Oregon Harvested Wood Products Carbon Inventory 1906 – 2018

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Revisions

Revisions to the first version of this report include:

The Executive Summary was added and a correction was made for the estimate of the amount of carbon in bark associated with logs harvested between 1906 and 2017 from 92.21 MMT C (338.15 MMT CO_2e) to 98.78 MMT C (362.24 MMT CO_2e).

This sentence on page 19 was changed from “The cumulative HWP stock was 350.7 MMT C, about 43.1% of cumulative TPO since 1906” to now read “The size of the HWP stock since 1906 increased to approximately 350.7 MMT C, about 43.1% of cumulative TPO since 1906.”

Figure 3 on page 21 was changed from a line graph to a bar graph to better depict annual quantities. The line in Figure 3 depicting the net change in the combined pool of HWP C is now calculated by adding the amount of annual change in PIU with annual change in SWDS (which already accounts for transfers of C to emissions categories) rather than adding annual change in the combined pool of HWP C with the negative values of annual change in the emissions categories.

The sentence on page 22 that began with “The net difference between the annual change in the pool of HWP C and biogenic emissions…” was modified to now read “The annual change in the combined pool of HWP C (PIU + SWDS) was greater than zero for each year of the time series because transfers to the SWDS pool were large enough to offset times when the annual change in the PIU pool dropped below zero (i.e., in 1933, each year from 1995 through 2000, and again from 2009 through 2011 (Figure 3).”

The caption for Figure 7 on page 26 was modified and now reads: “Monte Carlo simulation mean and 90% confidence intervals for the size of the pool of carbon in PIU and SWDS and the cumulative emissions with and without energy capture from timber harvested in Oregon from 1906 to 2017.”

The last two sentences before the Discussion section on page 30 were changed to now read: “After accounting for the average HWP emissions with energy capture from burning fuelwood (EEC = 1.6 MMT CO_2e/year) and average emissions without energy capture (EWOEC = 15.6 MMT CO_2e/year) for the 2001-2016 time period, the balance of carbon in the pool of HWP was approximately 8.4 MMT CO_2/year. Therefore, the combined average net change for the pool of carbon in Oregon’s forests and HWP for this time period (including PIU and SWDS) was approximately 38.9 MMT CO_2e/year (10.6 MMT C/year).”

Executive Summary

Introduction

While reducing emissions from combustion of geologic sources of energy (e.g., coal, oil, and natural gas) remains the most effective and direct way for humans to control rising levels of atmospheric carbon (Holl and Brancalion 2020), managing forests to increase carbon sequestration and storage is often cited as a major element in addressing the climate crisis (McKinley et al. 2011). Having a reliable inventory of the stock and flux of carbon in forests and the wood products generated from timber harvesting is fundamental to understanding the capacity of forests and wood products to mitigate fossil fuel emissions.

The Oregon Forest Ecosystem Carbon Report (Christensen et al. 2019) provided estimates of the amount of carbon stored in seven pools of forest carbon based on the Forest Inventory and Analysis (FIA) Program's annual inventory of field plots distributed across Oregon's forests. These were initially measured from 2001 to 2010. Estimates of the amount of carbon flux through those pools was based on measurements of 60% the same field plots revisited from 2011 to 2016. Estimates of forest carbon flux in the ecosystem report were based on calculations of tree growth, mortality, and removals between the two periods.

Although the amount of carbon stored in harvested wood products (HWP C) constitutes a relatively small fraction of the carbon in forest ecosystems, it is a fundamental component of carbon accounting and base of information for evaluating various strategies to reduce atmospheric carbon dioxide (CO2) concentrations. Forest C removed by timber harvest is not released immediately into the atmosphere because timber harvests transfer a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time mostly in the form of CO2 as it decomposes or is burned as fuelwood or waste reduction. This report provides estimates for the storage and flux of carbon in wood products manufactured from trees harvested in Oregon since 1906 (Andrews and Kutara 2005, Simmons et al. 2016). It was made possible through a partnership with ODF, PNW-FIA, and the Bureau of Business and Economic Research (BBER) at the University of Montana.

Objectives and Methods

The objectives of this analysis were to: 1) Use the production accounting approach to generate estimates and confidence intervals for the stocks and flux of carbon in the HWP pool for timber harvested from 1906 to 2017 within the State of Oregon; 2) Generate estimates and confidence intervals for the cumulative emissions of CO_2 from burning fuelwood for energy capture and from the decay and burning of discarded wood products; 3) Compare the amount of carbon in HWP among the major Oregon forest ownerships that contributed harvested timber to the pool of HWP from 1962-2017; 4) Combine the estimate of stock and flux for the HWP pool with the average in Oregon's forest ecosystems to evaluate the total stocks and flux in forests and HWP from 2001-2016; 5) Provide a reporting framework for subsequent HWP C analyses in Oregon that can be applied to other regions with available timber harvest and end-product data.

Estimates were calculated using a model of wood flow based on the Intergovernmental Panel on Climate Change (IPCC) Tier 3 production accounting approach which only considers timber harvested in a particular area of study. The HWP C model has been used by several National Forest System (NFS) regions to quantify carbon stored in wood products manufactured from NFS timber (Anderson et al. 2013, USURS 2013, Butler et al. 2014, Loeffler et al. 2014, Stockmann et al. 2012). It has also been used to produce state-specific estimates for California (Loeffler et al. 2019). There are four main data sets required to run the HWP C model including:

1) annual timber harvest volume; 2) annual timber product ratios; 3) annual primary product ratios and 4) end use ratios that allocate the primary products to a larger set of end use products.

Results

State-wide HWP Carbon Stocks and Flux

Based on 111 years of timber harvest in Oregon the cumulative amount of carbon in timber product output (TPO) was approximately 814.4 MMT C. By 2017 about 201.1 MMT (24%) of that carbon was stored as products in use, about 149.6 MMT C (18%) was in Landfills and dumps, about 156 MMT C (571 MMT CO_2e) (19%) had been emitted back to the atmosphere from burning fuelwood, and the rest (39%) had been emitted from decay or burning. The cumulative amount of carbon in bark associated with logs harvested and delivered to mills from 1906 to 2017 was approximately 98.8 MMT C (362.2 MMT CO_2e).

For 2017 the size of the pool of products in use increased by about 0.6 MMT C (2.3 MMT CO_2e), solid waste disposal (SWDS) sites increased by about 1.9 MMT C (7.0 MMT CO_2e), and approximately 16.7 MMT CO_2e was emitted through decay or burning of the historical pool of wood products no longer in use but either in landfills or dumps.

Monte Carlo Simulation Results

The HWP C model includes a Monte Carlo uncertainty analysis (MC) that generates confidence intervals for the amount of carbon distributed to the pools of HWP C and the amount emitted from burning fuelwood and decay. For 2018, the final year of model output, the MC estimate for the mean of the combined pool of PIU and SWDS combined was 349.7 MMT C with a lower bound of 291.0 and an upper bound of 410.0 MMT C. Confidence intervals for just the pool of carbon as products-in-use ranged from 163.3 to 236.8 MMT and the pool in SWDS ranged from 122.5 to 179.3 MMT. The MC analysis estimated that emissions from burning fuelwood might have ranged between 118.7 and 197.3 MMT C (435.3 to 723.5 MMT CO_2e) and emissions without energy capture might have been anywhere between 249.9 and 373.2 MMT C (916.4 to 1368.5 MMT CO_2e).

Stocks and Flux of HWP Carbon by Ownership, 1962-2017

Harvest volumes by ownership are only available from 1962 to 2017 because there is an absence of reliable harvest data for each ownership and the lack of quantitative information from mill studies prior to 1962 from which timber product and primary product ratios are developed. The five ownership classes include USFS, BLM, Tribal, Private (industrial and non-industrial lands combined) and State and other public (including ODF and other state lands, county, and municipal lands). From 1962 to 2017 the cumulative amount of carbon in TPO for all ownership classes was 514.5 MMT C, from approximately 346.9 bbf Scribner of harvested timber. The volumes and relative proportions by ownership vary from year to year. Nonetheless, the average for each ownership across the time series shows that the percentage of total TPO from industrial ownerships accounted for 47.2%, USFS 29.5%, BLM 10.2%, NIP 7.7%, State and other public 4.1%, and Tribal 1.3%. Since 1962, PIU account for about 57% (164.4 MMT

C) and SWDS account for about 43% (123.6 MMT C) of the total HWP C pool. About 288.0 MMT C (56%) of the TPO since 1962 remains in the HWP pools, while 44% (226.5 MMT C or 830.6 MMT CO2e) was emitted through burning or decay. The annual net increase in HWP C from USFS forests up to 1990 averaged about 2.8 MMT C/year whereas the annual average dropped to -0.2 MMT C/year after 1990.

Net change in HWP C originating from BLM forests increased at an annual average of 0.9 MMT C/year from 1963 to 1990 but the annual average was slightly negative (-0.04 MMT C)/year) after 1990 (Figure 9). Net change in HWP C from State and other public forests averaged 0.2 MMT C/year through 1990 and increased to 0.3 MMT C/year after 1990. Net change of HWP C from Tribal forests increased steadily at an annual average of about 0.1 MMT C/year.

Evaluating estimates of HWP C relative to Oregon's forest ecosystem carbon

By 2016 the amount of carbon remaining in the pool of HWP was equivalent to approximately 10.7% of the total C in Oregon's forests (3,239.7 ± 32.8 MMT C) and about 31.1% of the aboveground portion of live and dead trees (1,118.3 MMT C). The total combined amount of carbon in Oregon's forests and HWP in 2016 was approximately 3,587.8 MMT C. The estimate for average annual TPO output for 2001 to 2016 was approximately 7.0 MMT C/year (25.5. MMT CO_2e), approximately 73% of the average cut volume reported in the FIA Oregon Forest Ecosystem Carbon Report. After accounting for the average HWP emissions with energy capture from burning fuelwood (EEC = 1.6 MMT CO_2e/year) and average emissions without energy capture (EWOEC = 15.6 MMT CO_2e/year) for the 2001-2016 time period, the balance of carbon in the pool of HWP was approximately 8.4 MMT CO_2/year. Therefore, the combined average net change for the pool of carbon in Oregon's forests and HWP for this time period (including PIU and SWDS) was approximately 38.9 MMT CO_2e/year (10.6 MMT C/year)..

Discussion

The dynamics in the output of timber products from Oregon's forests generally reflected changes in the economy and changes in NFS land management through the 1906 to 2017 period. TPO increased from less than 2 MMT C/year in 1906 to upwards of 13 MMT C/year in 1972, followed by a steep decline upon implementation of the Northwest Forest Plan. Part of the annual additions to the SWDS C pool are proportional to additions to the pool of PIU because the model transfers 8% of the carbon in primary products directly to the discarded pool to account for waste generated during manufacturing and construction of end-products each year. Wood products with a short half-life such as crates, pallets, concrete forms, etc., enter the waste stream relatively quickly after production, which also maintains the waste stream along with the regular demolition of older products.

The current balance in the pool of HWP C from 2001-2016, reflects the decline in federal harvest combined with the Great Recession in 2009-2011. This amounts to less carbon being added to the HWP C pool more recently than in the past while burning and decay of wood waste remained relatively constant. The contribution of carbon to the atmosphere from discarded HWP could be significantly reduced with further advances in wood waste management. Indeed, end-of-life management of wood products is perhaps the single most significant variable for the full life cycle carbon profile of wood products (Sathre and O'Connor 2010).

Differences between the FIA estimates of cut from Oregon forests and TPO can be attributed to a combination of differences between forests and HWP accounting methodologies, and “additional” items in the FIA removals estimate that are not part of TPO. For example, logging residue generated during timber harvesting, such as needles, branches, tops, and other removals of non-merchantable material during operations such as pre-commercial thinning, are included in FIA’s estimate of cut. Of the harvested tree, the stem represents about 67.54%, while residues (tops, branches, and foliage) represent about 32.46% of total biomass (Ganguly et al. 2020). In contrast, the HWP C estimates are calculated exclusively from log (wood fiber) volumes delivered to timber-processing mills. It is also important to note that the HWP and FIA estimates were developed from very different data sets and methodologies that prevent direct comparisons. For example, FIA’s estimates of average annual cut from forests are based on re-measurements of a sample of field inventory plots over a 10-year cycle, while the HWP estimates are based on annual timber harvest records.

The information presented in this report is fundamental to the wood products dimension of Oregon’s forest carbon accounting framework. It is consistent with the IPCC Tier-3 production accounting approach that was used for the HWP C section in the California Forest Carbon Inventory (Loeffler et al. 2019, Christensen et al. 2018) and multiple USFS regions and forests (Stockmann et al. 2012, Anderson et al. 2013, Butler et al. 2014, Loeffler et al. 2014). The data, modeling framework and results are fundamental to evaluating how the dynamics of Oregon’s past and current timber harvest levels have influenced the annual growth of the pool of HWP C and total forest carbon stock levels. The modeling framework does not include estimates for the emissions associated with timber harvesting, log transportation, HWP manufacturing, substitution effects of wood products, bioenergy, or leakage.

Introduction: Forest Carbon Accounting in Oregon

Forest ecosystems are an important and dynamic component of the carbon cycle. While reducing emissions from combustion of geologic sources of energy (e.g., coal, oil, and natural gas) remains the most effective and direct way for humans to control rising levels of atmospheric carbon (Holl and Brancalion 2020), managing forests to increase carbon sequestration and storage is often cited as a major element in addressing the climate crisis (McKinley et al. 2011). Understanding the capacity for forests to mitigate fossil fuel emissions requires a reliable inventory of the stock and flux of carbon in forests and the wood products generated from timber harvesting. Indeed, there has been a decades-long demand for a reliable forest carbon accounting framework in Oregon to better inform forest managers about the capacity for increasing carbon sequestration and storage. For example, legislation passed as early as 2001 required the State Forester to develop a forest carbon accounting system (ORS 526.783). Through the 2011 Forestry Program for Oregon, the Board of Forestry established goals for developing a system for monitoring carbon in forests and harvested wood products (HWP). Further, the Oregon Global Warming Commission (OGWC) was mandated to track and evaluate the carbon sequestration potential of Oregon's forests and the carbon stored in tree-based building materials (ORS 468A.250(1)(i)). More recently, the Forest Carbon Accounting Report (OGWC 2018) described Oregon's long-standing need for a reliable forest carbon accounting system to monitor the status and trends of carbon storage and annual changes (flux) in carbon storage in forest ecosystems and HWP.

Recognizing the need for proper forest carbon accounting in Oregon, the Forest Ecosystem Carbon Report (Christensen et al. 2019) presented the forest ecosystem dimension of the accounting framework. That report provided estimates of the amount of carbon stored in seven pools of forest carbon based on the Forest Inventory and Analysis (FIA) Program's annual inventory of field plots distributed across Oregon's forests. These were initially measured from 2001 to 2010. The report also provided estimates of the amount of carbon flux to and from those pools based on measurements of the same field plots revisited from 2011 to 2016. Estimates of forest carbon flux in the ecosystem report were based on calculations of tree growth, mortality, and removals between the two periods. The report was a result of a partnership between the Governor's Office of Carbon Policy, Oregon Department of Forestry (ODF), and the Pacific Northwest Research Station (PNW) of the USDA Forest Service.

Reliable estimates of stocks and flux of carbon in forest ecosystems and HWP provide a basis for analyses of trade-offs between carbon storage and other forest management objectives, which can inform forest managers, policy-makers, and the public (Galik and Jackson 2009, Ryan et al. 2010, McKinley et al. 2011). Although HWP C constitutes a relatively small fraction of forest carbon relative to ecosystem carbon (Loeffler et al. 2019), it is a fundamental component of carbon accounting and base of information for evaluating various strategies to reduce atmospheric carbon dioxide (CO_2) concentrations.

Forest C removed by timber harvest is not released immediately into the atmosphere because timber harvests transfer a portion of the C stored in wood to a "product pool." Once in a product pool, the C is emitted over time mostly in the form of CO_2 as it decomposes. When discarded wood products are burned, other greenhouse gases (CH_4, N_2O, CO, and NOx) are emitted. The rate of emission varies considerably among different product pools. For example, if timber is harvested for fuelwood to produce energy, combustion releases C immediately but if timber is harvested and used as lumber in a house, it may be many decades or even centuries before the lumber decays and C is released to the atmosphere. If wood products are disposed of in solid waste disposal sites (SWDS), the C contained in the wood may be released many years or decades later or may be stored almost permanently in SWDS (EPA 2020).

This report provides estimates for the storage and flux of carbon in wood products manufactured from trees harvested in Oregon since 1906 (Andrews and Kutara 2005, Simmons et al. 2016). It was made possible through a partnership with ODF, PNW-FIA, and the Bureau of Business and Economic Research (BBER) at the University of Montana.

Objectives

The objectives of this analysis were to:

1) Use the production accounting approach to generate estimates and confidence intervals for the stocks and flux of carbon in the HWP pool for timber harvested from 1906 to 2017 within the State of Oregon.

2) Generate estimates and confidence intervals for the cumulative emissions of CO_2 from burning fuelwood for energy capture and from the decay and burning of discarded wood products.

3) Compare the amount of carbon in HWP among the major Oregon forest ownerships that contributed harvested timber to the pool of HWP from 1962-2017 harvests.

4) Combine the estimate of stock and flux for the HWP pool with the average in Oregon's forest ecosystems to evaluate the total stocks and flux in forests and HWP from 2001-2016.

5) Provide a reporting framework for subsequent HWP C analyses in Oregon that can be applied to other regions with available timber harvest and end-product data.

This report neither advocates any particular course of action for forest carbon management, nor does it include a life-cycle analysis (LCA) of wood products, estimates for the substitution benefits of wood products, leakage, or estimates of greenhouse gas emissions associated with timber harvesting, wood products manufacturing or related transportation.

