980s and 1990s, toward minimal harvest in the 2000s (see Figure 5.2). This decline in harvest resulted in less HWP entering the storage pool than the emissions from the products (from prior harvests) that are leaving the storage pool; hence the net losses to the pool beginning about the year 100. The 100-year-average method depicts the 100-year climate contribution of the long-term storage from each year's harvest. In years where harvest is higher, the 100-year-average number is bigger, and vice versa. Both methods should also be assessed in conjunction with the forest ecosystem carbon balance, to get a complete picture of forest and HWP carbon.

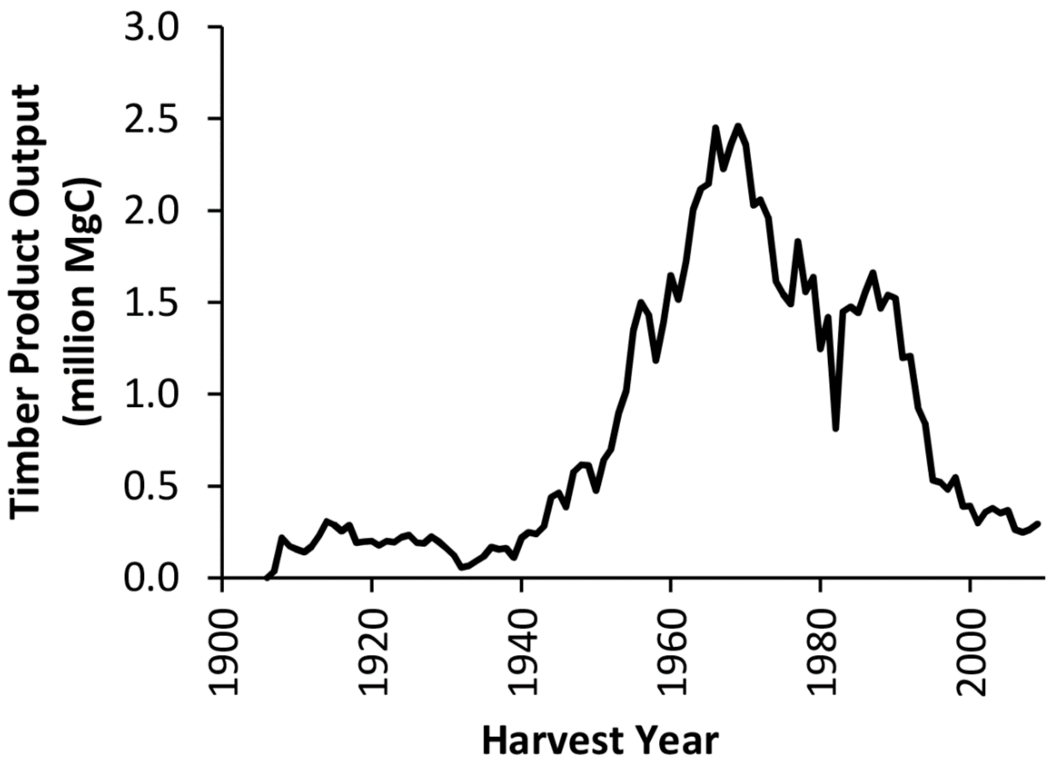

Figure 5.2: Annual timber product output in the Northern Region, 1906 to 2010, based on data collected from USDA Forest Service archives and cut/sold reports (Stockmann et al. 2012, Figure 3).

Several states and regions are interested in understanding the contribution of HWP carbon in their boundary. The IPCC method seeks to estimate change in carbon stored in wood products during a given current year for a region, and the 100-year-average method seeks to estimate the future climate impact of carbon stored in wood products produced in the current year. The first method applies production-approach estimates for specific regions – e.g., national forests or states – with results akin to national-level estimates of annual carbon change. This method is part of an international accounting framework to account for all greenhouse gas emissions and changes in carbon sinks across all sectors. The second method may be used by forest owners, wood product producers, and wood product users and regions to estimate the potential climate impact of wood products they produce or use. A state may have reason to want to answer both these questions, in which case both methods may be applicable.

5.5 Oregon HWP report

The state of Oregon has recently commissioned an Oregon Harvested Wood Products Carbon Inventory 1906-2017 (Morgan et al. 2020 *in press*). The report, which is still in draft form at the time of publication of this report, includes tables summarizing much information on carbon stored in harvested wood products. This report will be updated online, and this section will be expanded when the Oregon Harvested Wood Products Carbon Inventory report is finalized.

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CHAPTER 6: Current and Future Markets for Carbon and Co-Benefits from Oregon Forests

David Ford, L&C Carbon, and Sheldon Zakreski, The Climate Trust

6.0 Introduction

Forests offer a vital role as a natural mechanism to remove and store carbon from the atmosphere. Trees capture carbon dioxide from the atmosphere and store the carbon in leaves, branches, trunks, roots and soil, and in long-lived wood products. Forests account for 92% of all terrestrial biomass globally, storing approximately 400 billion tons of carbon (Pan et al. 2013).

U.S. forests and associated wood products currently capture and store about 16% of U.S. annual emissions from burning fossil fuels (Joyce et al. 2014). It is unclear whether forests will be able to maintain their ability to sequester carbon at current rates. In many parts of the United States, reforestation and the succession of young forests to older age classes has been a primary source of carbon uptake, and this sink may not be as strong in the future due to changing climatic conditions (Birdsey et al. 2006).

Carbon markets are an important mechanism to address mitigating climate change. Forests are the most sought-after source of carbon offsets in voluntary and compliance markets, because of their ability to economically remove and store large quantities of carbon and generate a wide array of environmental and social benefits to society.

This chapter 1) describes the role of forests in mitigating climate change; 2) provides an overview of carbon markets and market mechanisms that can drive investments in forest management resulting in increased removal and storage of carbon; 3) reviews the types of forest carbon projects available to forest landowners; and 4) provides a summary of offset credits issued in California's regulated and voluntary markets.

6.1 The role of forests in mitigating climate change

From a global perspective, forests have four major roles in climate change: they contribute to global carbon emissions when degraded or converted to a non-forest use; they react sensitively to a changing climate; when managed sustainably, they produce wood-based fuels as a more benign alternative to fossil fuels and wood building materials, with lower embodied carbon than non-renewable materials; and finally, they have the potential to absorb about one-tenth of the global carbon emissions projected for the first half of this century into their biomass, soils and products, and store them – in principle, in perpetuity (FAO 2019).

The United States has the fourth-largest forest estate in the world, representing about 7.5% of the world's forests. The United States has nearly 750 million acres of forestland, covering about a third of the country's land area. Most U.S. forests are owned by private entities, with 245 million acres owned by families holding parcels between 10 and 5,000 acres, totaling one-third of all forestland in the United States (Oswalt et al. 2014).