Methods

Harvested wood products include lumber, panels, paper, paperboard, and wood used for fuel, and the HWP C pool includes both products currently in use, products-in-use (PIU), and products that have been discarded to SWDS. Additions to the HWP C pool are made through harvesting timber for wood products, and emissions that occur from the decay and combustion of wood products subtract from the pool.

The HWP C analysis described in this paper was based on timber harvested and processed in the State of Oregon, as well as timber that was harvested in Oregon and processed (or burned as fuelwood) outside the state. It does not include timber from outside Oregon that was processed by Oregon facilities (mills) or used directly by residents of Oregon. Material left in the forest after harvest (i.e., logging residue) is not accounted for in this report as HWP C but can represent approximately 32% of total tree biomass as treetops, branches, and foliage (Ganguly et al. 2020).

Nearly all (over 99%) of the bark on logs delivered to primary processing facilities is burned for energy or used for mulch and other landscaping products (Brandt et al. 2006, Simmons et al. 2016, Simmons et al. 2019). Therefore, bark is considered a short-lived by-product with negligible contribution to the pool of HWP C. Nevertheless, approximations were made for the amount of biogenic emissions occurring from utilization of bark following Harmon (1996). Oregon records timber harvest with the Scribner decimal c log rule (32-foot log West OR, 16-foot log East Oregon), which uses inside-bark measurements to quantify wood volume. Total harvest volumes were converted from board foot volumes to cubic feet based on the conversion factors listed in Table 1 (page 8) and the carbon in bark was approximated with the following equation:

$$Carbon\ in\ Bark = Fraction\ of\ Bark\ \times \left(\frac{Carbon\ in\ Wood}{1 - Fraction\ of\ Bark}\right)$$

All timber harvested in a specific year is utilized as PIU, SWDS or fuelwood for energy capture throughout the year of harvest with the final amounts for each pool reported in the subsequent year. The model will generate estimates for emissions with energy capture from discarded wood products when reliable information for parameterization becomes available.

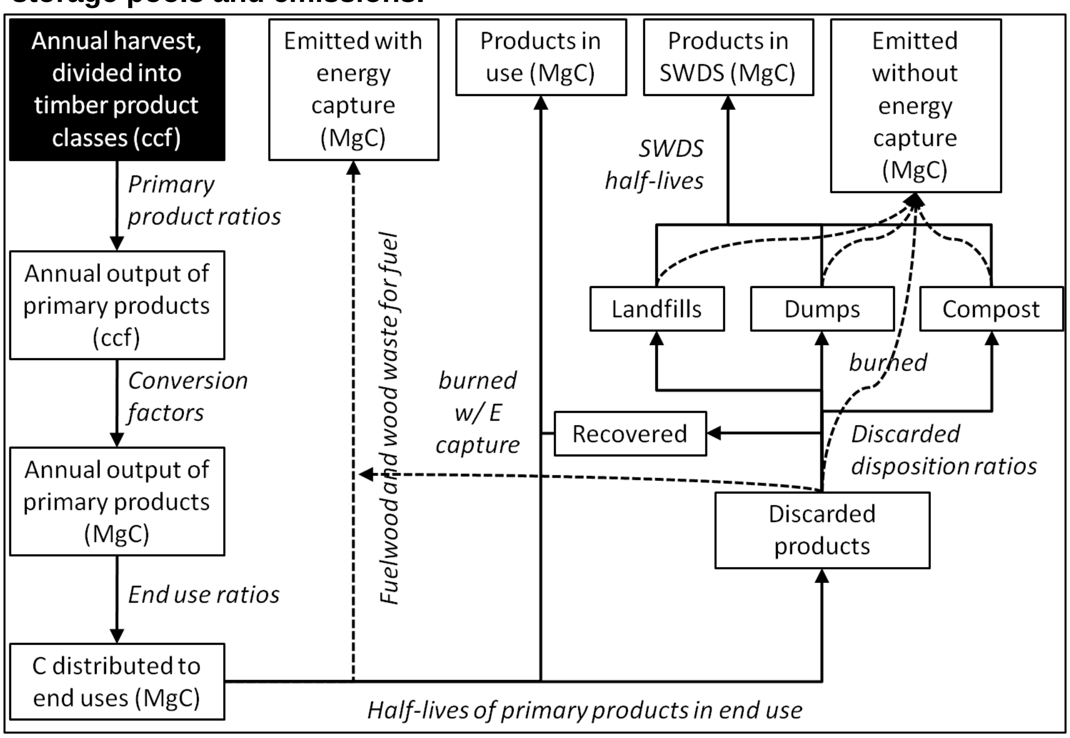
Model

As pointed out by Stockmann et al. (2012) and Loeffler et al. (2019), monitoring systems for HWP C have been implemented at the national level. There are well-established and robust inventory-based methods for estimating carbon stocks and fluxes in forest ecosystems, with several tools available to forest managers (Galik et al. 2009, Smith et al. 2004, Smith et al. 2006, Zheng et al. 2010). However, some of these tools, such as the U.S. Forest Carbon Calculation Tool (Smith et al. 2006), do not provide estimates of HWP C, while others, such as WOODCARB II (Skog 2008) are restricted to national level HWP C accounting. Neither of these models are accessible or practical tools for estimating and monitoring stocks and fluxes in HWP C at the state level (Ingerson 2011, Stockmann et al. 2012).

Estimates of HWP C for the state of Oregon were calculated using the Intergovernmental Panel on Climate Change (IPCC) Tier 3 production accounting approach[1], which only considers timber harvested in a particular area of study. The HWP C model has been used by several National Forest System (NFS) regions to quantify carbon stored in wood products manufactured from NFS timber (Anderson et al. 2013, USURS 2013, Butler et al. 2014, Loeffler et al. 2014, Stockmann et al. 2012). It has also been used to produce state-specific estimates for California (Loeffler et al. 2019). The software to run the HWP C model was programmed in R by Groom Analytics and available online at www.ODF.gov.

The HWP C model uses a series of calculations to estimate carbon storage and emissions for timber that is harvested and used for wood products. Stockmann et al. (2012) provide a flow chart of the model (Figure 1) demonstrating how HWP C is tracked through a product's life, from timber harvest through timber products, primary wood products, end use products, and finally to disposal. For a more detailed description of the model assumptions and calculations, see Stockmann et al. (2012) and Loeffler et al. (2019).

Figure 1. Diagram of the harvested wood products model used to quantify carbon storage pools and emissions.



Source: Stockmann et al. 2012

[1] IPCC Tier 3 denotes the availability of highly detailed data (e.g., from field plots) and the use of simulation models, whereas Tier 1 and 2 use more general data that result in higher uncertainty.

Four sets of inputs are required to run the HWP C model: 1) annual timber harvest volume; 2) annual timber product ratios that allocate harvest to different timber product classes; 3) annual primary product ratios allocating the timber products to a variety of primary products and residue uses, and 4) end use ratios that allocate the primary products to a larger set of end use products. For this Oregon HWP C analysis, the input files were developed from Oregon-specific data, the sources for which are outlined below.

Data Sources

Timber Harvest Data

Data for Oregon's timber harvest volume is quite extensive but somewhat incomplete for the earliest years. Andrews and Kutara (2005) compiled state-level harvest volumes going back to 1925 and state-level lumber production as far back as 1849. County-level timber harvest data with three ownership classes (Tribal, U.S. Forest Service [USFS], private and state combined) have been compiled since 1953, and with the seven ownership classes currently in use (industrial private, non-industrial private [NIP], Tribal, State, Bureau of Land Management [BLM], USFS, and other public) since 1962. Both classifications are from the Oregon Department of Forestry (Andrews and Kutara 2005, ODF 2019). The earliest vintage allowed by the HWP C model is 1906 because it was originally developed for use by the NFS, which was transferred to the Department of Agriculture's U.S. Forest Service in 1905.

Estimates of Oregon timber harvest volumes without ownership classifications are available from 1906 to 1961. Harvest volumes by ownership are available for a shorter time—from 1962 to 2017—allowing for an ownership-level analysis for this period. The major limitation associated with the data for years prior to 1962 is the absence of reliable harvest data for each ownership and the lack of quantitative information from mill studies necessary for developing timber product and primary product ratios for each ownership.

The five ownership classes reported in this analysis include USFS, BLM, Tribal, Private (including industrial and non-industrial lands) and State and other public (including ODF and other state lands, county, and municipal lands). See Appendix 1, table 1A, for Oregon timber harvest by ownership class. State-level Oregon timber harvest data for 1906 to 2017 are included in Appendix 1, table 1B.

Because it was originally developed for use by NFS, the HWP C model requires timber harvest input files with volumes expressed in hundred cubic feet (ccf). Timber harvested in Oregon were reported in a mix of thousand board feet (mbf) Scribner, log rule and mbf lumber tally (Andrews and Kutara 2005) and were converted to cubic feet (cf) of logs using conversion factors from literature and an ordinary least squares regression equation (r-square = 0.9871) formulated from published bf/cf factors (Table 1).

Timber Product and Primary Product Data

Oregon harvest and mill studies (Andrews and Cowlin 1940; Cowlin et al. 1942; Metcalf 1965; Manock et al. 1970; Schuldt and Howard 1974; Howard and Hiserote 1978; Howard 1984; Howard and Ward 1988, 1991; Ward 1995, 1997; Ward et al. 2000; Brandt et al. 2006; Gale et al. 2012; Simmons et al. 2016) were used to develop ratios for timber products (e.g., softwood sawlogs, softwood pulpwood, etc.) and primary products (e.g., softwood lumber, softwood plywood, softwood mill residue used for energy, etc.). For years when specific product ratios could not be determined from the literature, ratios from the previous or following mill study year were used.

Table 1. Conversion factors used in the Oregon HWP C analysis

Conversion	Units	Source
8.596	bf per cf, timber harvest 1906 – 1910	Regression Equation
8.141	bf per cf, timber harvest 1911 – 1920	
7.6923	bf per cf, timber harvest 1921 – 1930	Andrews and Cowlin (1940)
7.231	bf per cf, timber harvest 1931 – 1940	Regression Equation
6.776	bf per cf, timber harvest 1941 – 1950	
6.321	bf per cf, timber harvest 1951 – 1960	
5.866	bf per cf, timber harvest 1961 – 1970	
5.42	bf per cf, timber harvest 1971 – 1979	Keegan et al. (2010)
5.17	bf per cf, timber harvest 1980 – 1989	
4.55	bf per cf, timber harvest 1990 – 1999	
4.0674	bf per cf, timber harvest 2000 – 2003	Brandt et al. (2006)
4.1813	bf per cf, timber harvest 2004 – 2008	Gale et al. (2012)
4.0161	bf per cf, timber harvest 2009 – 2017	Simmons et al. (2016)
33 to 42	lbs per cubic foot, primary products	Smith et al. (2006)
2204.6	lbs per metric ton (MT)	
0.95 to 1.0	Metric ton wood fiber per metric ton product	
0.5	Metric ton carbon (MT C) per dry metric ton wood fiber	
0.71 to 0.91	MT C per ccf, primary products[1]	

[1] See Appendix 1, table 1C (embedded .pdf file), for the model's ccf to MT C conversion for each primary product.

The model utilizes 40 timber product classes (Appendix 1, table 1D embedded .pdf file), requiring harvest to be allocated to timber product categories. Since Oregon timber harvest records contain only harvest volume and do not allocate harvest among different timber product types, harvest and mill studies that quantified the volume of timber used for different products were used to calculate the proportion of total timber harvest that went into each timber product category. Quantitative information from two published reports for the period 1906 to 1941 was used to develop timber product ratios for timber from the Douglas-fir and ponderosa pine regions of Washington and Oregon (Andrews and Cowlin 1940, Cowlin et al. 1942). Timber product ratios were developed from Metcalf (1965) for the period 1942 to 1961.

Data for developing timber product ratios for harvest after 1961 were more readily available[2]. The portion of the harvest allocated to each timber product class was calculated for each harvest year for which data were reported. Although there are 40 timber product classes in the model, most of the harvested timber was softwood sawtimber for both periods (Table 2). See Appendix 2, embedded .pdf file A, for Oregon timber product ratios from 1906 to 2017.

Table 2. Average annual Oregon timber product ratios, 1906-1961 and 1962-2017.

Products class	**1906 to 1961**		**1962 to 2017**	
	Mean	*Std. deviation*	*Mean*	*Std. deviation*
Sawtimber, hardwood	0.003	0.001	0.016	0.010
Sawtimber, softwood	0.818	0.030	0.921	0.061
Pulpwood, hardwood	0.002	0.002	0.011	0.013
Pulpwood, softwood	0.034	0.035	0.042	0.040
Poles, softwood	0.003	0.000	0.004	0.002
Fuelwood, softwood	0.128	0.004	0.002	0.017
Other	0.012	0.010	0.004	0.004

There were 64 primary product classes with ratios, developed from the USFS Pacific Northwest Region HWP C report (Butler et al. 2014) used for the 1906 to 1941 period, and Oregon-specific primary product ratios developed from Manock (1970) that were used for 1942 to 1961. For 1962 and later, primary product ratios were developed from the same literature used to calculate timber product ratios[3]. Mill residues are included as primary wood products, with some entering solid waste disposal sites (SWDS) immediately, some being burned for energy, and some being converted into products that rely on mill residues as raw material, such as particleboard and paper. See Appendix 2, embedded file B, for Oregon's primary products ratios 1906 to 2017. Estimates of primary products volume (in ccf) were converted to metric tons of carbon (MT C) using product specific conversion factors (Smith et al. 2006; Appendix 1, table 1C, embedded .pdf file)

[2] Metcalf 1965; Manock et al. 1970; Schuldt and Howard 1974; Howard and Hiserote 1978; Howard 1984; Howard and Ward 1988, 1991; Ward 1995, 1997; Ward et al. 2000; Brandt et al. 2006; Gale et al. 2012; Simmons et al. 2016.
[3] Manock et al. 1970; Schuldt and Howard 1974; Howard and Hiserote 1978; Howard 1984; Howard and Ward 1988, 1991; Ward 1995, 1997; Ward et al. 2000; Brandt et al. 2006; Gale et al. 2012; Simmons et al. 2016.

End-Use Data

The fate of HWP C is highly dependent on the end use of the primary products. For example, the release of carbon from lumber used in new home construction has a longer duration than carbon released from lumber used for shipping containers, which is released into the atmosphere more quickly through combustion and decay. Fuelwood products are assumed to have full emissions with energy capture in the year they were produced.

Following the methodology advanced by Stockmann et al. (2012) and Loeffler et al. (2019), annual primary product output is distributed to specific end-use categories within the HWP C model according to annual wood product consumption estimates (McKeever 2009, McKeever and Howard 2011). The model's primary products and corresponding end use categories are shown in Appendix 1, table 1E (embedded .pdf file). A national data set was used for a series of analyses and reports generated for all NFS Regions (USFS 2019) for the distribution of primary products to end uses (Appendix 2, embedded .pdf file C).

The HWP model has 224 different possible end uses for HWP per harvest year (e.g., softwood lumber/new housing/single family, softwood lumber/new housing/multifamily, softwood lumber/new housing/manufactured housing, softwood lumber/manufacturing/furniture, softwood lumber/packaging and shipping, etc.). The amount of carbon remaining in use during each inventory year was calculated based on the products' half-lives (Appendix 2, embedded file D) and the number of years that have passed between the year of harvest and the inventory year. An end-use product's half-life value is the decay rate at which carbon in the PIU category passes into the discarded-products category, representing the transition between the two pools (Appendix 1, table 1F, embedded .pdf file). The amount of HWP C remaining in use in any given year was calculated for each end use from all prior years with the standard decay formula:

$$N_t = N_0 \exp\left(\frac{-t\ln(2)}{t_{1/2}}\right)$$

where N_t is the amount of carbon remaining in use in inventory year t, N is the amount of carbon in the end use category in the vintage year of harvest, t is the number of years since harvest, $t_{1/2}$ is the half-life of carbon in that end use, and exp is notation for the exponential function. In our calculations, the starting amount (N_0, at n=0) is adjusted downward by an 8% loss factor (McKeever 2004, Skog 2008) to reflect an immediate transfer to the pool of discarded products before entering the PIU pool. This "loss in use" accounts for waste when primary products (e.g., softwood lumber) are put into specific end uses (e.g., new single-family residential housing).

For a given inventory year, the balance of HWP C that is not in use and not emitted with energy capture is assumed to be in the discarded products category. Carbon in discarded products falls into one of five disposition categories: burned, recovered, compost, landfills, and dumps[4]. The proportion of discarded products that ends up in each of these five categories is different for paper vs. solid wood products, and changes over time. Prior to 1970, wood and paper waste were generally discarded to dumps, where it was subject to higher rates of decay than in

[4] Dumps are open-air disposal sites with high decomposition rates, while landfills are environments with lower decomposition rates.

modern landfills. Since then, the proportion of discarded wood and paper going to dumps has dropped, while the proportion going to landfills has risen, with the remainder going to the other two disposition categories, composting and recovery. Composting and recovery (i.e., recycling and reuse) have become a more prominent part of contemporary waste management systems. In the HWP C model, carbon in compost is assumed to transition directly to emissions while carbon in recovery has a half-life decay factor that treats the discarded portion as emissions. The model's disposal of carbon in paper and solid wood products to dumps and landfills categories is based on discarded products disposition ratios (Appendix 2, embedded file E) from Skog (2008). Following the passage of the Resource Conservation and Recovery Act of 1976 (RCRA, 42 USC § 6901), a much larger portion of discarded HWP goes into modern landfills rather than aerobic dumps or disposed through open burning, which were the dominant form of SWDS prior to RCRA. The model assumes that carbon from discarded products that are burned or composted is emitted without energy capture due to a lack of reliable data to support the alternative (Stockmann et al. 2012, Loeffler et al. 2019). Carbon in the recovered category re-enters the PIU category in the year of recovery. Carbon in products discarded to landfills and dumps are subject to decay determined by their respective half-lives. Only a fraction of the discarded products pool in landfills is subject to decay and associated with emission of carbon. The portion of the discarded products pool not subject to decay is considered "fixed carbon" (Appendix Table 1F embedded .pdf file). For a given year, the carbon remaining in SWDS is the sum of fixed carbon and the carbon remaining after decay.