Sustainably managing forests has been recognized as a relatively cost-effective strategy for offsetting greenhouse gas (GHG) emissions (Canadell and Schulze 2014). U.S. forests have the potential to store even more carbon through healthy, sustainable forest management practices. Some of the greatest opportunities to sequester and store more carbon are on U.S. family forestlands.

Recent research published by The Nature Conservancy and 21 other institutions in Science Advances (Fargione et al. 2018) demonstrates that nature-based solutions can help absorb about one-third of the carbon pollution produced in the United States. These solutions include actions such as reforestation, and practices that improve soil health and forest carbon management and restore coastal wetlands, as well as practices that prevent conversion of natural and working lands – all these can increase carbon storage and reduce greenhouse gas emissions (Figure 6.1). Essentially, these practices offer significant climate change mitigation that is cost-effective compared to other mitigation methods, while also providing benefits for people, water and wildlife. The research concludes that a suite of forestry practices offers the greatest opportunity at the lowest cost to mitigate climate change, compared to other natural solutions.

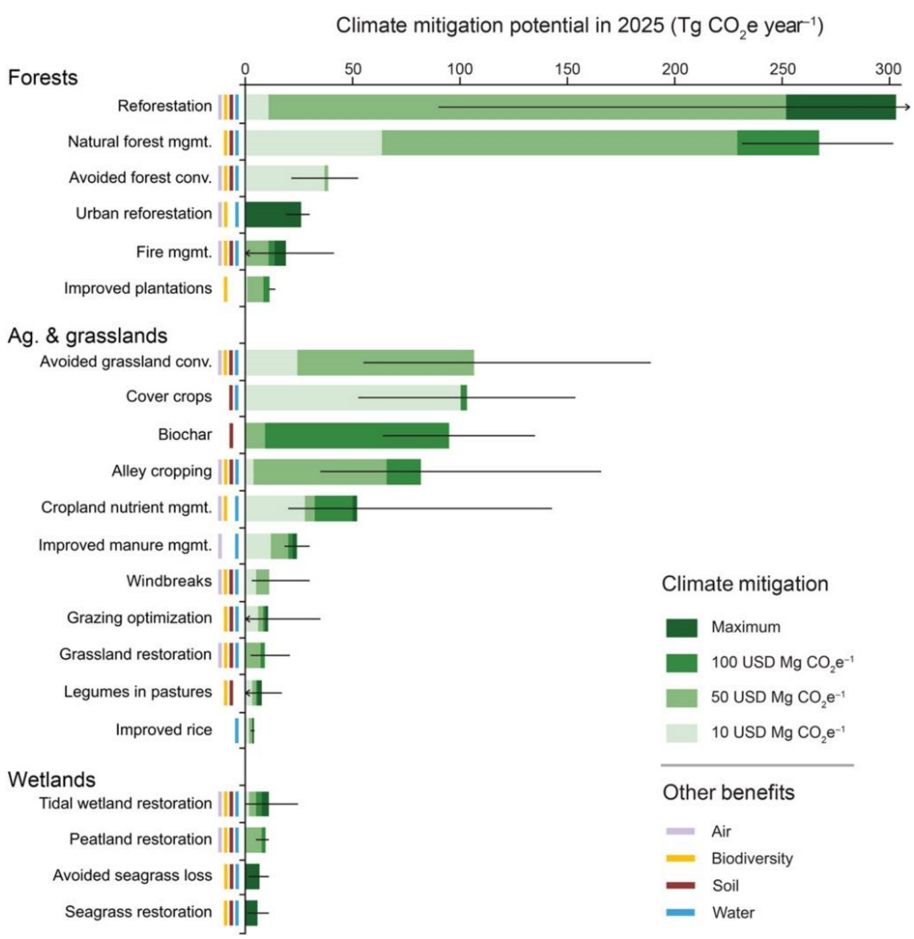

Figure 6.1: Carbon mitigation potential of natural and working lands (Fargione et al. 2018).

In Oregon, there are about 30 million acres of forestland, which is equal to about one-half of the total area of the state (Figure 6.2). About one-third of the state's forestland is owned by private entities, of which 3.6 million acres is owned by families with less than 5,000 acres.

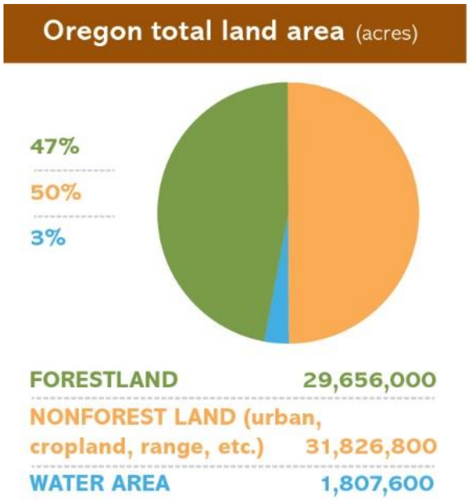

Figure 6.2: Oregon forestland (Oregon Forest Resources Institute 2019).

As documented in Chapter 2 of this publication, Oregon's forests store about 3.2 billion metric tons of carbon stocks in all pools, including forest floor and forest soils, across all ownerships. National forests in Oregon are storing over half the carbon stocks (52%), while private ownerships store 30%, and state and local government store 4.5% of the carbon stocks (Christensen et al. 2019).

Currently, Oregon's forests sequester about 30.9 million metric tons of CO_2 equivalents per year. On a per-acre basis, Oregon's lands are net sequestering an average of 1.04 metric tons CO_2e per acre per year, based on net growth [net primary production minus removals (harvest) and mortality (fire, insects and disease, or natural/other)] (Christensen et al. 2019).

6.2 The role of carbon markets in mitigating climate change

Markets are an important mechanism to address mitigating climate change. Market-based mechanisms offer flexible instruments designed to achieve environmental goals at a lower cost and in a more flexible manner than traditional regulatory measures (Climate Policy Info Hub 2019). There are three market mechanisms currently employed across the United States to mitigate climate change: 1) compliance carbon markets (emissions trading); 2) voluntary carbon markets (emissions trading); and 3) incentive programs.

Compliance carbon markets are marketplaces through which regulated entities obtain and surrender emissions permits (allowances) or offsets, in order to meet predetermined regulatory greenhouse gas reduction targets. In the case of cap and trade programs, participants – often including both emitters and financial intermediaries – can trade allowances in order to make a profit from unused allowances or to meet regulatory requirements.