The HWP C model calculates and reports HWP C stock reductions (i.e., emissions) in MT C, and does not estimate the different forms of C emissions (e.g., as methane, carbon monoxide, carbon dioxide, etc.). Estimates for carbon emissions from HWP were multiplied by the atomic weight of carbon dioxide divided by the atomic weight of carbon (i.e., 44/12) to find the carbon dioxide equivalent (CO_2e). All landfill and dump emissions are considered emissions without energy capture. Methane remediation that includes combustion and subsequent emissions with energy capture at landfills is not modelled. These methods are used to calculate annual HWP C in the PIU and SWDS pools and emissions for all inventory years from 1906 through 2017.

Uncertainty Analysis

A Monte Carlo (MC) simulation analysis was conducted to estimate the uncertainty associated with estimates generated with the HWP C model following methods described by Skog (2008) and used by Anderson et al. (2013) and Stockmann et al. (2012). The goal of the MC simulation was to produce 90% confidence intervals for the cumulative amount of carbon classified in four categories: SWDS, PIU, emissions without energy capture (EWOEC), and emissions with energy capture (EEC) from fuelwood. To achieve this goal, the MC simulation directly altered 16 different variables within the model according to their associated parameters (Appendix 3, table 3a). These 16 variables were allowed to vary by amounts that were based on estimates from Skog (2008) and professional judgement. Random values were drawn from triangular distributions that have a peak value of 1.0 (Appendix 3, table 3a) and symmetrically taper to given 90% confidence interval bounds. The random values from the triangular distribution were used as proportions for adjusting parameter values for each iteration of the simulation. A full description of the methods for the MC simulation is provided in Appendix 3. Software to operate the HWP C model and MC simulation was written in the R (2020) programming environment.

Results

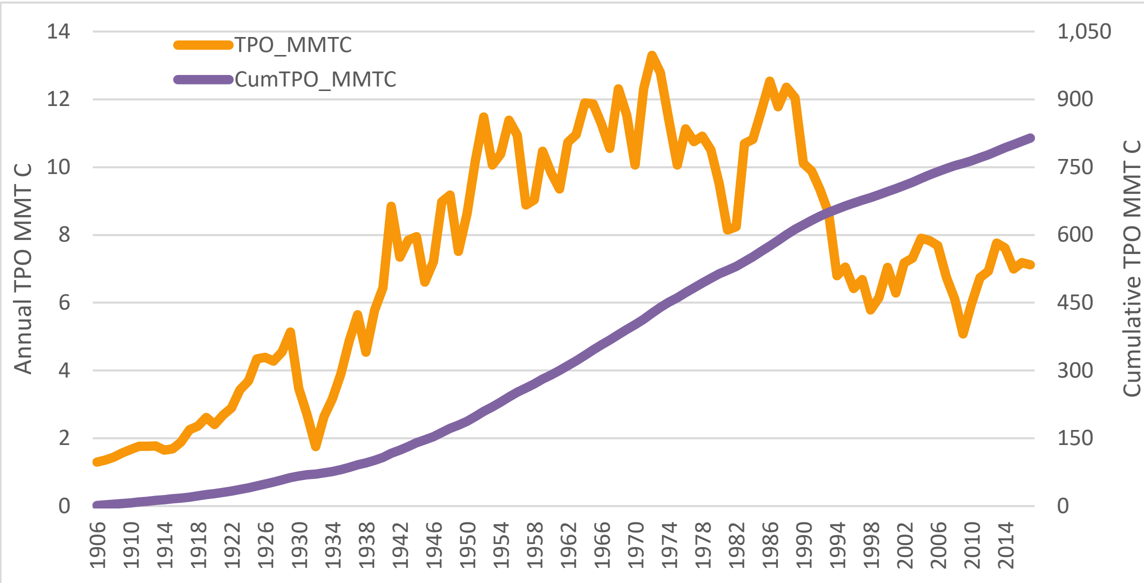
Estimates of HWP C stocks and flux for Oregon's timber harvests from 1906 to 2017 are reported below, followed by results of the uncertainty analysis. Next, HWP C estimates at the ownership level are reported for the 1962 to 2017 harvest period. Finally, HWP C stock and flux estimates are evaluated with results from the Oregon Forest Ecosystems Carbon Report (Christiansen et al. 2019).

State-wide HWP Carbon Stocks and Flux, 1907–2018

Changes in Oregon's timber harvest levels by county and ownership have been well documented (Andrews and Kutara 2005, ODF 2019). Recent trends in harvest ownership, species, and product mix have been discussed in the context of wood products markets, and the broader economy, as well as changing forest policy and industry infrastructure (Brandt et al. 2006, Gale et al. 2012, Simmons et al. 2016). The analysis that follows focuses on the consequences of Oregon's dynamic timber harvest levels and national wood use and disposal on the stock and flux of HWP C since 1906. Timber product output (TPO) refers to the quantity of carbon in harvested timber as estimated by the model.

In 1906, annual TPO was approximately 1.3 MMT C and grew to 5.1 MMT C by 1929 (Figure 2). Timber harvest steadily increased, after dropping to 1.8 MMT C of TPO in 1932, with greater demand for wood products during World War II and the housing boom that followed (Andrews and Kutara 2005, Brandt et al. 2006).

Figure 2. Annual and cumulative timber product output (TPO) in MMT C from Oregon's forests, 1906-2017.



Annual TPO reached a peak in 1972 at 13.3 MMT C and decreased to 8.2 MMT C by 1981 from three recessions between 1973 and 1982. Annual TPO recovered to 12.5 MMT C in 1986 before its descent during the 1990s when the USFS timber harvest dropped steeply with implementation of the Northwest Forest Plan (Spies et al. 2019). Recent notable changes occurred around the Great Recession in 2009, when annual TPO and harvest declined by one-third, to less than 5.1 MMT C, before rebounding to pre-recession levels of 7.6 MMT C in 2014 (Table 3). In 2017, the last year of timber harvest data at the time of analysis, annual TPO was 7.1 MMT C, and cumulative TPO was 814.4 MMT C (Table 3).

The carbon in TPO is added to the pool of HWP carbon as PIU, which consists of all 224 end-use products. The carbon in the PIU pool matriculates into the SWDS pool and is emitted to the atmosphere as wood decays, is burned as fuelwood for energy capture, or burned without energy capture. For instance, the 1962 total harvest volume of approximately 8.5 bbf Scribner represented TPO of 10.7 MMT C, with about 7.2 MMT C added to the PIU pool and about 11.4 MMT CO2e emitted from burning fuelwood and wood disposal.

Table 3. Oregon timber harvest, timber product output (TPO) and cumulative TPO, 2000-2017.

Harvest year	Timber harvest	Timber product output	Cumulative TPO
	bbf Scribner	*MMT C*	*MMT C*
2000	3.9	7.0	696.0
2001	3.4	6.3	702.3
2002	3.9	7.2	709.4
2003	4.0	7.3	716.8
2004	4.5	7.9	724.7
2005	4.4	7.8	732.5
2006	4.3	7.7	740.2
2007	3.8	6.7	746.9
2008	3.4	6.1	753.1
2009	2.7	5.1	758.1
2010	3.2	6.0	764.1
2011	3.6	6.7	770.8
2012	3.7	6.9	777.8
2013	4.2	7.8	785.5
2014	4.1	7.6	793.1
2015	3.8	7.0	800.1
2016	3.9	7.2	807.3
2017	3.9	7.1	814.4

See Appendix 1, table 1B, for all annual harvest and TPO data years.

Carbon in PIU is held in end-use or recovered products, and carbon in SWDS is held in landfills or in dumps. Over time, stored carbon is emitted with energy capture (e.g., using fuelwood for energy) or without energy capture (i.e., emitted from landfills, dumps, recovered products, burning and compost). Emissions from the burning of discarded products with energy capture are treated as zero in this report because reliable data were not available to parameterize that portion of the HWP model (Appendix 2, embedded .pdf file C). Approximately 1,700.5 MMT CO_2e (463.8 MMT C) was emitted through combustion and decomposition of wood products since 1906 (Table 4). Thus, total biogenic emissions from HWP account for 56.9% of cumulative TPO. The size of the HWP stock since 1906 increased to approximately 350.7 MMT C, about 43.1% of cumulative TPO since 1906. Products-in-use account for 57.3% (201.1 MMT C) of the total HWP C stock, while products in SWDS account for 42.7% (149.6 MMT C) of the total HWP C stock.

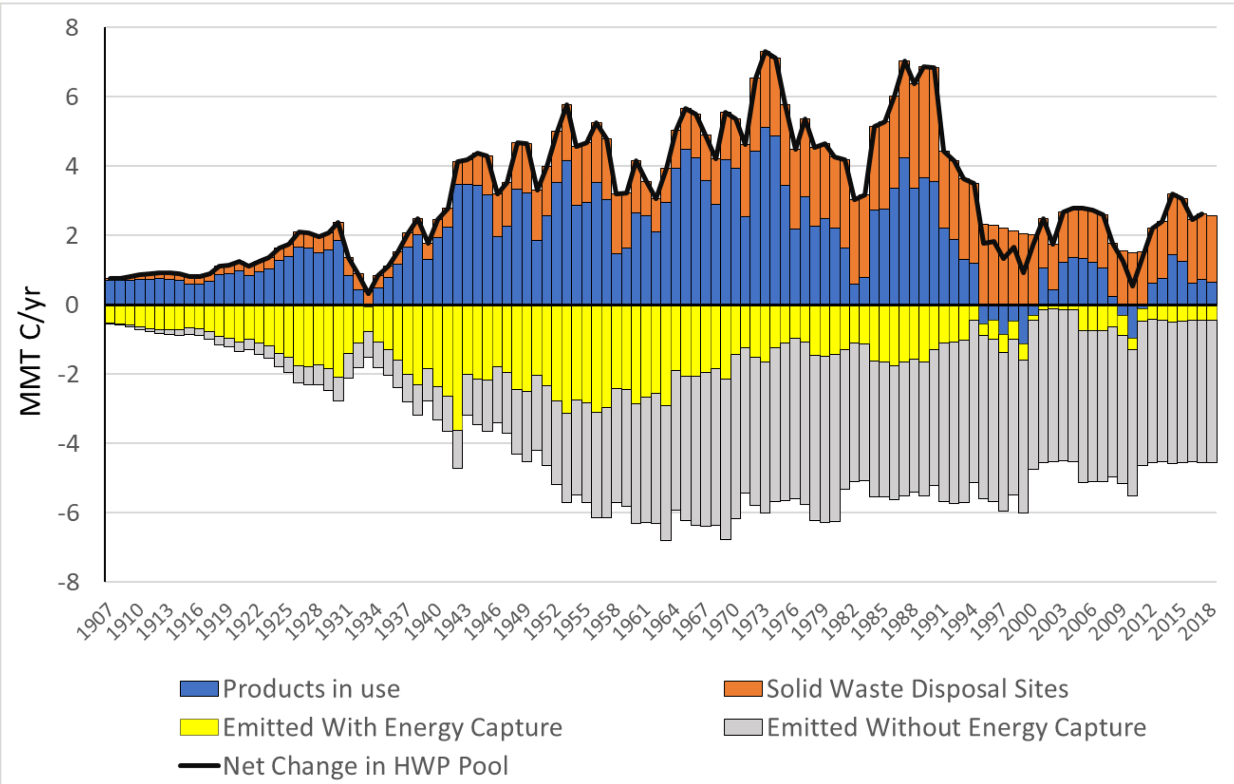
Table 4. Cumulative TPO, HWP C stocks, and emissions from Oregon timber harvests, 1906-2017.

Cumulative TPO	*MMT C*	
1906-2017	814.4	
Cumulative storage as of 2018		
Products-in-use	201.1	
End-use products	194.9	
Recovered products	6.2	
Products in SWDS	149.6	
Landfills	138.2	
Dumps	11.4	
Total HWP stock	350.7	
Cumulative emissions as of 2018	*MMT C*	*MMT CO_2e*
Emissions with energy capture	155.6	570.4
Emissions without energy capture	308.2	1130.2
Landfills	30.6	112.3
Dumps	130.0	476.5
Recovered products	46.4	170.0
Burning	92.6	339.7
Compost	8.6	31.7
Total emissions	463.8	1700.5

The model output reveals a serrated pattern of annual change to the PIU pool (Figure 3) that generally reflects the history of timber harvest and TPO (Figure 2). For most years between 1906 and 1992, changes to the PIU pool were positive – more C entered the pool through TPO and HWP manufacturing than was transferred to SWDS or emissions (Appendix Table 1G). The time series for this pool can be divided into three basic time periods. Up until 1940 the annual change to the PIU pool averaged about 1 MMT C/year but then climbed to about 3 MMT C/year up until 1992, after which it declined to 0.4 MMT C/year until the end of the time series. The annual change in the PIU pool dropped to below zero during the Great Depression in 1933, near the end of the Federal timber harvest declines in 1995-2000, and in response to the Great Recession and housing bust in 2009-2011. During periods of negative annual change, more carbon transitioned into SWDS than was added to the pool of PIU from harvests, usually because of one or more years of steeply declining timber harvest.

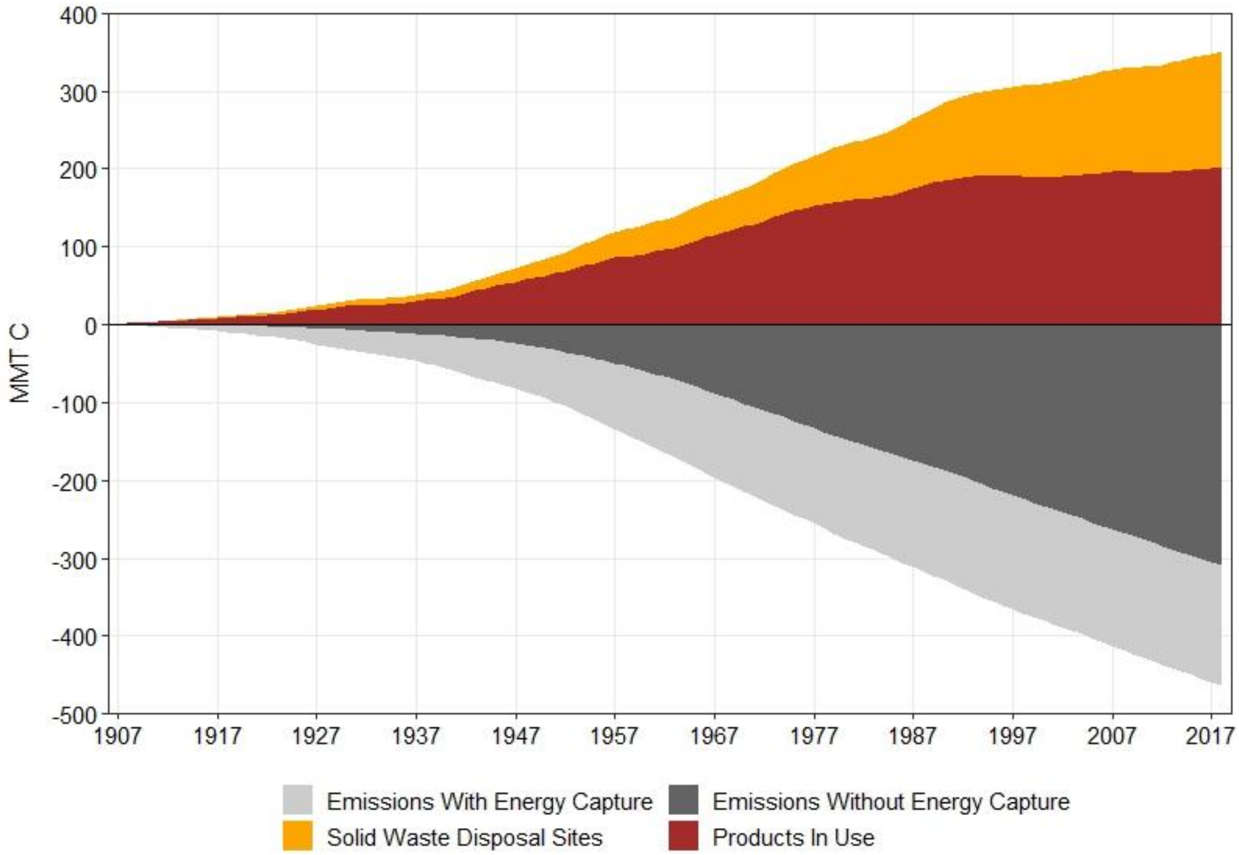
The pool of C in SWDS has continued to grow as HWP from earlier harvest years matriculates out of PIU and into SWDS (Figure 3 and 4). This movement of HWP C into SWDS, particularly landfills, has contributed to the overall positive net change in HWP C. The annual change in the SWDS pool (Figure 3) was positive across the time series and increased in a linear fashion up until its peak in 1990 at approximately 3.3 MMT C/year. With the decline in timber harvest from federally owned forests in the 1990s, the annual change in the SWDS pool dropped to approximately 1.3 MMT C/year by 2002, after which it climbed to about 1.9 MMT C/year by the end of the time series. Consequently, the size of PIU C pool increased at a smaller rate after 1992 (Figure 4). For instance, the size of the PIU pool increased by approximately 10 MMT C in the 25 years from 1993 to 2018, whereas in the 12 years from 1980 to 1992 it increased by approximately 30.7 MMT C.