Currently, there are two U.S. compliance carbon markets, one associated with California's cap and trade program and one associated with the Regional Greenhouse Gas Initiative (RGGI) that operates in Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island and Vermont. To date, RGGI has not transacted any forest offsets in its program.

The California Air Resources Board (ARB) operates the California cap and trade program. ARB approves protocols for their compliance market, and requires offset projects to be registered through one of the ARB-approved registries. There are currently six approved California compliance protocols available for use in the United States, including Oregon. These include forestry, urban forestry, livestock, ozone-depleting substances, mine methane capture and rice cultivation.

Offset projects located in Oregon can qualify to participate in California's cap and trade program. For example, the Confederated Tribes of the Warm Springs and Green Diamond Resource Company both operate registered and approved forest carbon offset projects under California's cap and trade program. However, the California Legislature enacted limits on the number of offsets that may be used in the cap and trade program from projects outside the state between 2021 and 2030, unless these projects can demonstrate a direct environmental benefit to the air or waters of the state of California.

The **voluntary carbon marketplace** encompasses all transactions whereby offsets are purchased with the intent to re-sell, retire to meet carbon-neutral or other environmental claims, or be used by airlines under a United Nations-mandated program to offset emissions from international flights (see section 6.3.1.3). Voluntary markets co-exist with compliance offsets, and are primarily driven by private corporations seeking to achieve corporate social responsibility objectives. In Oregon, the city of Astoria operates a registered and approved voluntary forest carbon offset project within its watershed.

Incentive programs can be powerful mechanisms to drive behavior change. The U.S. federal government offers a range of incentives to forestland owners. Examples include Natural Resources Conservation Service programs, such as the Environmental Quality Incentives Program (EQIP), the Healthy Forests Reserve Program (HFRP) and the Wildlife Habitat Incentives Program (WHIP).

A new incentive program being developed by American Forest Foundation and The Nature Conservancy is the Family Forest Carbon Program (FFCP). The program incentivizes individual and family forest owners to adopt specific forest management practices that have been scientifically demonstrated to increase carbon sequestration, improve forest health and provide other important ecosystem benefits.

The FFCP offers a new model of climate finance that will provide rural landowners with the funding required to sustainably manage their forests. The program is designed to remove one of the most significant barriers for family forest owners – the high cost of forest management activities – while also providing technical assistance and professional guidance to landowners on the best options for their forests while achieving positive climate benefits. By managing just 20% of family forest acres (54 million) in the United States with practices that optimize carbon sequestration by 2030, approximately 3,500 BMT CO_2e could be sequestered through the end of the century (American Forest Foundation 2019).

6.3 Current and future market mechanisms to mitigate climate change

There is a range of market mechanisms, from international to local levels, being operated by governments and the private sector. This section provides an overview of current and future market mechanisms that can contribute to climate mitigation.

6.3.1 International mechanisms

6.3.1.1 UN Paris Agreement – In response to growing global concern about climate change and rapid increases of greenhouse gases in the atmosphere, the Paris Agreement was ratified in 2016. The Paris Agreement builds upon the UN's Framework Convention on Climate Change adopted in 1994, and for the first time brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries in doing so. As such, it charts a new course in the global climate effort.

The Paris Agreement's central goal is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (United Nations 2019).

The Paris Agreement requires all parties to put forward their best efforts through nationally determined contributions (NDCs), and to strengthen these efforts in the years ahead. This includes requirements that all parties report regularly on their emissions and their implementation efforts. There will also be a global review every five years to assess the collective progress toward achieving the purpose of the agreement and to inform further actions by parties to the agreement.

To date, 187 of the 197 parties to the convention have ratified the Paris Agreement. On November 4, 2019, the Trump administration notified the UN Secretary-General of its decision to withdraw from the agreement. As a result of the U.S. federal government withdrawing from the agreement, individual states and private-sector companies have begun to accelerate legislative, regulatory and voluntary actions that will help achieve U.S. commitments under the Paris Agreement.

6.3.1.2 The Clean Development Mechanism (CDM), created under the Kyoto Protocol, allows a country with an emission-reduction or emission-limitation commitment to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits, each equivalent to one MT of CO_2e, which can be counted toward meeting an emissions target.

The CDM is the first global, environmental investment and credit program of its kind, providing a standardized emission offset instrument. The mechanism stimulates sustainable development and emission reductions, while giving industrialized countries some flexibility in how they meet their emission targets.

A CDM project activity might involve, for example, a rural electrification project using solar panels, or planting trees or restoring degraded tropical forests. At the end of 2019, about 2 billion CERs have been issued by just over 3,200 projects. Over half the CERs (57.6%) have been issued to China (UNEP 2019), as shown in Figure 6.3.

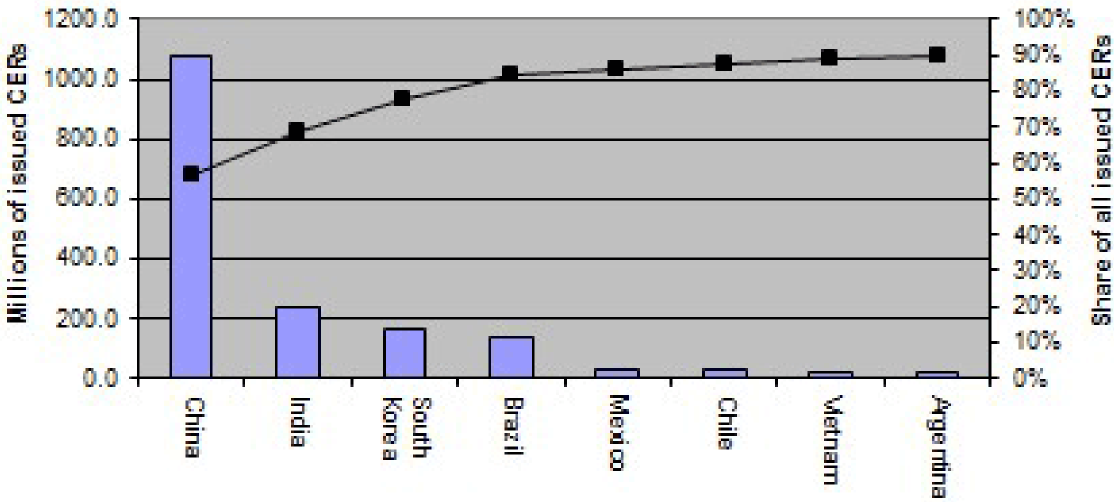

Figure 6.3: Top countries by issued CERs (UNEP DTU Partnership).

6.3.1.3 International Civil Aviation Organization – ICAO is a UN specialized agency, established by member states in 1944 to manage the administration and governance of the Convention on International Civil Aviation (Chicago Convention). ICAO works with its 193 member states and industry groups to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies, in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector (International Civil Aviation Organization 2019).