Figure 3. Net annual change in the combined HWP pool of products-in-use (PIU) and solid waste disposal sites (SWDS) from timber harvested in Oregon from 1906 through 2017. Annual emissions with and without energy capture (in MMT C/yr) are represented as negative values. The magnitude of change in the HWP pools combined with emissions for a given year is equivalent to the amount of TPO C from the prior year (Figure 2).



The amount of annual biogenic emissions from burning fuelwood with energy capture (EEC) peaked in 1942 at 3.6 MMT C/year (13.2 MMT CO_2e/year) but then declined in a linear fashion after 1963 to the end of the time series (emissions are represented as negative values in Figure 3 and 4). Annual biogenic emissions from the decay and burning of discarded HWP without energy capture (EWOEC) peaked in 1980 at 4.8 MMT C/year (17.7 MMT CO_2e/year) and have averaged about 4.3 MMT C/year (15.8 MMT CO_2e/year) since then. From 1906 to 1975, EEC was greater than EWOEC but since 1975 EWOEC exceeded EEC (Figure 3). These facts are likely due to several related factors: 1) the SWDS pool continues to grow as a function of cumulative TPO and PIU reaching the end of their useful lives (Figure 4); 2) emissions from the SWDS pool are all EWOEC because the model lacks data on EEC from SWDS; 3) industrial and residential fuelwood use and the burning of wood waste, as reflected by Oregon's timber product ratios, primary product ratios and annual EEC, have generally declined; and 4) markets for mill residue (e.g., sawdust and chips) in Oregon, as reflected in the primary product ratios, are mainly for pulp and particleboard, rather than biomass energy.

Figure 4. Cumulative stocks of HWP C from timber harvested in Oregon 1906-2017 for products-in-use (PIU) and solid waste disposal sites (SWDS). Cumulative emissions with energy capture (EEC) and emissions without energy capture (EWOEC) are represented as negative values.

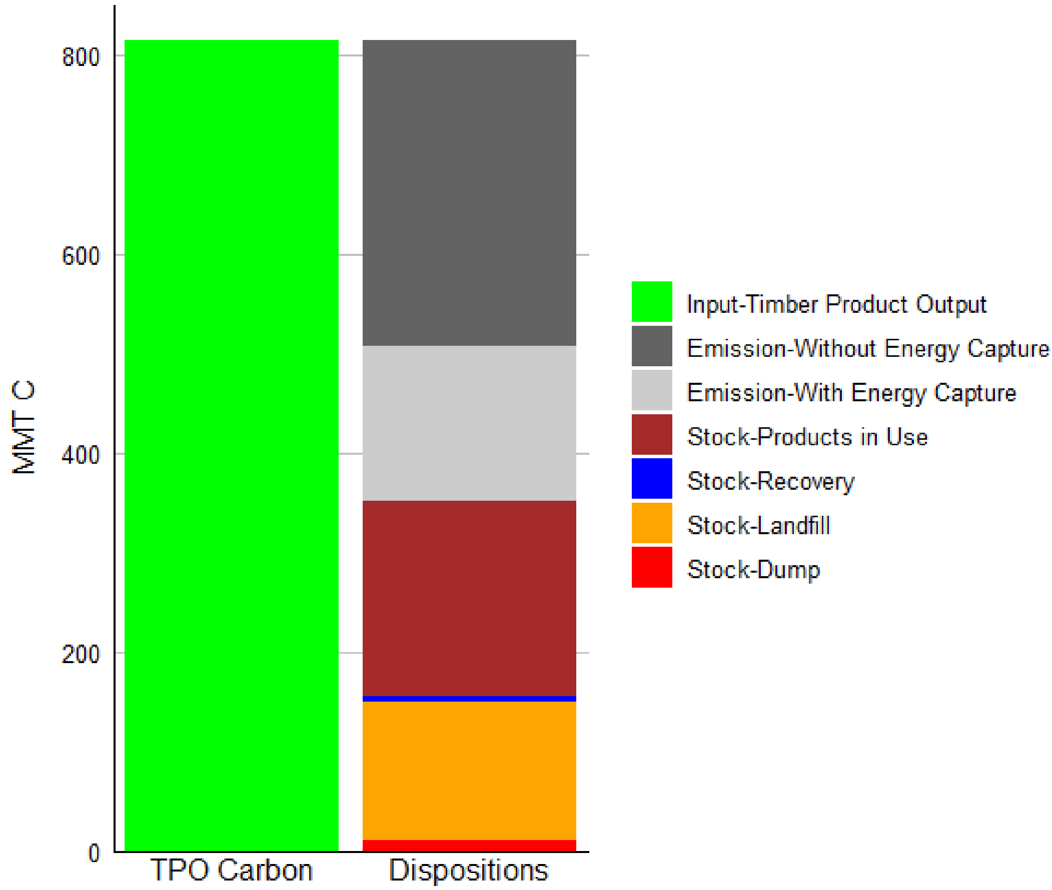


The annual change in the combined pool of HWP C (PIU + SWDS) was greater than zero for each year of the time series because transfers to the SWDS pool were large enough to offset times when the annual change in the PIU pool dropped below zero (i.e., in 1933, each year from 1995 through 2000, and again from 2009 through 2011 (Figure 3).

Based on the methods from Harmon (1996) and the BF/CF conversion factors in Table 1, the cumulative amount of carbon in bark associated with logs harvested from 1906 to 2017 was approximately 98.78 MMT C (362.24 MMT CO_2e). To better understand how much bark was generated at Oregon facilities in a contemporary year we can compare the estimates for bark from Brandt et al. (2006) with the bark estimate using Harmon's (1996) method. According to the former, Oregon's facilities generated about 1.5 MMT (1.422 million bone dry units (BDU)) of bark during 2003 while processing timber, 80 percent of which was used as fuel, with nearly all the remaining 20 percent used for decorative bark or soil additives (Brandt et al. 2006). This amount of bark constitutes a possible lower limit of approximately 2.84 MMT CO_2e/year in biogenic emissions, whereas the estimate for 2003 using Harmon's (1996) method was slightly higher at 3.24 MMT CO_2e/year, constituting a possible upper limit. Emissions from bark utilization for energy production are provided in the Oregon Sawmill Energy Consumption report (Donahue et al. 2021). Finally, the HWP C model does not treat bark as a wood product and carbon in bark is accounted for and integrated within the "cut" estimates in the Oregon Forest Ecosystem Carbon Inventory (Christensen et al. 2019). Therefore, the above annual approximations for bark associated with harvested wood products would be included in the "cut" estimates of the Forest Ecosystem Carbon Inventory. To avoid double counting biogenic emissions from the combustion and decomposition of bark, these bark quantities should not be added to HWP C unless they are subtracted from the Forest Ecosystem Carbon Inventory.

The computational methods associated with the IPCC production accounting approach requires carbon to be followed through the duration of a product's life from harvest through disposal, applying appropriate ratios and half-lives at each stage (Stockmann et al. 2012). Hence, the HWP C model accounts for all of the carbon that enters the system as TPO each year and follows that carbon through its duration as new and recovered PIU, then into the landfills at the end of product usefulness, and finally as emissions with and without energy recovery. Indeed, the cumulative amount of all carbon that entered the HWP C model as TPO through 2017 (814.4 MMT C) was accounted for in each of the disposition categories through 2018 (Figure 5; Appendix 1, table 1H).

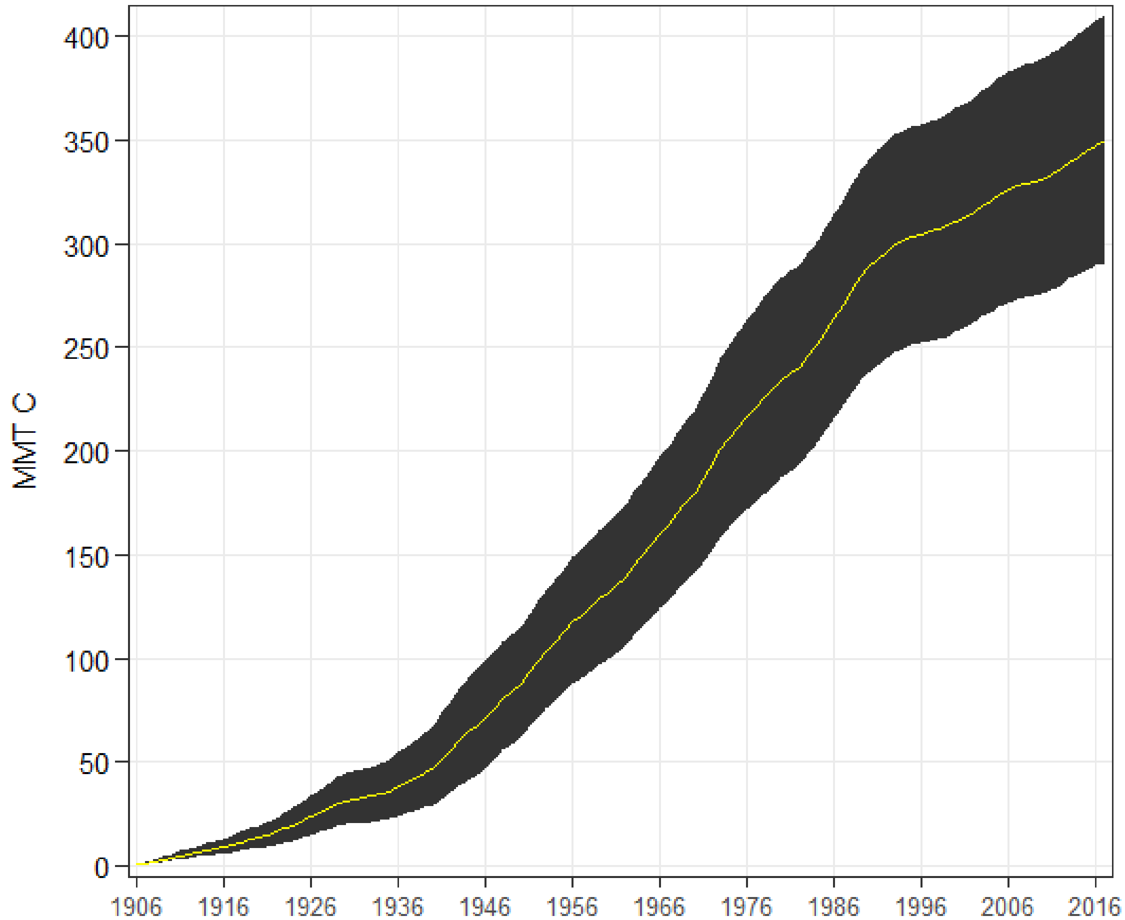
Figure 5. Carbon Mass Balance showing that the cumulative amount of carbon entering the HWP pool, as Timber Product Output (TPO) for 1906-2017, is equal to the sum of the cumulative amounts of carbon in each disposition category through 2018.



Monte Carlo (MC) Simulation Results

After 2,000 iterations, the MC simulation stabilized on values for the mean and the 90% confidence intervals for the cumulative amount of carbon in the combined HWP pools of PIU and SWDS (Figure 6). For 2018, the MC estimate for the mean of these two pools combined was 349.7 MMT C with a lower bound of 291.0 and an upper bound of 410.0 MMT C. The width of the confidence intervals through the time series reflected the effect of altering parameter values for amounts of carbon entering the model and being emitted or distributed to different pools. The precision of parameter estimates for harvest and the ratios for timber and primary products was modelled as improving over time (Appendix 3, table 3a). Between 1906 and 1920, the difference between the lower bound relative to the simulated mean averaged about 37% and the upper bound about 42%. From 2010 to 2017, both the lower and upper bounds averaged about 17% relative to the mean. The difference between the MC simulation means and the HWP C model values for the combined pool of PIU and SWDS were less than 1% for most of the time series, except for the years prior to 1944, when it was slightly larger.

Figure 6. Monte Carlo simulated mean and 90% confidence interval for the cumulative amount of HWP C in PIU and SWDS pools combined.



Confidence intervals were generated separately for the cumulative amount of carbon in the PIU, SWDS, EEC, and EWOEC pools (Figure 7). The small differences (< 2 MMT C) between the MC simulated means for these pools in 2018 and the respective estimates from the HWP C model (Table 5) indicate that the simulation operated as expected given the parameters in Appendix 3, table 3A. The 2018 MC confidence intervals for EEC, relative to the mean, were the widest of these four disposition categories at about 24% and 26% for the lower and upper limits, respectively. Conversely, the width of the 2018 confidence intervals for PIU were the narrowest at about 18% and 19% of the mean for the lower and upper limits, respectively.

Figure 7. Monte Carlo simulation mean and 90% confidence intervals for the size of the pools of carbon in PIU and SWDS and the cumulative emissions with and without energy capture from timber harvested in Oregon from 1906 to 2017.

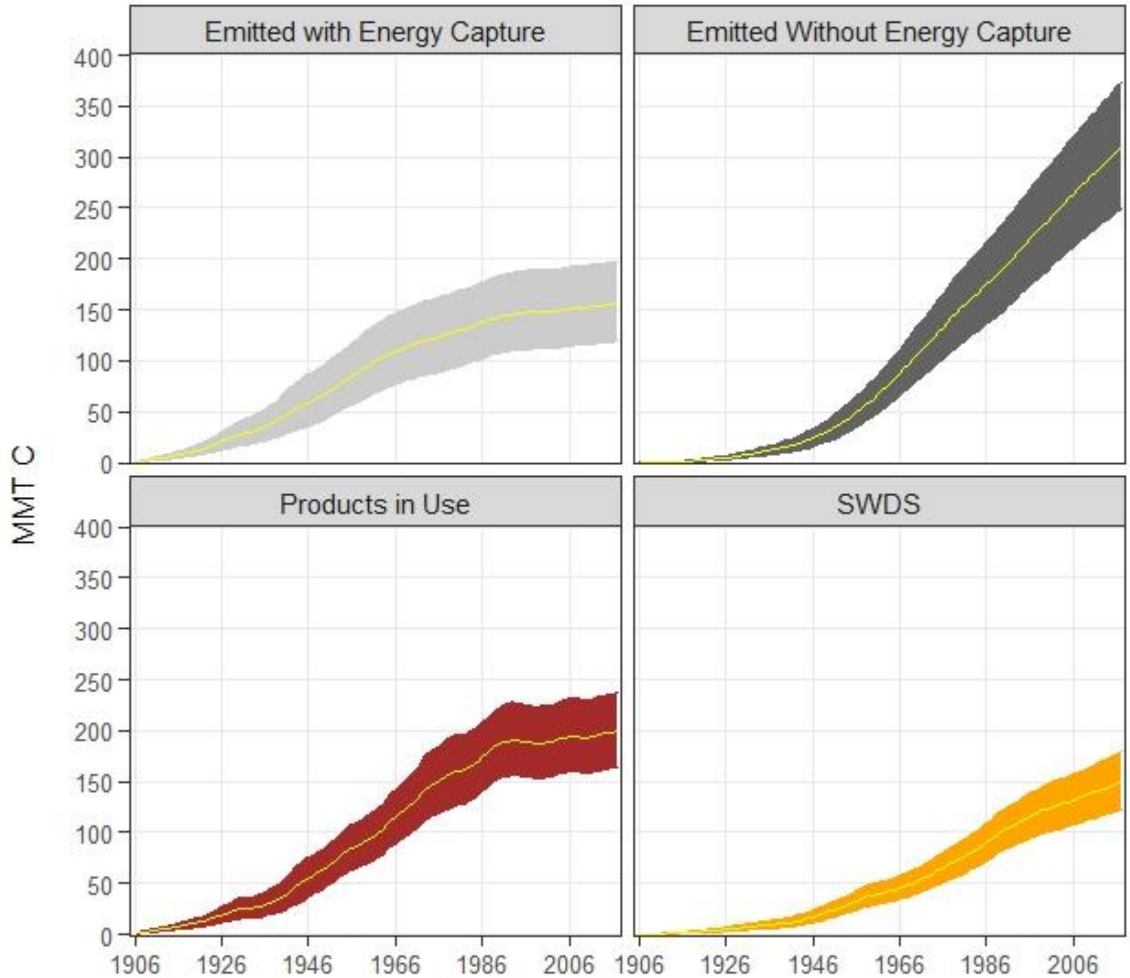


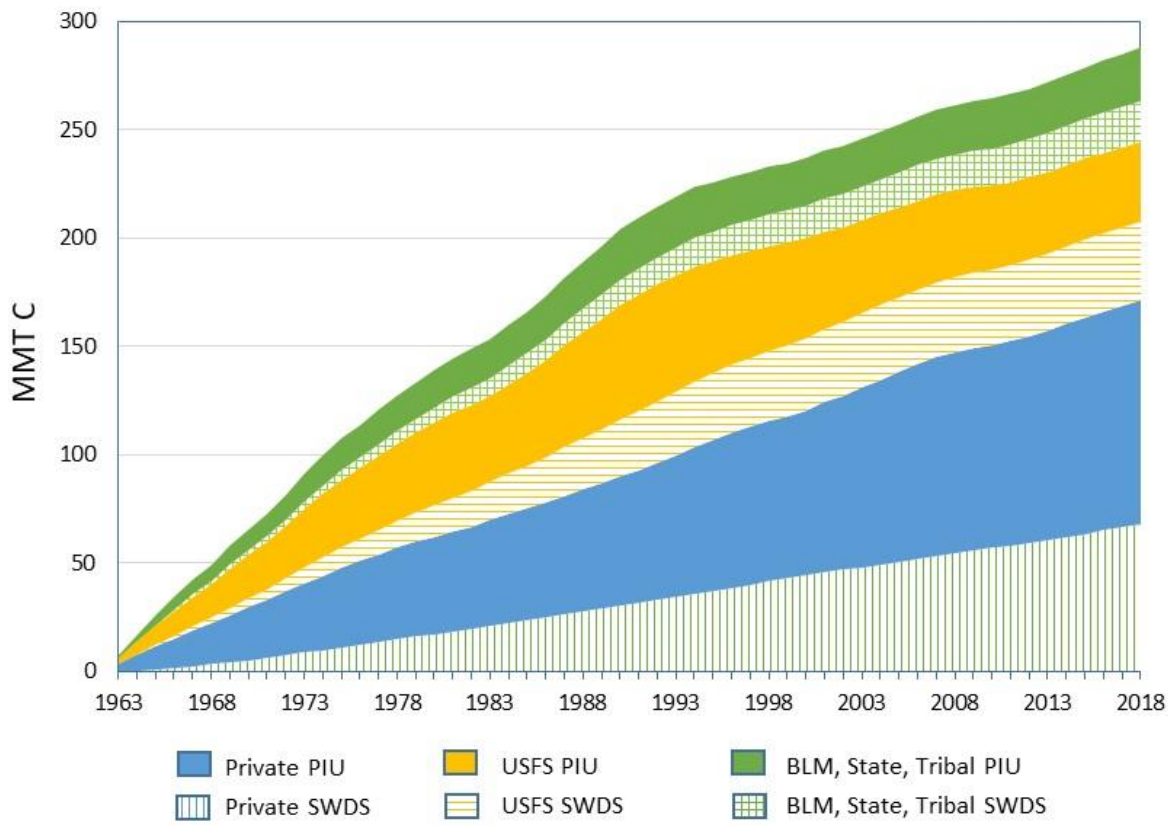
Table 5. Estimates of HWP C (in MMT) for PIU, SWDS, EEC, and EWOEC for the 2018 HWP C model output compared with means and 90% confidence intervals from the MC simulation.