In 2010, ICAO adopted a resolution on climate change that included market-based mechanisms to limit or reduce CO_2e emissions from international civil aviation. Then, in 2016 ICAO created the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

CORSIA is an ICAO program with a goal of capping CO_2e emissions from international aviation at 2020 levels. A future goal is to reduce net carbon emissions 50% by 2050, compared to 2005 levels. Carbon emissions from domestic aviation are outside the scope of this program.

Preparatory activities for CORSIA began in 2018, and reporting of baseline emissions data is required in 2019-20. A pilot phase (with voluntary emissions offsetting) is scheduled to run from 2021-23, with the first phase of mandatory compliance running from 2024-26. The second mandatory compliance phase goes from 2027-35. It is estimated that over the 2021-35 time period, carbon emissions from flights covered by CORSIA will average over 600 million metric ton of CO_2e per year (International Civil Aviation Organization 2019). Offsets with a vintage of no earlier than 2016 are eligible, and the following third-party standards were recently approved as eligible sources of supply: American Carbon Registry, China GHG voluntary emission reduction program, Climate Action Reserve, The Gold Standard, the Clean Development Mechanism, and the Verified Carbon Standard.

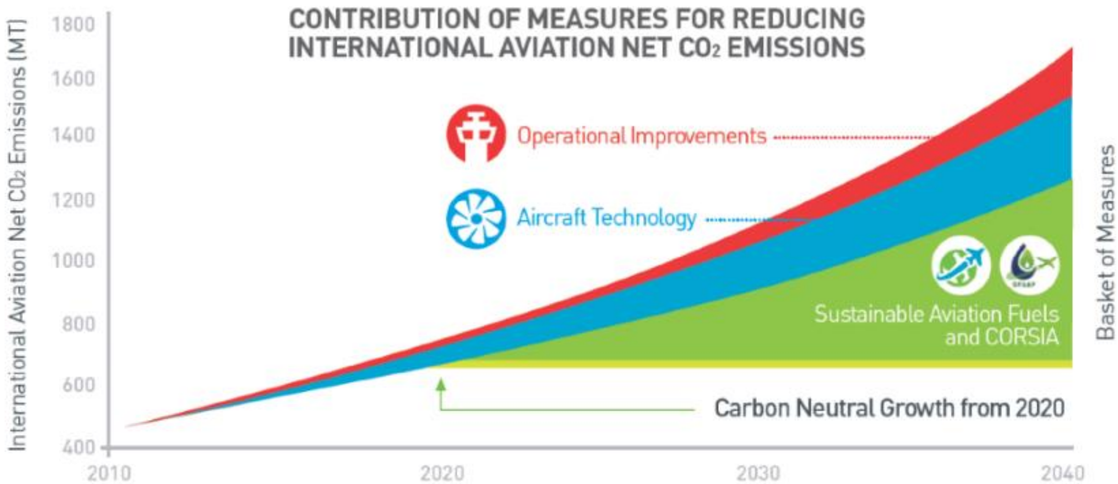

Figure 6.4: Potential offset demand from international aviation (International Civil Aviation Organization).

Carbon offsets will be a key component of ICAO's market-based mechanisms to achieve emissions targets. Currently, ICAO is reviewing existing carbon offset methodologies to determine those that will be accepted under CORSIA. Based on the sheer number of offsets that will be required by the international aviation industry, it is likely carbon offset demand will increase over the next decade (Figure 6.4).

6.3.1.4 Other potential international market mechanisms – The two most significant potential market mechanisms that could develop early in this decade are international shipping and cloud computing.

<u>6.3.1.4.1 International shipping</u> – The top 10 international container shipping companies generate nearly $200 billion (USD) annually, and all are headquartered in countries that ratified the Paris Agreement.

For example, the Maersk Line, the world's largest overseas cargo and freight carrier, is based in Denmark. They have 324 offices in 115 countries worldwide and operate 590 container ships. They estimate they ship $675 billion worth of goods each year, almost as much as the GDP of Switzerland (MoverDB.com 2019).

In 2018, the member states of the UN's International Maritime Organization (IMO) adopted an initial strategy on the reduction of greenhouse gas emissions (GHG) from ships, setting out a vision to reduce GHG emissions from international shipping and phase them out as soon as possible in this century. The strategy states that emissions should peak as soon as possible, and then reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time pursuing efforts toward phasing them out entirely (United Nations International Maritime Organization 2019). The strategy outlines technological innovation and the global introduction of alternative fuels and/or energy sources for international shipping as the key pathways to achieve its overall targets.

Although carbon offsetting is not specifically identified in IMO's strategy to reduce GHG emissions, the Maersk Line and other large international container shipping companies are watching the international aviation sector's CORSIA initiative. It is possible that this sector may add a carbon offsetting component to the IMO strategy in the coming years.

6.3.1.4.2 Cloud computing – Cloud computing is the delivery of computing services – including servers, storage, databases, networking, software, analytics and intelligence – over the internet ("the cloud"), to offer faster innovation, flexible resources and economies of scale. Cloud computing is made possible by data centers located throughout the world, with the United States being home to 3 million data centers – roughly one for every 100 Americans (Fortune 2019). Prineville, Ore., is home to three giant data centers, and two more are planned to be built to serve the growing demand for cloud-based services.

Information and communications technology (ICT) ecosystems mostly driven by cloud computing consume a significant and growing amount of energy. Today, data centers consume about 2% of electricity worldwide; that could rise to 8% of the global total by 2030, according to a study by Anders Andrae, who researches sustainable information and communications technology for Huawei Technologies Ltd. (Andrae and Edler 2015). That puts ICT's carbon footprint on par with the international aviation industry's emissions from fuel.

Today, data centers contribute 0.3% to global carbon emissions, according to Nature; the ICT sector as a whole contributes over 2%, and those numbers could increase (Jones 2018). The biggest players in the cloud computing and data storage space are Microsoft, Amazon Web Service, Salesforce, IBM, Google, SAP, Oracle, Facebook and Apple. All these companies are committed to reducing their GHG footprints over the next three decades, and several have already funded forest projects as part of their mitigation strategy.

It is hard to forecast future energy consumption and the carbon footprint associated with cloud computing. However, it seems likely that even with dramatic energy efficiencies implemented over time, GHG emissions will be globally significant, and carbon offsets could play a meaningful role as a mitigation strategy.

6.3.2 Federal and state policy mechanisms

6.3.2.1 Federal government – Dozens of federal departments and agencies are engaged in climate change research, policy tool development and greenhouse gas accounting. Those agencies that manage forestland, primarily the U.S. Forest Service and the Bureau of Land Management, are actively engaged in developing policy and land management strategies for public and private lands across the United States.

The United States Department of Agriculture (USDA) Climate Hubs network is leading efforts to identify land management actions that maintain or increase carbon storage in forests. One important contribution to the policy toolkit is a recent paper published in the Journal of Forestry titled *Forest Management for Carbon Sequestration and Climate Adaptation* (Ontl et al. 2019).

The paper presents a Forest Carbon Management Menu to help translate broad carbon management concepts into actionable tactics that help managers reduce risk from expected climate impacts in order to meet desired management goals. Examples of real-world forest-management planning projects are described that integrate climate change information with this resource, to identify actions that simultaneously benefit forest carbon along with other project goals.

6.3.2.2 U.S. Climate Alliance, founded in June 2017, is a bipartisan coalition of governors committed to reducing greenhouse gas emissions consistent with the goals of the Paris Agreement. Coordinated state action can ensure that the United States continues to contribute to the global effort to address climate change (United States Climate Alliance 2020a). The Alliance represents 55% of the U.S. population. Together, their combined economies represent $11.7 trillion, economically larger than all countries but the United States as a whole and China. As of December 2019, 25 states including Oregon were part of the U.S. Climate Alliance.

The U.S. Climate Alliance is based on three core principles:

1. States are continuing to lead on climate change: Alliance states recognize that climate change presents a serious threat to the environment and our residents, communities, and economy.
2. State-level climate action is benefiting our economies and strengthening our communities: Alliance members are growing our clean energy economies and creating new jobs, while reducing air pollution, improving public health, and building more resilient communities.
3. States are showing the nation and the world that ambitious climate action is achievable: Despite the U.S. federal government's decision to withdraw from the Paris Agreement, Alliance members are committed to supporting the international agreement, and are pursuing aggressive climate action to make progress toward its goals.

In 2018, the U.S. Climate Alliance created the Natural and Working Lands Challenge (United States Climate Alliance 2020b) to help achieve its commitments. Under this challenge, states commit to:

- improve inventory methods for land-based carbon flux
- identify best practices to reduce GHG emissions and increase resilient carbon sequestration
- advance programs, policies and incentives to reduce GHG emissions and enhance resilient carbon sequestration
- undertake actions that will support a collective, Alliance-wide goal to maintain natural and working lands as a net sink of carbon and protect and increase carbon storage capacity, while balancing near- and long-term sequestration objectives
- integrate priority actions and pathways into state GHG mitigation plans by 2020

The Challenge requires states to consider and, as appropriate, adopt practices that increase long-term carbon sequestration in forests and forest products; reduce losses from catastrophic wildfire and land-use change; protect existing natural and working lands from conversion; support healthy soils on farms and ranches; restore coastal wetlands and sub-tidal habitats that protect shorelines against sea level rise; restore ecosystems and open space for watershed protection and recreation; and grow the urban forest and other greenspace to improve health and livability.

The U.S. Climate Alliance, in cooperation with non-governmental organization (NGO) partners, hosted a series of Learning Labs from mid-2018 through 2019 to help policymakers from the member states develop a deep understanding of what drives carbon benefits in the land sector, and to assist them in developing action plans to address ways natural and working landscapes can contribute to climate mitigation. Oregon state agency and NGO representatives participated in the 2018 national Learning Lab and the 2019 western regional Learning Lab, and are currently developing a statewide action plan for natural and working lands.

6.3.2.3 Forest Climate Working Group (FCWG) – The Forest Climate Working Group is the nation's only forest-sector coalition to represent every aspect of U.S. forests' government agencies, landowners, forest products companies, conservation and wildlife groups, academics and carbon finance experts. It develops and advocates for federal, state and local policy mechanisms that will ensure U.S. forests contribute to mitigating climate change. FCWG members encourage all levels of government to consider a wide range of tools to deliver financial incentives for forest-sector carbon mitigation(Forest-Climate Working Group 2019).

The FCWG authored a policy solutions toolkit designed for state and local governments that offers a wide range of tools to deliver financial incentives for forest-sector carbon mitigation, including offsets, cost-share payments, grants, and tax incentives. *Tapping into U.S. Forests to Mitigate Climate Change: A Policy Toolkit* is available for free at the Forest Climate Working Group website, http://forestclimateworkinggroup.org.

6.3.2.4 California Air Resources Board – climate investment fund – California Climate Investments (CCI) is a statewide initiative that puts cap and trade dollars to work reducing greenhouse gas emissions, strengthening the economy and improving public health and the environment – particularly in disadvantaged communities, low-income communities and low-income households. Funding comes from cap and trade auction proceeds. The California Legislature appropriates money from the Greenhouse Gas Reduction Fund (GGRF) to state agencies that administer California Climate Investments programs (California Air Resources Board 2020). This is a market mechanism that uses incentives (payments) to landowners for implementing practices that contribute to climate mitigation.

California's natural and working lands comprise three-quarters of the state's land base. A key component of the state's natural and working land strategy is forest management and wildfire programs. These programs are administered by the California Department of Forestry and Fire Protection (CalFire), and have received $560 million to invest through its grant programs (CAL FIRE 2019). The Forest Health Program funds reforestation, forest fuel reduction, pest management, conservation easements and fee acquisitions, and forest biomass utilization projects.

6.3.2.5 Oregon – Oregon has a long history of debate and action around climate change, dating back to the 1990s (Yost 2019). In 1997, the Legislature passed HB 3283 regulating carbon dioxide emission from baseload gas plants, non-baseload, fossil fuel powered plants and non-generating facilities that emit carbon dioxide. This was the nation's first legislation to reduce emissions of carbon dioxide.

Also, in 1997 The Climate Trust was founded as a 501(c) (3) nonprofit organization to acquire carbon offsets on behalf of new fossil-fueled power plants regulated by the Oregon Carbon Dioxide Standard, established by HB 3283. The Climate Trust was the first institutional buyer of carbon offsets at the beginning of the U.S. carbon market, and created a process for a supply of offsets, protocols and quality standards that did not exist.

In 1999, the Forest Resource Trust was established and received $1.5 million in funding from the Klamath Co-Generation Project in south-central Oregon to invest in carbon offsets. The practice used to generate offsets is reforestation on non-industrial private lands. Reforestation is the process of converting formerly forested lands that are currently in agricultural use, rangelands or poorly stocked forestland back into healthy, productive forests through by establishing new forests. This program has seldom been utilized, due to lack of funding.

In 2001, HB 2200 was enacted, providing the State Forester authority to enter into agreements with nonfederal forest landowners as a means to market, register, transfer or sell forestry carbon offsets on behalf of the landowners, to provide a stewardship incentive for nonfederal forestlands. Since the establishment of HB 2200, this authority has not been utilized by the Oregon Department of Forestry.