Disposition Categories	HWP C Model Output	MC Simulation Mean and 90% Confidence Interval
Products in Use (PIU)	201.1	163.3 < 199.3 < 236.8
Solid Waste Disposal Sites (SWDS)	149.6	122.5 < 150.4 < 179.3
Emissions With Energy Capture (EEC)	155.6	118.7 < 156.0 < 197.3
Emissions Without Energy Capture (EWOEC)	308.2	249.9 < 309.4 < 373.2

Stocks and Flux of HWP Carbon by Ownership, 1962-2017

Consistent timber harvest data by ownership class are available for Oregon since1962, which provides the opportunity to understand how much each ownership has contributed to the pool of HWP C (Figure 8). From 1962 to 2017, the cumulative TPO for all ownership classes was 514.5 MMT C, from approximately 346.9 bbf Scribner of harvested timber. The volumes and relative proportions by ownership class vary from year to year and are documented in historic and recent reports (Andrews and Kutara 2005, Simmons et al. 2019). For example, in 2016, industrial timberlands accounted for 63.3% of harvest, followed by NIP timber (13.1%), USFS (9.0%), State (7.3%), BLM (4.7%), Tribal (1.5%) and other public (1.1%). However, the average for each ownership across the time series shows that timber from industrial ownerships accounted for 47.2%, USFS 29.5%, BLM 10.2%, NIP 7.7%, State and other public 4.1%, and Tribal 1.3%.

Figure 8. Accumulation of HWP C stock as products-in-use (PIU) and at solid waste disposal sites (SWDS) by ownership from timber harvested in Oregon, 1962-2017.

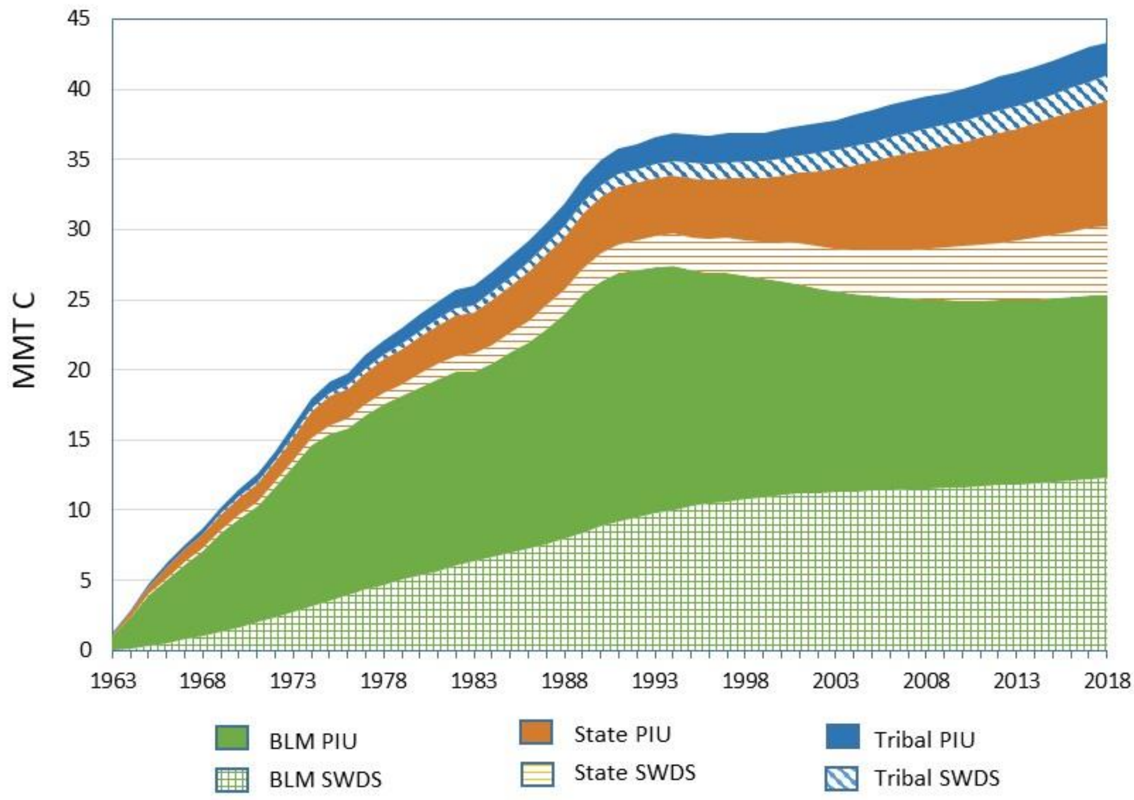


Note: The ownership group "Private" includes industrial and non-industrial private forest owners, and "BLM, State, Tribal" includes BLM, State and other public, and Tribal forest owners (see Appendix 1, Table 1J).

Net additions to the HWP stock have generally diminished with declines in total timber harvest in Oregon from the peaks of the 1970s and '80s. This is especially the case for the USFS ownership that significantly curtailed timber harvest in the 90's and the consequent decline in the accumulation in HWP C. Indeed, the annual net increase in HWP C from USFS forests up to 1990 averaged about 2.8 MMT C/year whereas the annual average dropped to -0.2 MMT C/year after 1990 (Appendix 1, table 1J). Nevertheless, the all-owner total HWP C pool continued to increase, albeit at a lower rate, with timber harvest from other ownerships. Since 1962, PIU account for about 57% (164.4 MMT C) and SWDS account for about 43% (123.6 MMT C) of the total HWP C pool. About 288.0 MMT C (56%) of the TPO since 1962 remains in the HWP pools, while 44% (226.5 MMT C or 830.6 MMT CO_2e) was emitted through burning or decay.

Net change in HWP C originating from BLM forests increased at an annual average of 0.9 MMT C/year from 1963 to 1990 but the annual average was slightly negative (-0.04 MMT C)/year) after 1990 (Figure 9). Net change in HWP C from State and other public forests averaged 0.2 MMT C/year through 1990 and increased to 0.3 MMT C/year after 1990. Net change of HWP C from Tribal forests increased steadily at an annual average of about 0.1 MMT C/year from 1963 to 2018 (Appendix 1, table 1J). However, the annual change was slightly negative for 2018.

Figure 9. Accumulation of HWP C stock as products-in-use (PIU) and at solid waste disposal sites (SWDS) for the BLM, State and other, and Tribal owners from timber harvested in Oregon, 1962-2017.



Evaluating estimates of HWP C relative to Oregon's forest ecosystem carbon

Measurements from field plots monitored by the FIA Program indicate that for the 2016 reporting period Oregon's forests contained approximately 3,239.7 ± 32.8 MMT C in living and dead trees, understory vegetation, downed wood, roots, forest floor and forest soils across all ownerships (Christensen et al. 2019; table 4.13a). About 1,118.3 MMT C were in the aboveground parts of live and dead trees. For the 2017 HWP inventory year (which includes carbon from timber harvests from 1906 through 2016), the model estimated the amount of carbon accumulated in the HWP pool was 348.1 MMT C (Table 6), which is equivalent to approximately 10.7% of the total C in Oregon's forests and about 31.1% of the aboveground portion of live and dead trees (1,118.3 MMT C). Finally, the total combined amount of carbon in Oregon's forests and HWP in 2016 was approximately 3,587.8 MMT C.

Table 6. Annual accumulation of HWP C stock, since 2001, in solid waste disposal sites (SWDS) and products-in-use (PIU) for Oregon timber harvested from 1906-2017.

Inventory Year	PIU	SWDS	Total HWP C
	MMT C		
2001	189.5	122.3	311.8
2002	190.0	123.6	313.6
2003	191.2	125.1	316.3
2004	192.6	126.5	319.1
2005	193.9	127.9	321.8
2006	195.1	129.4	324.6
2007	196.2	131.0	327.2
2008	196.4	132.5	328.9
2009	196.1	134.1	330.2
2010	195.1	135.6	330.7
2011	195.0	137.1	332.1
2012	195.7	138.7	334.3
2013	196.4	140.3	336.7
2014	197.9	142.1	339.9
2015	199.1	143.9	343.0
2016	199.7	145.7	345.5
2017	200.5	147.6	348.1
2018	201.1	149.6	350.7

The net vegetation flux of carbon in Oregon's forested ecosystems was approximately 30.5 MMT CO_2e/year (8.3 MMT C/year), after accounting for the transfer of 25.3 MMT CO_2e/year (6.9 MMT C/year) to dead wood pools from tree mortality, and 34.8 MMT CO_2e/year (9.5 MMT C/year) from trees being cut (Christensen et al. 2019, tables 4.6 and 4.7a). Comparing the FIA estimates for the amount of carbon cut from forests with estimates for the average TPO is challenging due to live trees being cut between field plot measurements, with growth equations being used to estimate tree diameter and height at the midpoint of the measurement interval in order to calculate C at the time of cutting. Moreover, harvesting of timber represented in the FIA cut estimates could have occurred in any year from 2001 to 2016. The estimate for average annual TPO output for 2001 to 2016 was approximately 7.0 MMT C/year (25.5. MMT CO_2e), approximately 73% of the average cut volume reported in the FIA Oregon Forest Ecosystem Carbon Report (Christensen et al. 2019).

After accounting for the average HWP emissions with energy capture from burning fuelwood (EEC = 1.6 MMT CO_2e/year) and average emissions without energy capture (EWOEC = 15.6 MMT CO_2e/year) for the 2001-2016 time period, the balance of carbon in the pool of HWP was approximately 8.4 MMT CO_2/year. Therefore, the combined average net change for the pool of carbon in Oregon's forests and HWP for this time period (including PIU and SWDS) was approximately 38.9 MMT CO_2e/year (10.6 MMT C/year).

Discussion

Oregon has a long history of timber harvest and manufacturing of wood products that continue to retain carbon throughout their use and disposal. Just like the various pools of carbon in forest ecosystems, the pools of HWP C have dynamic rates of input and output. The analysis described in this report used the IPCC production approach to generate estimates for the stocks and flux of carbon in HWP for timber harvested within the State of Oregon from 1906 to 2017. It also provides estimates for the cumulative emissions of CO_2e from burning fuelwood for energy capture and from the decay and burning of discarded wood products. Reliable estimates for timber harvest among the different ownerships in Oregon are not available prior to 1962, therefore, this report provides estimates of carbon in HWP for the major forest ownerships that contributed to HWP C pools from 1962-2017 harvests. The results of the HWP study were combined with those from the Oregon Forest Ecosystem Carbon Report (Christiansen et al. 2019) to calculate the total stocks and flux of carbon in both forests and HWP. This report provides the HWP dimension of an overall forest carbon accounting framework for Oregon that can be used for subsequent HWP C analyses and applied to other regions (e.g., California, Washington; Christensen et al. 2018) with timber harvest, timber product, primary product, and end-use product data.

Carbon emissions from fossil fuels used in harvest, transportation, and manufacturing of HWP were not estimated and therefore were not deducted from the HWP pools. Although the HWP C model generates estimates of emissions from burning HWP with energy capture, this study did not make estimates for substitution of fossil fuel carbon, potentially reducing fossil fuel emissions in some scenarios (Jones et al. 2010). Furthermore, the HWP C model does not address carbon or energy associated with substituting HWP for construction materials such as metal or concrete. While emissions trade-offs from product substitution are outside the scope and purpose of this report, there are well-developed methods of life cycle analysis (LCA) that account for all carbon emissions associated with manufactured products and that facilitate the comparison between wood products and alternative products (Rebitzer et al. 2004, Lippke et al. 2011, CORRIM 2018). The production approach used in this analysis provides information that could be used to inform an LCA of wood products generated in Oregon.

The dynamics in TPO for Oregon generally reflected changes in the economy and changes in NFS land management through the 1906 to 2017 period. TPO increased from less than 2 MMT C/year in 1906 to upwards of 13 MMT C/year in 1972, followed by a steep decline upon implementation of the Northwest Forest Plan. Part of the annual additions to the SWDS C pool are proportional to additions to the pool of PIU because the model transfers 8% of the carbon in primary products directly to the discarded pool to account for waste generated during manufacturing and construction of end-products each year. Wood products with a short half-life such as crates, pallets, concrete forms, etc., enter the waste stream relatively quickly after production, which also maintains the waste stream along with the regular demolition of products with longer durations of use. Consequently, the waste stream of wood products was relatively smooth during the time series, although it reflects declines following major decreases in harvest. Many discarded products were disposed of in SWDS rather than burning, which has resulted in significant quantities of HWP C transferred to these long-term storage pools rather than being rapidly released into the atmosphere (Skog 2008). The net change in the HWP pool follow the pattern of annual additions to PIU, slightly lagged, with periods of negative changes following downturns in the economy and the large decline in federal harvest starting in 1987. The negative balance of PIU that occurred between 1995-2016 reflect the federal harvest decline followed by another decline associated with the Great Recession of 2009-2011.

Approximately 25% of the 814 MMT C in the cumulative TPO output since 1906 is currently in PIU, 18% in SWDS, 19% has been emitted back to the atmosphere from burning fuelwood for energy capture, and about 38% has been emitted through decomposition or burning without energy capture. The contribution of carbon to the atmosphere from discarded HWP could be significantly reduced with further advances in wood waste management. Indeed, end-of-life management of wood products is perhaps the single most significant variable for the full life cycle carbon profile of wood products (Sathre and O'Connor 2010).

Estimates of HWP C pools by ownership would be different than reported here if consistent, reliable harvest information by ownership were available prior to 1962. However, HWP C storage estimates by ownership for harvests since 1962 show that 59% of the HWP C pool in 2017 originated from private forestlands, 35% from federal forests, and 6% from State, Tribal and local governments.

Comparing the stocks and flux of carbon in Oregon's forests and HWP with estimates at the national level is problematic because the flux of carbon across U.S. forests is based on stock changes and reported annually, whereas C flux values reported in the Oregon Forest Ecosystem Carbon Report were based on changes in measurements of individual trees and averaged over the six years that plot re-measurements were available (EPA 2018; Christiansen et al., 2019). Nonetheless, Oregon's forests have been accumulating carbon with an annual average total forest carbon flux of 30.5 MMT CO_2e/year (8.3 MMT C/year). This represents about 5.5% of the average national total forest carbon flux for 2016 of 565.5 MMT CO_2e/year (154.2 MMT C/year).

The EPA (2018) estimated that the total stock of HWP C for 2016 (2,591 MMT C) was about 4.7% of the total forest carbon stock for the continental U.S. plus coastal Alaska (55,592 MMT C). The total stock of HWP C for 2016 in Oregon was 345.5 MMT C (Table 6), which is equivalent to approximately 10.7% of the estimate for the total C in Oregon's forests and about

13.3% of the national stock of HWP C. For 2017, the total annual input to HWP C from Oregon was 9.7 MMT CO_2e/year (Appendix 1, table 1G), which represents about 10.1% of the 2017 national HWP flux of 95.7 MMT CO_2e/year. These results demonstrate that Oregon contributes a significant amount to the national pool of HWP C.

Differences between the FIA estimates of cut from Oregon forests and TPO can be attributed to a combination of differences between forests and HWP accounting methodologies, and "additional" items in the FIA removals estimate that are not part of TPO. For example, logging residue generated during timber harvesting, such as needles, branches, tops, and other removals of non-merchantable material during operations such as pre-commercial thinning, are included in FIA's estimate of cut. Of the harvested tree, the stem represents about 67.54%, while residues (tops, branches, and foliage) represent about 32.46% of total biomass (Ganguly et al. 2020). In contrast, the HWP C estimates are calculated exclusively from log (wood fiber) volumes delivered to timber-processing facilities. (i.e., mills). It is also important to note that the HWP and FIA estimates were developed from very different data sets and methodologies that prevent direct comparisons. For example, FIA's estimates of average annual cut from forests are based on re-measurements of a sample of field inventory plots over a 10-year cycle, while the HWP estimates are based on annual timber harvest records. Completion of the full re-measurement cycle for all FIA field plots by 2021 will increase the confidence in the estimates of the stocks and flux of forest carbon, which should also transfer to comparing and combining estimates of HWP carbon. There has not been a comprehensive analysis comparing FIA estimates of removals to timber harvest records in Oregon since FIA began using the current plot measurement system in 2001.

Conclusions

The pool of carbon in harvested wood products (HWP) is significant in size and should be considered in decision making associated with carbon monitoring and climate change adaptation and mitigation (Stockmann et al. 2012). This report provides an empirical accounting of carbon in timber harvested in Oregon since 1906, with annual estimates of HWP C stocks and changes in PIU and SWDS. It also includes estimates of C emissions from HWP with and without energy capture. The information presented here is fundamental to the wood products dimension of Oregon's forest carbon accounting framework. It is consistent with the IPCC Tier-3 production accounting approach that was used for the HWP C section in the California Forest Carbon Inventory (Loeffler et al. 2019, Christensen et al. 2018) and multiple USFS regions and forests (Stockmann et al. 2012, Anderson et al. 2013, Butler et al. 2014, Loeffler et al. 2014). The data, modeling framework and results are fundamental to evaluating how the dynamics of Oregon's past and current timber harvest levels have influenced the annual growth of the pool of HWP C and total forest carbon stock levels. The modeling framework does not include estimates for the emissions associated with timber harvesting, log transportation, HWP manufacturing, substitution effects of wood products, bioenergy, or leakage.

While this analysis was generated at the state level with details for ownership class back to 1962, it provides an analytical framework that can be used for smaller regions in the state as well. Published literature with a relatively long time-series of county-level harvest volume data is available for Oregon (Andrews and Kutara 2005, ODF 2019), including quantitative information needed for allocating harvest estimates to timber and primary product distributions to reflect the changes in wood product manufacturing. Clearly, the pool of carbon in HWP generated from Oregon's past timber harvests has grown to a large, active pool and, as such, is a significant consideration when monitoring or developing (forest) carbon management policy. Total forest carbon integrates the carbon dynamics of forest ecosystems and wood products manufactured from timber, as well as changing forest management policies and wood product markets. Periodically updated HWP end-use estimates would allow better HWP C storage and flux estimates; however, no regional or state-level variations of product end use have been identified in the literature (Loeffler et al. 2019).

The analysis presented above provides the historical perspective of carbon dynamics in the pool of HWP C harvested from Oregon's forests. Given the limitations already stated, the model was not applied to potential future timber harvest levels. There are several different forest modeling systems that can be used to predict the outcomes of alternative forest management regimes for carbon mitigation. The ODF is currently working with partners from the USFS, California, Washington, and British Columbia in evaluating these different forest-modeling systems to compare their capabilities for generating the carbon outcomes of alternative scenarios for managing forests and HWPs across this large geographic region. The Carbon Budget Model (CBM) of the Canadian Forest Sector is currently being tested for forests in Oregon and California in collaboration with American Forests, ODF, and CalFire, with results expected in 2022. The CBM model will be used to quantify and understand the carbon outcomes of alternative strategies for managing forests and wood products that integrate new technologies and policies for recycling and waste disposal.

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Appendix 1

Table 1A. Oregon timber harvest by ownership in billion board feet (bbf) Scribner and cumulative TPO in MMT C, 1962-2017.

Harvest year	Private		USFS		BLM		State and other		Tribal	
	bbf	MMT C	bbf	MMT C	bbf	MMT C	bbf	MMT C	bbf	MMT C
1962	4.1	5.2	3.1	3.9	1.1	1.4	0.2	0.2	0.1	0.1
1963	3.8	9.9	3.2	8.0	1.4	3.1	0.2	0.5	0.1	0.2
1964	4.0	15.0	3.4	12.3	1.6	5.2	0.2	0.8	0.1	0.3
1965	4.0	20.1	3.8	17.1	1.2	6.8	0.3	1.1	0.1	0.4
1966	4.1	25.3	3.3	21.2	1.2	8.3	0.2	1.4	0.1	0.4
1967	3.8	30.2	3.2	25.2	1.1	9.7	0.1	1.6	0.1	0.6
1968	4.4	35.7	3.6	29.8	1.5	11.6	0.2	1.8	0.1	0.7
1969	4.2	40.9	3.5	34.2	1.2	13.1	0.2	2.1	0.1	0.8
1970	3.9	45.8	2.8	37.8	1.0	14.4	0.2	2.3	0.1	0.9
1971	4.2	51.6	3.2	42.2	1.3	16.2	0.2	2.5	0.1	1.0
1972	3.9	56.9	3.9	47.5	1.5	18.3	0.3	2.9	0.1	1.2
1973	3.6	61.9	3.8	52.8	1.5	20.4	0.3	3.3	0.1	1.3
1974	3.8	67.1	3.2	57.1	1.0	21.8	0.2	3.7	0.1	1.4
1975	3.8	72.2	2.7	60.7	0.6	22.6	0.2	3.9	0.1	1.6
1976	3.6	77.1	3.2	65.1	1.1	24.1	0.2	4.2	0.1	1.7
1977	3.6	82.0	2.9	69.0	1.0	25.5	0.2	4.5	0.1	1.9
1978	3.5	86.9	3.2	73.4	0.8	26.6	0.3	4.9	0.1	2.1
1979	3.2	91.2	3.2	77.8	1.0	27.9	0.3	5.2	0.1	2.2
1980	3.1	95.7	2.4	81.2	0.8	29.1	0.2	5.5	0.1	2.4
1981	2.7	99.6	2.0	84.0	0.7	30.0	0.2	5.9	0.1	2.5
1982	3.4	104.5	1.7	86.4	0.3	30.5	0.2	6.1	0.1	2.7
1983	3.4	109.3	2.9	90.6	0.8	31.6	0.3	6.6	0.1	2.8
1984	3.1	113.8	3.2	95.1	0.9	32.9	0.3	7.0	0.1	3.0
1985	3.3	118.5	3.5	100.1	0.9	34.2	0.3	7.4	0.1	3.2
1986	3.5	123.5	3.9	105.6	1.0	35.7	0.3	7.8	0.1	3.3
1987	3.3	128.2	3.5	110.6	1.1	37.3	0.3	8.1	0.1	3.5
1988	3.3	132.9	3.5	115.6	1.4	39.4	0.3	8.6	0.1	3.7

Table 1A. Oregon timber harvest by ownership in billion board feet (bbf) Scribner and cumulative TPO in MMT C, 1962-2017.

Harvest year	Private		USFS		BLM		State and other		Tribal	
	bbf	MMT C	bbf	MMT C	bbf	MMT C	bbf	MMT C	bbf	MMT C
1989	3.7	138.2	3.3	120.3	1.0	40.8	0.2	8.9	0.1	3.8
1990	3.2	143.5	2.0	123.6	0.7	42.0	0.2	9.2	0.1	4.0
1991	3.3	148.9	2.1	127.0	0.5	42.8	0.1	9.4	0.1	4.1
1992	3.6	154.7	1.4	129.2	0.5	43.6	0.2	9.7	0.1	4.3
1993	3.6	160.6	1.1	131.0	0.4	44.2	0.1	9.9	0.1	4.4
1994	3.2	165.9	0.6	132.0	0.1	44.3	0.2	10.2	0.1	4.6
1995	3.4	171.5	0.5	132.9	0.1	44.5	0.1	10.4	0.1	4.7
1996	3.0	176.4	0.4	133.5	0.3	45.0	0.1	10.6	0.1	4.8
1997	3.1	181.6	0.5	134.4	0.1	45.2	0.2	11.0	0.1	4.9
1998	2.8	186.2	0.3	134.9	0.1	45.4	0.2	11.2	0.1	5.1
1999	3.0	191.1	0.2	135.3	0.1	45.7	0.3	11.7	0.1	5.2
2000	3.2	196.9	0.2	135.7	0.1	45.8	0.3	12.3	0.1	5.3
2001	2.9	202.2	0.1	136.0	0.0	45.9	0.3	12.8	0.1	5.4
2002	3.3	208.3	0.2	136.3	0.1	46.0	0.3	13.4	0.1	5.5
2003	3.3	214.4	0.2	136.7	0.1	46.1	0.3	14.0	0.1	5.6
2004	3.6	220.8	0.3	137.3	0.1	46.3	0.3	14.6	0.1	5.8
2005	3.5	227.0	0.3	137.9	0.1	46.5	0.4	15.3	0.1	5.9
2006	3.6	233.4	0.2	138.2	0.1	46.8	0.3	15.9	0.1	6.0
2007	3.1	238.8	0.2	138.6	0.1	47.0	0.3	16.4	0.1	6.1
2008	2.7	243.7	0.2	139.0	0.1	47.2	0.3	17.0	0.1	6.2
2009	2.1	247.5	0.2	139.4	0.1	47.5	0.3	17.5	0.1	6.3
2010	2.4	252.0	0.3	139.8	0.1	47.7	0.3	18.1	0.1	6.5
2011	2.7	257.1	0.4	140.5	0.2	48.0	0.3	18.7	0.1	6.6
2012	2.9	262.4	0.4	141.2	0.1	48.3	0.3	19.2	0.1	6.7
2013	3.3	268.4	0.4	141.9	0.2	48.6	0.3	19.8	0.1	6.8
2014	3.2	274.3	0.4	142.6	0.2	49.0	0.3	20.3	0.1	6.9
2015	2.8	279.6	0.4	143.3	0.2	49.4	0.3	21.0	0.1	7.0
2016	3.0	285.0	0.4	144.0	0.2	49.7	0.3	21.6	0.1	7.1
2017	3.0	290.6	0.3	144.6	0.2	50.0	0.3	22.2	0.0	7.1

Table 1B. Oregon timber harvest in billion board feet (bbf) with annual and cumulative TPO in MMT C, 1906-2017.

Harvest Year	Harvest (bbf)	Timber Product Output (MMT C)	Cumulative TPO (MMT C)
1906	1.5	1.3	1.3
1907	1.6	1.4	2.7
1908	1.7	1.4	4.1
1909	1.8	1.6	5.7
1910	1.9	1.7	7.3
1911	1.9	1.8	9.1
1912	1.9	1.8	10.9
1913	1.9	1.8	12.6
1914	1.8	1.6	14.3
1915	1.8	1.7	16.0
1916	2.1	1.9	17.9
1917	2.5	2.3	20.1
1918	2.6	2.4	22.5
1919	2.9	2.6	25.1
1920	2.6	2.4	27.5
1921	2.8	2.7	30.2
1922	3.0	2.9	33.1
1923	3.6	3.4	36.5
1924	3.8	3.7	40.2
1925	4.5	4.3	44.6
1926	4.5	4.4	48.9
1927	4.4	4.3	53.2
1928	4.7	4.5	57.8
1929	5.3	5.1	62.9
1930	3.6	3.5	66.4
1931	2.6	2.7	69.1
1932	1.7	1.8	70.8
1933	2.6	2.6	73.5
1934	3.1	3.2	76.7
1935	3.8	3.9	80.6
1936	4.8	4.9	85.4
1937	5.5	5.6	91.1
1938	4.4	4.5	95.6
1939	5.6	5.8	101.4
1940	6.3	6.4	107.8
1941	8.1	8.8	116.7
1942	6.7	7.3	124.0
1943	7.2	7.8	131.9
1944	7.3	7.9	139.8
1945	6.0	6.6	146.4

Table 1B. Oregon timber harvest in billion board feet (bbf) with annual and cumulative TPO in MMT C, 1906-2017.

Harvest Year	Harvest (bbf)	Timber Product Output (MMT C)	Cumulative TPO (MMT C)
1946	6.6	7.2	153.6
1947	8.2	9.0	162.6
1948	8.4	9.2	171.8
1949	6.9	7.5	179.3
1950	7.9	8.6	187.9
1951	8.7	10.2	198.1
1952	9.8	11.5	209.6
1953	8.6	10.1	219.7
1954	8.9	10.4	230.0
1955	9.7	11.4	241.4
1956	9.3	10.9	252.4
1957	7.6	8.9	261.3
1958	7.7	9.0	270.3
1959	8.9	10.5	280.8
1960	8.4	9.8	290.6
1961	7.4	9.4	299.9
1962	8.5	10.7	310.7
1963	8.7	11.0	321.6
1964	9.4	11.9	333.5
1965	9.4	11.9	345.4
1966	8.9	11.3	356.7
1967	8.4	10.6	367.2
1968	9.7	12.3	379.5
1969	9.2	11.5	391.1
1970	8.0	10.1	401.1
1971	9.0	12.3	413.4
1972	9.7	13.3	426.7
1973	9.4	12.8	439.5
1974	8.4	11.4	451.0
1975	7.4	10.1	461.0
1976	8.1	11.1	472.2
1977	7.9	10.8	482.9
1978	8.0	10.9	493.8
1979	7.7	10.5	504.3
1980	6.6	9.5	513.8
1981	5.7	8.2	522.0
1982	5.8	8.2	530.2
1983	7.5	10.7	540.9
1984	7.5	10.8	551.7
1985	8.1	11.6	563.4
1986	8.7	12.5	575.9

Table 1B. Oregon timber harvest in billion board feet (bbf) with annual and cumulative TPO in MMT C, 1906-2017.

Harvest Year	Harvest (bbf)	Timber Product Output (MMT C)	Cumulative TPO (MMT C)
1987	8.2	11.8	587.7
1988	8.6	12.4	600.0
1989	8.4	12.0	612.1
1990	6.2	10.1	622.2
1991	6.1	9.9	632.1
1992	5.7	9.3	641.4
1993	5.3	8.6	650.1
1994	4.2	6.8	656.9
1995	4.3	7.0	663.9
1996	3.9	6.4	670.3
1997	4.1	6.7	677.0
1998	3.5	5.8	682.8
1999	3.8	6.1	688.9
2000	3.9	7.0	696.0
2001	3.4	6.3	702.3
2002	3.9	7.2	709.4
2003	4.0	7.3	716.8
2004	4.5	7.9	724.7
2005	4.4	7.8	732.5
2006	4.3	7.7	740.2
2007	3.8	6.7	746.9
2008	3.4	6.1	753.1
2009	2.7	5.1	758.1
2010	3.2	6.0	764.1
2011	3.6	6.7	770.8
2012	3.7	6.9	777.8
2013	4.2	7.8	785.5
2014	4.1	7.6	793.1
2015	3.8	7.0	800.1
2016	3.9	7.2	807.3
2017	3.9	7.1	814.4

Appendix Table 1C. Hundred cubic feet (ccf) to metric tons (MT) carbon conversion factors (embedded .pdf file).

Table 1C.pdf

Table 1D. Timber products and corresponding primary products (embedded .pdf file).

Table1D_Timber productsToPrimaryPr(

Table 1E. Primary products and corresponding end use products (embedded .pdf file).

Table1E_PrimaryProd ToEndUseProds.pdf

Table 1F. Discarded harvested wood and paper half-lives and landfill fixed ratios (embedded .pdf file).

DiscardedWood&Pa perHalfLives&FixedRa

Table 1G. Annual changes and cumulative stocks in products-in-use and solid waste disposal sites (SWDS) and annual and cumulative emissions with and without energy capture, from Oregon timber harvested 1906-2017.

Inventory year	Products-in use (end-use and recovered)		Products in SWDS (landfills and dumps)		Emissions w/energy capture (fuelwood and discard burning)		Emissions w/o energy capture (landfills, dumps, recovered products, burning and compost)	
	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)
1907	0.72	0.72	0.04	0.04	1.94	1.94	0.05	0.05
1908	1.42	0.70	0.11	0.07	3.97	2.03	0.17	0.12
1909	2.11	0.70	0.21	0.10	6.13	2.16	0.35	0.18
1910	2.84	0.73	0.34	0.13	8.48	2.35	0.61	0.25
1911	3.59	0.74	0.50	0.16	10.97	2.49	0.94	0.33
1912	4.34	0.76	0.67	0.18	13.61	2.64	1.35	0.41
1913	5.07	0.72	0.87	0.19	16.26	2.65	1.83	0.48
1914	5.76	0.69	1.07	0.20	18.91	2.65	2.39	0.56
1915	6.35	0.60	1.28	0.21	21.38	2.47	3.02	0.63
1916	6.95	0.60	1.49	0.21	23.90	2.52	3.71	0.69
1917	7.64	0.69	1.71	0.22	26.73	2.83	4.48	0.77
1918	8.51	0.87	1.95	0.24	30.11	3.38	5.33	0.85
1919	9.39	0.89	2.20	0.25	33.64	3.54	6.27	0.94
1920	10.38	0.99	2.48	0.27	37.56	3.91	7.32	1.04
1921	11.22	0.83	2.76	0.28	41.16	3.60	8.45	1.13
1922	12.18	0.96	3.06	0.30	45.19	4.03	9.68	1.23
1923	13.22	1.04	3.37	0.31	49.53	4.34	11.02	1.34
1924	14.51	1.29	3.71	0.34	54.66	5.13	12.49	1.46
1925	15.88	1.38	4.08	0.37	60.18	5.52	14.09	1.60
1926	17.56	1.68	4.49	0.41	66.67	6.49	15.85	1.76
1927	19.19	1.63	4.94	0.45	73.24	6.57	17.78	1.93
1928	20.68	1.49	5.41	0.47	79.64	6.40	19.87	2.09
1929	22.26	1.59	5.90	0.49	86.45	6.80	22.12	2.25
1930	24.12	1.85	6.42	0.52	94.13	7.69	24.55	2.43
1931	24.97	0.85	6.93	0.51	99.33	5.19	27.10	2.55
1932	25.40	0.43	7.39	0.46	103.37	4.05	29.71	2.62
1933	25.33	-0.07	7.78	0.39	106.00	2.63	32.35	2.64
1934	25.81	0.48	8.13	0.35	109.96	3.96	35.04	2.69
1935	26.59	0.78	8.47	0.34	114.70	4.73	37.79	2.76
1936	27.77	1.18	8.83	0.36	120.55	5.85	40.66	2.86
1937	29.44	1.67	9.23	0.40	127.86	7.31	43.66	3.01
1938	31.45	2.01	9.68	0.46	136.30	8.44	46.85	3.19
1939	32.76	1.31	10.16	0.47	143.10	6.80	50.18	3.33

Table 1G. Annual changes and cumulative stocks in products-in-use and solid waste disposal sites (SWDS) and annual and cumulative emissions with and without energy capture, from Oregon timber harvested 1906-2017.