In 2007, HB 3543 established the Oregon Global Warming Commission. The commission's mission is to recommend ways to coordinate state and local efforts to reduce Oregon's greenhouse gas emissions, and to help the state, local governments, businesses and individual Oregonians prepare for the effects of climate change. The commission may recommend statutory and administrative changes, policy measures and other actions to be carried out by state and local governments, businesses, nonprofit organizations and Oregon residents.

In 2018, HB 5201 created the Carbon Policy Office (CPO) to conduct research and analysis and engage stakeholders, to inform a statewide policy framework and to grow Oregon's economy while achieving Oregon's greenhouse gas reduction goals.

Funding was made available through the CPO for the Oregon Department of Forestry (ODF) to contract with the USDA Forest Service Forest Inventory and Analysis Program to produce an Oregon Forest Ecosystems Carbon Report, similar to the report FIA produced for California. Staff within ODF then used internal forest assessment funds to contract with FIA to have the Bureau of Business and Economic Research produce an Oregon Harvested Wood Products Carbon Report and an Oregon Sawmill Energy Report, which are expected to be completed in mid- to late 2020.

A summary of the Oregon Forest Ecosystems Carbon Report was presented to the Legislature in the fall of 2019, summarizing the total forest carbon stocks and flux by ecoregion, ownership, forest type and forest pool. The report supplies the information for Chapter 2 of this report, and is based on measurements collected by the USFS Forest Inventory and Analysis program on forest inventory plots in Oregon from 2001-16. The Oregon Forest Ecosystems Carbon Report is summarized in Chapter 2 of this publication.

In 2019, the Legislature considered HB 2020, a bill that would have established a cap and trade program with many similarities to California's cap and trade program. HB 2020 would have restricted the annual amount of GHG large-scale industrial plants could emit (the "cap" component) to 25,000 metric tons of carbon dioxide equivalent per year. Businesses that emitted amounts under the cap would be able to sell carbon credit allowances to those who emitted more (the "trade" component). Over time, the allowances available would decline, requiring producers across the state to reduce their emissions by 80% by 2050, through innovation of more efficient processes.

The bill included sections that established a carbon offsets program and a process to establish and approve carbon offset protocols. Carbon offsets generated from approved carbon projects could have been used to meet up to 8% of an emitter's annual obligation, with 4% demonstrating direct environmental benefit to the state.

The bill also included the creation of a climate investment fund that would receive monies generated from auctioning off carbon allowances. Forty percent of the fund would have been allocated for uses that benefit impacted communities, included rural communities, and 20% of the fund would have been allocated to natural and working lands, including for the purposes of planting trees and improving forest management practices on forestlands within the state.

HB 2020 passed the House with a super-majority in late 2019; however, the Senate did not act on the bill due to controversy surrounding many key provisions in the bill. The opponents' concerns were mostly about the impacts to rural Oregonians.

A revised cap and trade bill was considered in the 2020 legislative session, a 35-day session that was begun in February 2020. Governor Brown and legislative leaders made passing climate legislation a top priority of the 2020 legislative session. Changes were made to previously proposed climate legislation to address concerns raised by natural-resource-based businesses and rural Oregonians. The 2020 legislative session ended without any legislation being passed due to a walk-out by House and Senate Republicans over the proposed climate legislation.

On March 10, 2020, Governor Brown signed Executive Order NO. 20-04, which directs state agencies to take actions to reduce and regulate greenhouse gas emissions. The Executive Order includes a directive that the Oregon Global Warming Commission coordinate with the Oregon Department of Agriculture, the Oregon Department of Forestry and the Oregon Water Enhancement Board to prepare and submit a proposal to the governor by June 30, 2021, that offers recommendations of state goals for carbon sequestration and storage by Oregon's natural and working lands, including forests.

6.3.3 Private sector mechanisms

6.3.3.1 Corporate programs – The concept of corporate social responsibility (CSR) has been around for decades; it is an evolving business practice that incorporates sustainable development into a company's business model. These practices are designed to have a positive impact on social, economic and environmental factors.

To understand how critical CSR has become, research by Cone Communications found that more than 60% of Americans hope businesses will drive social and environmental change in the absence of government regulation. Nearly 90% of the consumers surveyed said they would purchase a product because a company supported an issue they care about. More importantly, roughly 75% will refuse to buy from a company if they learn it supports an issue contrary to their own beliefs (Cone Communications 2017).

For most corporations, climate change fits within social, economic and environmental considerations. BSR is a global nonprofit organization that works with its network of more than 250 member companies and other partners to build a just and sustainable world; the organization released its 11th annual GlobeScan State of Sustainable Business Survey (BSR 2019) in November 2019. The survey provides insight into the world of sustainable business and identifies common perceptions and practices of corporate sustainability professionals.

BSR's survey results find that companies citing climate change as a "very significant" sustainability focus jumped dramatically in 2019, increasing 14 percentage points to 52%. Climate change, ethics and integrity, and diversity and inclusion continue to be the top overall priorities. Corporations are also showing a greater interest in using Sustainability Development Goals (SDGs) to guide performance targets, with a nine-point jump from 2018, up to 48% in 2019.

One way corporations are addressing climate action is by instituting an internal price for carbon. An internal price places a monetary value on greenhouse gas emissions, which businesses can then factor into investment decisions and business operations.

Companies say that internal carbon pricing gives them an incentive to shift investments to low-carbon alternatives. It also helps them achieve their greenhouse gas targets, address shareholder concerns about disclosure, build resilient supply chains, gain a competitive edge and showcase corporate leadership.

According to 2016 disclosures to CDP Global (formerly the Carbon Disclosure Project), more than 1,200 companies worldwide are either pursuing internal carbon pricing or preparing to do so. While most companies pursuing internal carbon pricing are based in North America and Europe, the sharpest increase is by companies in emerging economies, including India, Brazil, Mexico and China (CDP Global 2016).

Corporations are also addressing climate action by purchasing carbon offsets. They use carbon offsetting to voluntarily reduce their GHG footprint, or to meet regulatory mandated targets. Carbon offsets are described in more detail in Section 6.4 of this chapter.

Carbon insetting is a new market mechanism that has yet to be fully defined. It is similar to carbon offsetting; however, the reduction must occur within the company's supply chain. A company may generate an inset by working with its suppliers to identify ways to procure needed supplies that reduce the carbon emissions and/or increase the carbon sequestration associated with producing those supplies. If the carbon emissions reductions accomplished through the change can be quantified, it can be reported as a reduction in the company's overall emissions.

It is safe to say that corporations are playing an important and growing role in creating demand for market-based solutions that contribute to mitigating climate change.