Inventory year	Products-in use (end-use and recovered)		Products in SWDS (landfills and dumps)		Emissions w/energy capture (fuelwood and discard burning)		Emissions w/o energy capture (landfills, dumps, recovered products, burning and compost)	
	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)
1940	34.71	1.95	10.67	0.51	151.74	8.64	53.69	3.51
1941	36.94	2.23	11.22	0.55	161.37	9.63	57.46	3.77
1942	40.40	3.46	11.88	0.66	174.60	13.23	61.54	4.08
1943	43.87	3.47	12.58	0.70	181.91	7.32	65.84	4.31
1944	47.31	3.44	13.52	0.94	189.74	7.82	70.71	4.87
1945	50.48	3.17	14.66	1.13	197.66	7.92	76.15	5.44
1946	52.45	1.96	15.88	1.23	204.25	6.59	82.09	5.94
1947	54.71	2.27	17.14	1.25	211.44	7.19	88.45	6.36
1948	58.05	3.34	18.46	1.32	220.38	8.95	95.31	6.86
1949	61.28	3.22	19.88	1.43	229.53	9.15	102.76	7.44
1950	63.12	1.85	21.34	1.46	237.02	7.49	110.70	7.94
1951	65.69	2.56	22.78	1.43	245.62	8.60	119.07	8.37
1952	69.20	3.52	24.27	1.49	255.78	10.17	127.93	8.87
1953	73.37	4.16	25.88	1.61	267.23	11.45	137.41	9.48
1954	76.24	2.87	27.58	1.70	277.26	10.03	147.49	10.08
1955	79.20	2.96	29.29	1.71	287.61	10.35	158.08	10.59
1956	82.73	3.52	31.03	1.74	298.96	11.35	169.19	11.11
1957	85.75	3.02	32.79	1.76	309.87	10.90	180.84	11.65
1958	87.22	1.47	34.50	1.71	318.73	8.86	192.89	12.06
1959	88.84	1.62	36.09	1.59	327.73	9.00	205.24	12.34
1960	91.49	2.64	37.61	1.52	338.17	10.44	217.91	12.67
1961	94.05	2.56	38.60	0.98	347.96	9.79	231.13	13.22
1962	96.14	2.09	39.57	0.97	357.29	9.33	244.88	13.75
1963	99.10	2.96	40.55	0.98	367.98	10.70	259.09	14.21
1964	103.04	3.94	41.64	1.09	374.96	6.97	273.86	14.77
1965	107.53	4.49	42.81	1.17	382.53	7.57	289.13	15.28
1966	111.77	4.24	44.07	1.26	390.08	7.55	304.92	15.79
1967	115.35	3.58	45.37	1.31	397.25	7.17	321.16	16.24
1968	118.24	2.89	46.68	1.31	403.97	6.72	337.76	16.60
1969	122.43	4.19	48.03	1.35	411.81	7.83	354.74	16.97
1970	126.37	3.94	49.46	1.43	417.03	5.22	372.16	17.42
1971	128.91	2.55	51.54	2.08	421.59	4.56	387.54	15.38
1972	133.34	4.43	53.65	2.11	427.17	5.58	403.17	15.63
1973	138.44	5.10	55.86	2.21	433.19	6.02	419.12	15.95

Table 1G. Annual changes and cumulative stocks in products-in-use and solid waste disposal sites (SWDS) and annual and cumulative emissions with and without energy capture, from Oregon timber harvested 1906-2017.

Inventory year	Products-in use (end-use and recovered)		Products in SWDS (landfills and dumps)		Emissions w/energy capture (fuelwood and discard burning)		Emissions w/o energy capture (landfills, dumps, recovered products, burning and compost)	
	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)
1974	143.30	4.85	58.13	2.27	437.69	4.51	435.39	16.28
1975	146.74	3.44	60.47	2.34	441.72	4.02	452.04	16.65
1976	148.92	2.18	62.77	2.30	445.26	3.55	468.97	16.93
1977	152.02	3.10	65.03	2.27	449.18	3.92	486.17	17.19
1978	154.29	2.26	67.30	2.26	454.55	5.37	503.63	17.46
1979	156.78	2.49	69.44	2.14	460.00	5.45	521.21	17.59
1980	158.99	2.21	71.48	2.04	465.24	5.24	538.89	17.68
1981	160.63	1.64	74.02	2.55	469.98	4.74	553.64	14.76
1982	161.22	0.59	76.47	2.45	474.05	4.07	568.31	14.67
1983	162.01	0.79	78.84	2.37	478.16	4.11	582.84	14.53
1984	164.73	2.72	81.27	2.42	484.11	5.95	597.23	14.39
1985	167.48	2.75	83.80	2.54	490.13	6.02	611.49	14.26
1986	170.83	3.35	86.47	2.66	496.60	6.48	625.65	14.16
1987	175.06	4.22	89.27	2.81	502.69	6.09	639.75	14.10
1988	178.42	3.36	92.28	3.01	508.42	5.72	653.87	14.12
1989	182.10	3.67	95.46	3.18	514.42	6.00	668.05	14.18
1990	185.64	3.55	98.76	3.30	519.21	4.79	682.33	14.27
1991	187.87	2.22	100.96	2.20	523.22	4.02	699.16	16.83
1992	189.75	1.89	103.22	2.26	527.15	3.93	716.25	17.09
1993	191.07	1.32	105.53	2.31	530.86	3.71	733.48	17.23
1994	192.27	1.20	107.83	2.30	532.45	1.60	750.71	17.23
1995	191.72	-0.55	110.15	2.32	533.71	1.26	767.92	17.21
1996	191.26	-0.46	112.45	2.30	535.72	2.01	785.02	17.09
1997	190.39	-0.87	114.65	2.20	537.55	1.83	801.85	16.84
1998	189.92	-0.47	116.78	2.13	539.45	1.90	818.38	16.52
1999	188.79	-1.13	118.83	2.06	541.10	1.65	834.56	16.18
2000	188.47	-0.32	120.86	2.03	541.53	0.43	850.39	15.84
2001	189.54	1.07	122.28	1.42	542.01	0.49	866.61	16.22
2002	189.95	0.42	123.62	1.34	542.45	0.44	882.80	16.19
2003	191.19	1.23	125.07	1.45	542.95	0.50	898.76	15.96
2004	192.56	1.37	126.49	1.42	543.46	0.51	914.83	16.06
2005	193.88	1.32	127.95	1.46	546.23	2.77	930.85	16.03
2006	195.12	1.23	129.44	1.49	548.97	2.74	946.85	16.00
2007	196.18	1.06	130.97	1.54	551.66	2.69	962.81	15.96

Table 1G. Annual changes and cumulative stocks in products-in-use and solid waste disposal sites (SWDS) and annual and cumulative emissions with and without energy capture, from Oregon timber harvested 1906-2017.

Inventory year	Products-in use (end-use and recovered)		Products in SWDS (landfills and dumps)		Emissions w/energy capture (fuelwood and discard burning)		Emissions w/o energy capture (landfills, dumps, recovered products, burning and compost)	
	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative stock (MMT C)	Annual stock change (MMT C/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)	Cumulative emissions (MMT CO_2e)	Annual emissions change (MMT CO_2e/year)
2008	196.41	0.23	132.52	1.55	554.02	2.36	978.67	15.86
2009	196.11	-0.30	134.07	1.54	556.16	2.14	994.38	15.71
2010	195.14	-0.97	135.57	1.51	557.34	1.18	1009.84	15.46
2011	195.04	-0.10	137.10	1.53	558.72	1.38	1025.09	15.25
2012	195.65	0.61	138.69	1.59	560.28	1.56	1040.18	15.09
2013	196.40	0.75	140.34	1.65	561.89	1.60	1055.16	14.98
2014	197.86	1.45	142.08	1.74	563.68	1.80	1070.11	14.95
2015	199.10	1.25	143.89	1.81	565.45	1.76	1085.09	14.98
2016	199.71	0.61	145.74	1.85	567.07	1.62	1100.09	15.00
2017	200.45	0.74	147.63	1.89	568.73	1.66	1115.12	15.03
2018	201.09	0.64	149.56	1.92	570.38	1.65	1130.16	15.04

Table 1H. Cumulative storage of HWP carbon in products-in-use and in solid waste disposal sites (SWDS), and cumulative emissions with and without energy capture from Oregon timber harvests, 1906-2017.

Inventory year	Products-in-use		Products in SWDS		Emissions w/ energy capture from:		Emissions w/o energy capture from:				
	End-use	Recovered	In landfills	In dumps	Fuelwood	Burning (discarded)	Landfills	Dumps	Recovered products	Burning	Compost
	Cumulative storage (MMT C)				Cumulative emissions ($MMTCO_2e$)						
1907	0.7	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.1	0.0
1908	1.4	0.0	0.0	0.1	4.0	0.0	0.0	0.0	0.0	0.2	0.0
1909	2.1	0.0	0.0	0.2	6.1	0.0	0.0	0.0	0.0	0.3	0.0
1910	2.8	0.0	0.0	0.3	8.5	0.0	0.0	0.1	0.0	0.5	0.0
1911	3.6	0.0	0.0	0.5	11.0	0.0	0.0	0.1	0.0	0.8	0.0
1912	4.3	0.0	0.0	0.7	13.6	0.0	0.0	0.2	0.0	1.1	0.0
1913	5.1	0.0	0.0	0.9	16.3	0.0	0.0	0.4	0.0	1.5	0.0
1914	5.8	0.0	0.0	1.1	18.9	0.0	0.0	0.6	0.0	1.8	0.0
1915	6.4	0.0	0.0	1.3	21.4	0.0	0.0	0.8	0.0	2.2	0.0
1916	7.0	0.0	0.0	1.5	23.9	0.0	0.0	1.0	0.0	2.7	0.0
1917	7.6	0.0	0.0	1.7	26.7	0.0	0.0	1.4	0.0	3.1	0.0
1918	8.5	0.0	0.0	2.0	30.1	0.0	0.0	1.7	0.0	3.6	0.0
1919	9.4	0.0	0.0	2.2	33.6	0.0	0.0	2.1	0.0	4.2	0.0
1920	10.4	0.0	0.0	2.5	37.6	0.0	0.0	2.6	0.0	4.8	0.0
1921	11.2	0.0	0.0	2.8	41.2	0.0	0.0	3.1	0.0	5.4	0.0
1922	12.2	0.0	0.0	3.1	45.2	0.0	0.0	3.6	0.0	6.1	0.0
1923	13.2	0.0	0.0	3.4	49.5	0.0	0.0	4.2	0.0	6.8	0.0
1924	14.5	0.0	0.0	3.7	54.7	0.0	0.0	4.9	0.0	7.6	0.0
1925	15.9	0.0	0.0	4.1	60.2	0.0	0.0	5.7	0.0	8.4	0.0
1926	17.6	0.0	0.0	4.5	66.7	0.0	0.0	6.5	0.0	9.4	0.0
1927	19.2	0.0	0.0	4.9	73.2	0.0	0.0	7.4	0.0	10.4	0.0
1928	20.7	0.0	0.0	5.4	79.6	0.0	0.0	8.4	0.0	11.5	0.0
1929	22.3	0.0	0.0	5.9	86.4	0.0	0.0	9.4	0.0	12.7	0.0
1930	24.1	0.0	0.0	6.4	94.1	0.0	0.0	10.6	0.0	13.9	0.0
1931	25.0	0.0	0.0	6.9	99.3	0.0	0.0	11.9	0.0	15.2	0.0

Table 1H. Cumulative storage of HWP carbon in products-in-use and in solid waste disposal sites (SWDS), and cumulative emissions with and without energy capture from Oregon timber harvests, 1906-2017.

Inventory year	Products-in-use		Products in SWDS		Emissions w/ energy capture from:		Emissions w/o energy capture from:				
	End-use	Recovered	In landfills	In dumps	Fuelwood	Burning (discarded)	Landfills	Dumps	Recovered products	Burning	Compost
	Cumulative storage (MMT C)				Cumulative emissions (MMTCO$_2$e)						
1932	25.4	0.0	0.0	7.4	103.4	0.0	0.0	13.2	0.0	16.5	0.0
1933	25.3	0.0	0.0	7.8	106.0	0.0	0.0	14.7	0.0	17.7	0.0
1934	25.8	0.0	0.0	8.1	110.0	0.0	0.0	16.2	0.0	18.8	0.0
1935	26.6	0.0	0.0	8.5	114.7	0.0	0.0	17.8	0.0	20.0	0.0
1936	27.8	0.0	0.0	8.8	120.6	0.0	0.0	19.5	0.0	21.2	0.0
1937	29.4	0.0	0.0	9.2	127.9	0.0	0.0	21.2	0.0	22.5	0.0
1938	31.5	0.0	0.0	9.7	136.3	0.0	0.0	23.0	0.0	23.9	0.0
1939	32.8	0.0	0.0	10.2	143.1	0.0	0.0	24.8	0.0	25.4	0.0
1940	34.7	0.0	0.0	10.7	151.7	0.0	0.0	26.8	0.0	26.9	0.0
1941	36.9	0.0	0.0	11.2	161.4	0.0	0.0	28.8	0.0	28.7	0.0
1942	40.4	0.0	0.1	11.8	174.6	0.0	0.0	30.9	0.0	30.6	0.0
1943	43.9	0.0	0.2	12.4	181.9	0.0	0.0	33.2	0.0	32.7	0.0
1944	47.3	0.0	0.2	13.3	189.7	0.0	0.0	35.5	0.0	35.2	0.0
1945	50.5	0.0	0.3	14.4	197.7	0.0	0.0	38.1	0.0	38.0	0.0
1946	52.4	0.0	0.4	15.5	204.2	0.0	0.0	40.9	0.0	41.2	0.0
1947	54.7	0.0	0.5	16.7	211.4	0.0	0.1	43.9	0.0	44.5	0.0
1948	58.1	0.0	0.6	17.9	220.4	0.0	0.1	47.3	0.0	48.0	0.0
1949	61.3	0.0	0.6	19.2	229.5	0.0	0.1	50.9	0.0	51.8	0.0
1950	63.1	0.0	0.7	20.6	237.0	0.0	0.1	54.8	0.0	55.8	0.0
1951	65.7	0.0	1.0	21.8	245.6	0.0	0.2	59.0	0.0	59.8	0.0
1952	69.2	0.0	1.3	23.0	255.8	0.0	0.2	63.6	0.0	64.1	0.0
1953	73.4	0.0	1.5	24.3	267.2	0.0	0.3	68.4	0.0	68.8	0.0
1954	76.2	0.0	1.8	25.8	277.3	0.0	0.4	73.5	0.0	73.7	0.0
1955	79.2	0.0	2.1	27.2	287.6	0.0	0.5	78.9	0.0	78.7	0.0
1956	82.7	0.0	2.4	28.6	299.0	0.0	0.6	84.6	0.0	84.0	0.0
1957	85.7	0.0	2.7	30.1	309.9	0.0	0.7	90.7	0.0	89.4	0.0

Table 1H. Cumulative storage of HWP carbon in products-in-use and in solid waste disposal sites (SWDS), and cumulative emissions with and without energy capture from Oregon timber harvests, 1906-2017.

Inventory year	Products-in-use		Products in SWDS		Emissions w/ energy capture from:		Emissions w/o energy capture from:				
	End-use	Recovered	In landfills	In dumps	Fuelwood	Burning (discarded)	Landfills	Dumps	Recovered products	Burning	Compost
	Cumulative storage (MMT C)				Cumulative emissions ($MMTCO_2e$)						
1958	87.2	0.0	3.0	31.5	318.7	0.0	0.9	97.1	0.0	94.9	0.0
1959	88.8	0.0	3.3	32.7	327.7	0.0	1.0	103.9	0.0	100.3	0.0
1960	91.5	0.0	3.6	34.0	338.2	0.0	1.2	110.9	0.0	105.8	0.0
1961	93.6	0.5	4.1	34.5	348.0	0.0	1.4	118.2	0.0	111.6	0.0
1962	95.3	0.8	4.5	35.0	357.3	0.0	1.6	125.5	0.4	117.3	0.0
1963	98.0	1.1	5.0	35.6	368.0	0.0	1.8	133.0	1.1	123.2	0.0
1964	101.7	1.3	5.4	36.2	375.0	0.0	2.1	140.5	2.1	129.2	0.0
1965	106.0	1.5	5.9	36.9	382.5	0.0	2.4	148.1	3.2	135.5	0.0
1966	110.1	1.7	6.4	37.7	390.1	0.0	2.7	155.8	4.5	142.0	0.0
1967	113.6	1.8	6.9	38.5	397.3	0.0	3.0	163.6	5.9	148.7	0.0
1968	116.3	1.9	7.4	39.3	404.0	0.0	3.3	171.6	7.4	155.4	0.0
1969	120.5	2.0	7.9	40.1	411.8	0.0	3.6	179.7	9.0	162.3	0.0
1970	124.3	2.0	8.5	41.0	417.0	0.0	4.0	188.0	10.7	169.4	0.0
1971	126.9	2.0	9.8	41.7	421.6	0.0	4.4	196.4	12.5	174.3	0.0
1972	131.3	2.0	11.2	42.5	427.2	0.0	4.8	205.0	14.2	179.1	0.0
1973	136.4	2.0	12.6	43.3	433.2	0.0	5.3	213.6	16.0	184.2	0.0
1974	141.3	2.0	14.0	44.1	437.7	0.0	5.9	222.4	17.7	189.4	0.0
1975	144.7	2.1	15.5	45.0	441.7	0.0	6.5	231.4	19.5	194.7	0.0
1976	146.8	2.1	16.9	45.8	445.3	0.0	7.2	240.5	21.2	200.1	0.0
1977	149.9	2.1	18.4	46.7	449.2	0.0	8.0	249.7	23.1	205.4	0.0
1978	152.1	2.1	19.8	47.5	454.5	0.0	8.8	259.1	24.9	210.8	0.0
1979	154.6	2.1	21.2	48.2	460.0	0.0	9.6	268.7	26.7	216.2	0.0
1980	156.9	2.1	22.6	48.9	465.2	0.0	10.5	278.4	28.5	221.4	0.0
1981	158.4	2.3	26.4	47.6	470.0	0.0	11.5	288.1	30.4	223.7	0.0
1982	158.9	2.3	30.1	46.3	474.1	0.0	12.6	297.6	32.3	225.8	0.0
1983	159.7	2.4	33.7	45.1	478.2	0.0	13.9	306.8	34.3	227.9	0.0

Table 1H. Cumulative storage of HWP carbon in products-in-use and in solid waste disposal sites (SWDS), and cumulative emissions with and without energy capture from Oregon timber harvests, 1906-2017.