6.4 Overview of carbon offsets and the projects generating offsets

6.4.1 Carbon offset projects

A carbon offset project is a third-party-verified activity that either avoids an emission of greenhouse gases or removes carbon from the atmosphere. A project must follow a set of rules contained in a protocol or methodology approved by the carbon program selected for use by the project proponent.

A carbon offset project generates carbon offsets. The United Nations Intergovernmental Panel on Climate Change (IPCC), in its 2014 glossary to the Fifth Assessment Report, defines "offset" (in climate policy) as a unit of CO_2 equivalent emissions that is reduced, avoided or sequestered to compensate for emissions occurring elsewhere (Allwood et al. 2014). One offset is equal to one metric ton of carbon dioxide equivalent (CO_2e).

There are two categories of carbon offset projects. The first category is an activity that avoids a greenhouse gas emission, include capturing and destroying greenhouse gases through activities such as managing ozone-depleting substances, coal mine methane, livestock manure digesters and organic waste composting. The second category is an activity that sequesters carbon from the atmosphere. These projects are based on natural and working landscapes and include activities that are referred to as Natural Climate Solutions (NCS). Categories of these projects include forestry, agricultural lands, grasslands and wetlands.

All carbon offset projects must demonstrate that they are additional, real, measurable, verifiable and permanent. Each carbon program and its approved protocols vary in the methods used to demonstrate these project attributes.

Additional – Climate benefits are above and beyond "business as usual" or a "baseline" of reductions that would have happened anyway.

Real and Measurable – A project must be able to measure and conservatively calculate the benefit it is providing.

Verifiable – An independent third party can confirm the project meets the protocol requirements and procedures, including the accuracy of the carbon offsets claimed.

Permanent – The project reductions must be equivalent to the emissions the project is offsetting. Forest carbon projects measure the number of years the carbon is stored.

6.4.2 Regulated and voluntary carbon offset registries

Today, there are five widely recognized carbon registries operating in the United States. Collectively these registries offer a wide range of protocols and methodologies that can generate carbon offsets.

American Carbon Registry (ACR) – ACR is a program of Winrock International, which is a nonprofit U.S. carbon market standard and registry. ACR was the first private voluntary greenhouse gas registry in the United States, and continues to lead voluntary carbon market innovation. ACR also serves as a registry for the California Air Resources Board's cap and trade program (American Carbon Registry 2019).

California Air Resources Board (ARB) – A program of California EPA, ARB manages the state's cap and trade program, established under California law. The Global Warming Solutions Act of 2006 (AB-32) is designed to return California emissions to 1990 levels by 2020. The cap and trade program, which includes forestry offsets, is designed to contribute to the statewide emissions target (California Air Resources Board 2019a).

Climate Action Reserve (CAR) – A national voluntary offset program focused on ensuring environmental integrity of GHG emissions reduction projects, to create and support financial and environmental value in the U.S. carbon market. CAR also serves as a registry for the ARB's cap and trade program (Climate Action Reserve 2019).

Gold Standard – An international nonprofit based in Switzerland, established in 2003 by World Wildlife Fund (WWF) and other international NGOs, works to ensure projects that reduce carbon emissions are featuring the highest levels of environmental integrity and contributing to sustainable development (Gold Standard 2019).

Verified Carbon Standard (VCS) – Founded in 2005, VCS is best known for projects under the Clean Development Mechanism (CDM), with a focus on Reduced Emissions from Deforestation and Degradation (REDD) projects in developing countries (Verra 2019).

A list of protocols or methodologies approved for use by each registry is available on their website. There are dozens of protocols and methodologies available for use, with most being applicable to natural and working lands.

It is important to note that carbon offset projects generate carbon offsets, while markets transact carbon credits. A carbon credit is an instrument that represents ownership of one metric ton of carbon dioxide equivalent that can be traded, sold or retired (Carbonfund.org 2012).

6.5 Forest carbon offset projects

A range of protocols or methodologies available for forest carbon projects are approved by each major carbon program operated by a registry. These are like recipe books that detail eligibility requirements, forest management commitments, carbon accounting rules, monitoring and verification frequency, reversal penalties, and potential enforcement actions and liabilities. For example, forest protocols or methodologies range in project time commitments from 30 years up to 200 years. Some protocols include prescriptive forest management requirements, while others offer flexibility in forest management activities.

Three types of forest projects qualify for offsets under the major carbon programs in the United States: reforestation, avoided conversion and improved forest management.

- **Reforestation –** These projects require tree planting or removal of impediments to natural reforestation on land that previously had no forest or had been subject to a significant disturbance that resulted in a considerable loss of aboveground carbon. For example, in California several landowners are working to register carbon projects where they voluntarily replanted trees in areas previously impacted by wildfire.

- **Avoided conversion –** These projects require a perpetual conservation easement that prevents the conversion of forestland to non-forest uses. The landowner must be able to demonstrate that there is a significant threat of conversion of the project lands to a non-forestland use.

- **Improved Forest Management (IFM) –** These are the most common forest projects, and require management practices that will result in storing more carbon than is required by law and regulation, and at higher levels than would be generated through common forestry practices in the local geographic area. For example, extending rotation age and harvesting less than annual growth are practices that could qualify under this project type. Projects located on lands that are economically marginal to manage can be a good fit, as by adding some carbon revenue to harvest and other revenue, the overall economic return of land management can be improved.

ARB publicly reports the number of offset credits issued by project type, on its website. At the end of 2019, ARB had issued just over 144 million compliance offset credits in four project type categories: ozone depleting substances (ODS), livestock, U.S. forest and mine methane capture (MMC). Forestry projects represented 84% (120 million) of all compliance offset credits issued (California Air Resources Board 2020b). See Table 6.1.

Table 6.1: California Air Resources Board offset credits issued
(https://ww3.arb.ca.gov/cc/capandtrade/offsets/offsets.htm).

Project type	ODS	Livestock	U.S. forest	Urban forest	MMC	Rice cultivation
Compliance	14,988,658	4,827,041	120,648,473	-	3,944,114	-

As of August 2019, ARB had issued compliance offset credits from 95 forest projects on about 4.2 million acres across the United States. Of these credits issued, 88% were generated from projects located outside California, on 91% of the total acres contained in all projects. California recently passed legislation that will limit the number of compliance offset credits that come from outside the state, beginning in 2021.

The voluntary market has been active in a variety of forms over the past three decades. Few, if any, formal standards and very little transparency marked the initial few decades as the voluntary market developed. Ecosystem Marketplace (EM), an initiative of Forest Trends, began tracking voluntary carbon markets in 2006. The voluntary markets are still somewhat opaque; however, EM has illuminated the transaction realm for over a decade, with more and better information as each year passes.

In December 2019, EM released its State of the Voluntary Carbon Markets 2019. This report includes a review of the past 30 years of the voluntary carbon market. The cumulative volume of carbon offsets since 2006 reported by EM now exceeds 1.2 BMT (Ecosystem Marketplace 2020b).

Globally, EM reports that 98.4 MMT of carbon equivalent was transacted in 2018, with a market value of $296 million (USD). Forestry and land use contributed 52% of the total carbon offsets transacted, accounting for 58% of the transaction value.

In the United States, carbon offsets generated through voluntary carbon projects are difficult to track, as each registry maintains its own project accounting. There is a growing interest in voluntary forest carbon projects in the United States, including projects being developed by The Nature Conservancy (TNC) through its Working Woodlands program; the Family Forest Carbon Program – a joint program of American Forest Foundation and TNC focused on incentivizing small family forestland owners to implement practices that remove and store more carbon; and some larger family forestland owners.

Co-benefits – While carbon credits are traded based on their climate benefits, many projects also have a host of additional impacts, known as co-benefits. These co-benefits are often in line with other aspects of sustainable development, such as supporting the local economy through job training and creation, preserving watershed areas that supply clean water, or safeguarding biodiversity. In many cases, co-benefits are integral to the project and often are one of the main reasons suppliers and buyers are engaged in voluntary carbon markets.

Several standards either incorporate co-benefits in their requirements or offer add-on certifications to measure co-benefits. Recently, many project developers and standards have begun aligning their co-benefits metrics with the United Nations' Sustainable Development Goals, which include everything from ending hunger to providing access to energy to conserving marine life. While there currently is no set of universally used metrics to measure many of these co-benefits, it is fair to say that many of the offsets issued since 2005 have provided additional benefits to the communities and ecosystems in which they operate (Ecosystem Marketplace 2020a).

6.6 Oregon carbon project cases

6.6.1 City of Astoria – Bear Creek Watershed IFM Carbon Project

Since the 1950s, the City of Astoria has owned and managed the Bear Creek watershed, which contains 3,423 acres of commercial forest. The watershed's primary purposes are to provide fresh drinking water to Astoria residents and timber harvest revenue to support city services.

In 2014, the Astoria City Council adopted a revised forest resource management plan that began its commitment to sequester carbon beyond all legal and regulatory requirements. Based on a 2013 forest inventory, it was determined that harvest levels could be substantially increased while still meeting the requirements of its Forest Stewardship Council certification, complying with federal and state law including the Oregon Forest Practices law, and continuing to produce high-quality water to its residents. However, the Astoria City Council decided to limit future timber harvest, trading off timber revenue for carbon revenue.

The City of Astoria initiated a voluntary Improved Forest Management project in 2014 under the American Carbon Registry. To date, the project has produced just over 260,000 carbon offsets, which have been purchased by The Climate Trust. The project is entering the seventh year of its initial 20-year crediting period. In 2020, the project is scheduled to be re-verified and will generate another tranche of voluntary carbon offsets.

6.6.2 Green Diamond Resource Company – Klamath Forest Carbon Projects

In 2014, Green Diamond Resource Company purchased more than 600,000 acres of forestland in the vicinity of Klamath Falls. In the several decades prior this purchase, these forestlands had been sold several times and heavily harvested by the previous owners. Thus, the carbon stocks at the time of purchase were less than one-half the common practice carbon value published by the California Air Resources Board (ARB) – the amount of carbon expected to be on similar land under private ownership in the Klamath Falls area.

In 2015, Green Diamond registered two ARB Improved Forest Management compliance projects on about 575,000 acres. These projects represent the first of their type – carbon stocks well below the common practice baseline value – which means carbon offsets are only generated by growing more volume than is harvested, from the beginning of the project. All other ARB IFM projects to date have been issued carbon offsets in the initial period for existing stocks above the common practice baseline value, generating a significant amount of revenue at the beginning of these projects.

Green Diamond's projects represent a long-term investment to improve forest health, increase productivity and enhance resiliency, to reduce pest outbreaks and wildfire occurrence while storing greater amounts of carbon over the next 100 years. Revenue generated through the sale of carbon offsets is being used to help restore these lands to a healthier and more productive condition. To date, nearly 1 million carbon offsets have been generated by these ARB-compliant projects.

6.6.3 Warm Springs Tribe – Forest Carbon Phase I Project

The Warm Springs Tribe in central Oregon decided to pursue a compliance project on 24,000 acres of the 440,000-acre Warm Springs Reservation Forest in 2015. A small parcel burned during the initial stages of project development, reducing the ultimate project size to 22,000 acres. The project is eligible to generate offsets because the Tribe's management practices on the parcels result in forest carbon stocks that are well above the regional baseline. To date, 2.7 million carbon offsets have been issued to the project.

6.7 Summary

Forests play an important role as a natural mechanism to remove and store carbon from the atmosphere. U.S. forests, including the 30 million acres of forestland in Oregon, have the potential to store even more carbon through healthy, sustainable forest management practices.

Markets are an important mechanism to address mitigating climate change. Market-based mechanisms offer flexible instruments designed to achieve environmental goals at a lower cost and in a more flexible manner than traditional regulatory measures.

There are a range of market mechanisms, from international to local levels, operated by governments and the private sector. These include the UN Paris Agreement, the Clean Development Mechanism and International Civil Aviation Organization. The two most significant potential market mechanisms that could develop early in this new decade are international shipping and cloud computing. In addition, federal, state and private-sector policy mechanisms offer a growing range of regulatory and incentive-based programs that are collecting and sharing data, developing action plans and implanting practices designed to reduce greenhouse gas emissions and remove carbon from the atmosphere.

Oregon was an early leader in climate change action, dating back to the 1990s. Recently, Oregon has focused more political and social capital on crafting legislation and developing programs to address climate change mitigation. The latest expression of this is Governor Brown's March 2020 Executive Order to reduce and regulate greenhouse gas emissions.

Finally, there are several regulatory and voluntary carbon offset programs operating in the United States and available for use in Oregon. These programs allow participants to develop a carbon offset project, which is a third-party-verified activity that either avoids an emission of greenhouse gases or removes carbon from the atmosphere (see Oregon Carbon Project sidebars). Many purchasers of carbon credits prefer forest projects because of the associated co-benefits, such as wildlife habitat, safeguarding biodiversity and protecting important drinking water supplies.

There is growing momentum across the world, within the United States and in Oregon to implement policies and programs to more aggressively mitigate climate change. Forests offer an undeniably clear and substantial role in mitigating climate change today and into the future, especially in the abundantly forested state of Oregon.

6.8 References in Chapter 6

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