Inventory year	Products-in-use		Products in SWDS		Emissions w/ energy capture from:		Emissions w/o energy capture from:				
	End-use	Recovered	In landfills	In dumps	Fuelwood	Burning (discarded)	Landfills	Dumps	Recovered products	Burning	Compost
	Cumulative storage (MMT C)				Cumulative emissions ($MMTCO_2e$)						
1984	162.4	2.3	37.3	44.0	484.1	0.0	15.3	315.6	36.3	230.0	0.0
1985	165.1	2.3	40.8	43.0	490.1	0.0	16.8	324.2	38.3	232.1	0.0
1986	168.5	2.3	44.4	42.1	496.6	0.0	18.5	332.6	40.3	234.3	0.0
1987	172.7	2.4	48.1	41.2	502.7	0.0	20.2	340.7	42.3	236.5	0.0
1988	176.0	2.4	51.8	40.5	508.4	0.0	22.1	348.6	44.4	238.8	0.0
1989	179.6	2.5	55.6	39.8	514.4	0.0	24.1	356.4	46.4	241.1	0.0
1990	183.1	2.6	59.5	39.2	519.2	0.0	26.3	364.0	48.6	243.5	0.0
1991	184.7	3.2	63.7	37.3	523.2	0.0	28.5	371.4	50.8	247.9	0.5
1992	186.1	3.7	67.7	35.5	527.2	0.0	30.9	378.5	53.6	252.2	1.1
1993	187.0	4.0	71.7	33.8	530.9	0.0	33.5	385.1	56.7	256.5	1.6
1994	188.0	4.3	75.6	32.2	532.5	0.0	36.2	391.4	60.2	260.8	2.2
1995	187.2	4.5	79.5	30.7	533.7	0.0	39.0	397.4	63.9	265.0	2.7
1996	186.6	4.6	83.2	29.2	535.7	0.0	41.9	403.0	67.7	269.2	3.2
1997	185.7	4.6	86.8	27.9	537.5	0.0	44.9	408.4	71.7	273.2	3.7
1998	185.3	4.6	90.2	26.6	539.5	0.0	48.0	413.5	75.7	277.0	4.2
1999	184.2	4.5	93.4	25.4	541.1	0.0	51.1	418.3	79.6	280.8	4.7
2000	184.0	4.4	96.6	24.2	541.5	0.0	54.4	422.9	83.5	284.5	5.1
2001	184.8	4.7	99.1	23.2	542.0	0.0	57.7	427.2	87.4	287.8	6.5
2002	184.9	5.0	101.5	22.1	542.5	0.0	61.0	431.4	91.4	291.2	7.9
2003	186.0	5.2	103.9	21.2	542.9	0.0	64.3	435.3	95.7	294.2	9.3
2004	187.2	5.4	106.3	20.2	543.5	0.0	67.5	439.0	100.2	297.3	10.8
2005	188.4	5.5	108.6	19.4	546.2	0.0	70.8	442.6	104.8	300.4	12.3
2006	189.4	5.7	110.9	18.5	549.0	0.0	74.1	446.0	109.5	303.4	13.8
2007	190.4	5.8	113.2	17.7	551.7	0.0	77.3	449.2	114.4	306.5	15.3
2008	190.5	5.9	115.5	17.0	554.0	0.0	80.6	452.3	119.4	309.6	16.8
2009	190.2	5.9	117.8	16.3	556.2	0.0	83.8	455.2	124.4	312.6	18.3

Table 1H. Cumulative storage of HWP carbon in products-in-use and in solid waste disposal sites (SWDS), and cumulative emissions with and without energy capture from Oregon timber harvests, 1906-2017.

Inventory year	Products-in-use		Products in SWDS		Emissions w/ energy capture from:		Emissions w/o energy capture from:				
	End-use	Recovered	In landfills	In dumps	Fuelwood	Burning (discarded)	Landfills	Dumps	Recovered products	Burning	Compost
	Cumulative storage (MMT C)				Cumulative emissions ($MMTCO_2e$)						
2010	189.3	5.9	119.9	15.6	557.3	0.0	87.0	458.0	129.5	315.5	19.8
2011	189.2	5.8	122.1	15.0	558.7	0.0	90.2	460.7	134.6	318.4	21.2
2012	189.9	5.8	124.3	14.4	560.3	0.0	93.4	463.3	139.6	321.3	22.6
2013	190.6	5.8	126.5	13.8	561.9	0.0	96.6	465.7	144.5	324.3	24.1
2014	192.0	5.8	128.8	13.3	563.7	0.0	99.7	468.1	149.5	327.3	25.6
2015	193.2	5.9	131.1	12.8	565.4	0.0	102.9	470.3	154.5	330.3	27.1
2016	193.7	6.0	133.5	12.3	567.1	0.0	106.0	472.4	159.5	333.4	28.6
2017	194.3	6.1	135.8	11.8	568.7	0.0	109.2	474.5	164.7	336.6	30.2
2018	194.9	6.2	138.2	11.4	570.4	0.0	112.3	476.5	170.0	339.7	31.7

Note: HWP storage and emissions resulting from 2017 and prior harvests are reported in 2018.

Table 1J. Cumulative storage of HWP carbon in products-in-use and SWDS by ownership in MMT C, from Oregon timber harvests, 1962-2017.

Inventory year	Private		USFS		BLM		State and other		Tribal	
	Products-in use	SWDS	Products-in use	SWDS	Products-in use	SWDS	Products-in use	SWDS	Products-in use	SWDS
1963	3.6	0.1	2.7	0.1	1.0	0.0	0.1	0.0	0.0	0.0
1964	7.0	0.5	5.6	0.4	2.2	0.1	0.3	0.0	0.1	0.0
1965	10.3	1.0	8.5	0.8	3.6	0.3	0.5	0.0	0.2	0.0
1966	13.4	1.7	11.5	1.4	4.5	0.6	0.8	0.1	0.2	0.0
1967	16.4	2.4	13.8	2.0	5.4	0.8	0.9	0.1	0.3	0.0
1968	18.8	3.2	15.8	2.7	6.0	1.1	1.0	0.2	0.4	0.1
1969	21.7	4.1	18.2	3.4	7.0	1.3	1.1	0.2	0.4	0.1
1970	24.4	5.0	20.5	4.2	7.8	1.6	1.2	0.3	0.5	0.1
1971	26.7	6.2	21.9	5.2	8.3	2.0	1.3	0.3	0.5	0.1
1972	29.6	7.4	24.0	6.1	9.2	2.4	1.4	0.4	0.6	0.1
1973	32.0	8.7	26.9	7.2	10.3	2.8	1.6	0.4	0.7	0.2
1974	34.1	9.9	29.6	8.3	11.4	3.2	1.9	0.5	0.7	0.2
1975	36.4	11.1	31.4	9.4	11.9	3.6	2.1	0.6	0.8	0.2
1976	38.6	12.4	32.5	10.5	11.9	4.0	2.1	0.7	0.9	0.3
1977	40.4	13.7	34.2	11.5	12.4	4.3	2.3	0.7	1.0	0.3
1978	42.0	14.9	35.4	12.6	12.9	4.7	2.4	0.8	1.0	0.3
1979	43.5	16.1	37.0	13.6	13.1	5.0	2.5	0.9	1.1	0.4
1980	44.7	17.3	38.5	14.6	13.4	5.4	2.7	1.0	1.2	0.4
1981	46.1	18.6	39.3	15.7	13.7	5.7	2.8	1.0	1.2	0.4
1982	47.0	19.8	39.7	16.8	13.8	6.1	2.9	1.1	1.3	0.5
1983	48.7	21.1	39.7	17.8	13.6	6.4	3.0	1.2	1.3	0.5
1984	50.3	22.4	41.2	18.8	13.9	6.6	3.2	1.3	1.4	0.6
1985	51.4	23.7	42.9	19.9	14.3	7.0	3.3	1.4	1.5	0.6
1986	52.9	25.1	45.0	21.0	14.7	7.3	3.5	1.5	1.5	0.7
1987	54.6	26.4	47.5	22.2	15.3	7.6	3.6	1.6	1.6	0.7
1988	56.0	27.8	49.3	23.6	16.0	8.0	3.8	1.7	1.6	0.8
1989	57.4	29.2	51.2	25.0	17.0	8.4	3.9	1.9	1.7	0.8
1990	59.3	30.7	52.8	26.4	17.4	8.9	4.0	2.0	1.8	0.9
1991	61.3	31.8	53.3	27.4	17.7	9.2	4.1	2.1	1.8	0.9
1992	63.3	33.0	53.9	28.4	17.6	9.5	4.1	2.1	1.9	0.9
1993	65.5	34.2	53.5	29.3	17.6	9.8	4.2	2.2	1.9	1.0
1994	68.0	35.5	52.9	30.1	17.4	10.0	4.2	2.3	2.0	1.0
1995	69.8	37.0	51.7	30.9	16.8	10.3	4.2	2.4	2.0	1.1
1996	71.5	38.5	50.4	31.6	16.4	10.5	4.3	2.4	2.0	1.1
1997	72.6	40.0	49.1	32.2	16.2	10.6	4.3	2.5	2.0	1.1

Table 1J. Cumulative storage of HWP carbon in products-in-use and SWDS by ownership in MMT C, from Oregon timber harvests, 1962-2017.

Inventory year	Private		USFS		BLM		State and other		Tribal	
	Products-in use	SWDS	Products-in use	SWDS	Products-in use	SWDS	Products-in use	SWDS	Products-in use	SWDS
1998	73.9	41.6	48.2	32.7	15.9	10.8	4.4	2.6	2.0	1.2
1999	74.7	43.1	47.0	33.1	15.5	11.0	4.5	2.7	2.1	1.2
2000	76.1	44.6	45.9	33.5	15.3	11.1	4.7	2.8	2.1	1.3
2001	78.5	45.8	45.0	33.8	15.0	11.2	5.1	2.9	2.1	1.3
2002	80.4	46.9	44.0	34.0	14.6	11.2	5.4	2.9	2.1	1.3
2003	83.0	48.1	43.1	34.1	14.3	11.3	5.7	3.0	2.2	1.3
2004	85.4	49.3	42.3	34.3	14.1	11.3	6.0	3.1	2.2	1.4
2005	87.7	50.6	41.7	34.5	13.9	11.4	6.3	3.2	2.2	1.4
2006	89.7	51.8	41.2	34.6	13.7	11.4	6.7	3.4	2.2	1.4
2007	91.8	53.1	40.6	34.8	13.6	11.5	6.9	3.5	2.3	1.4
2008	93.0	54.4	39.9	34.9	13.5	11.5	7.1	3.6	2.3	1.5
2009	93.6	55.7	39.3	35.0	13.4	11.6	7.3	3.7	2.3	1.5
2010	93.6	57.0	38.8	35.2	13.3	11.7	7.4	3.8	2.3	1.5
2011	94.1	58.2	38.3	35.3	13.2	11.7	7.6	4.0	2.4	1.6
2012	95.2	59.5	38.1	35.5	13.2	11.8	7.9	4.1	2.4	1.6
2013	96.4	60.8	37.9	35.6	13.1	11.9	8.0	4.2	2.4	1.6
2014	98.3	62.2	37.7	35.8	13.1	11.9	8.2	4.4	2.4	1.6
2015	100.0	63.6	37.5	36.0	13.1	12.0	8.3	4.5	2.4	1.7
2016	101.0	65.0	37.3	36.2	13.1	12.1	8.5	4.7	2.4	1.7
2017	102.1	66.5	37.0	36.4	13.1	12.2	8.7	4.8	2.4	1.7
2018	103.3	68.0	36.7	36.6	13.0	12.3	8.9	5.0	2.4	1.8

Note: HWP storage and emissions resulting from 2017 and prior harvests are reported in 2018.

APPENDIX 2

A Oregon timber product ratios (embedded .pdf file)

ORTimberProductRatios.pdf

B Oregon primary product ratios (embedded .pdf file)

ORPrimaryProductRatios.pdf

C End use product ratios (embedded .pdf file)

OREndUseProductRatios.pdf

D Harvested wood product end-use half-lives (embedded .pdf file)

OREndUseHalfLifeData.pdf

E Discarded product disposition ratios (embedded .pdf file)

DiscardDispositionData.pdf

F Discarded harvested wood and paper half-lives and landfill fixed ratios (embedded .pdf file)

DiscardedWood&PaperHalfLives&FixedRa

Appendix 3

MONTE CARLO SIMULATION

Simulation Specifications

The goal of the MC simulation was to produce estimates and confidence intervals for overall values for SWDS, PIU, EWOEC, EEC, and their combinations. To achieve this goal the Monte Carlo (MC) simulation directly alters 15 different parameters, listed in Table 3a below. The columns Min Value, Peak Value, and Max Value describe the desired 90% confidence interval for the range of random proportions against which the parameters of interest were adjusted. Parameters for harvest, timber product ratios and primary product ratios each have a set of three confidence intervals based on the years for which the estimates were provided. These parameters require a separate MC random variable for each year set. Finally, parameters for timber, product, and end use product ratios have a sum-to-one characteristic. For instance, timber product ratios (TPRs) represent the proportion of total harvest for a given year that is allocated to each of the 40 timber products. While the proportions change during the time series the full set of 40 TPR proportions will always sum to one.

Table 3a. Monte Carlo simulation target parameters and ranges.

Parameter ID	Parameter Name	First Year	Last Year	Min Value	Peak Value	Max Value	Sum-to-One
0	CCF to MgC conversion factors	n/a	n/a	0.95	1	1.05	No
1	Harvest	1906	1945	0.7	1	1.3	No
1	Harvest	1946	1979	0.8	1	1.2	No
1	Harvest	1980	2100	0.85	1	1.15	No
2	Timber product ratios	1906	1945	0.7	1	1.3	Yes
2	Timber product ratios	1946	1979	0.8	1	1.2	Yes
2	Timber product ratios	1980	2100	0.85	1	1.15	Yes
3	Primary product ratios	1906	1949	0.7	1	1.3	Yes
3	Primary product ratios	1950	1979	0.8	1	1.2	Yes
3	Primary product ratios	1980	2100	0.85	1	1.15	Yes
4	End use product ratios	n/a	n/a	0.85	1	1.15	Yes
5	Product half lives	n/a	n/a	0.85	1	1.15	No
6	Discarded disposition ratios (paper)	n/a	n/a	0.85	1	1.15	Yes
7	Discarded disposition ratios (wood)	n/a	n/a	0.85	1	1.15	Yes
8	Landfill decay limits (paper)	n/a	n/a	0.85	1	1.15	No
9	Landfill decay limits (wood)	n/a	n/a	0.85	1	1.15	No

10	Landfill half-lives (paper)	n/a	n/a	0.85	1	1.15	No
11	Landfill half-lives (wood)	n/a	n/a	0.85	1	1.15	No
12	Dump half-lives (paper)	n/a	n/a	0.85	1	1.15	No
13	Dump half-lives (wood)	n/a	n/a	0.85	1	1.15	No
14	Recovered half-lives (paper)	n/a	n/a	0.85	1	1.15	No
15	Recovered half-lives (wood)	n/a	n/a	0.85	1	1.15	No

Simulation Sampling

As in other HWP publications such as Stockmann et al. (2012) and Anderson et al. (2013), the random variables in the Monte Carlo simulations are drawn from triangular distributions. The distributions all have a peak value of 1.0 (Table 3a) and symmetrically taper to given 90% confidence interval bounds. The values from the triangular distribution are used as proportions for adjusting parameter values.

Drawing random variables from triangular distributions is a multi-step process. The first step involves drawing random variables from a standard uniform (0, 1) distribution using a Latin Hypercube Sampling (LHS) process. The standard uniform distribution is an excellent starting place for randomly selecting points along other distributions because random uniform points can be translated as locations along some other distribution's Cumulative Distribution Function (CDF). However, purely random sampling may be inefficient because with unorganized, truly random draws of random uniform variables for more than one distribution there is a strong probability that samples will, by chance, fall in the same local region for several of the 22 distributions. Many iterations are needed to obtain a full suite of the possible MC values across distributions. LHS offers a method for partitioning the uniform distributions across the range of possible values from which the random selections can be drawn, thus preventing clumping. With LHS many fewer iterations are needed to achieve stable estimates from the MC simulation.

The function "randomLHS" in the R package "lhs" was used to conduct a random LHS sample. The lhs package divides the uniform distribution into as many partitions as there are iterations and then randomly selects a value from the range of values within each partition. The order of the selected values was also randomized.

Once the matrix from the LHS (rows = number of iterations, columns = desired number of distributions) has been created the cell values are transformed into draws from triangular distributions (Wikipedia: Triangular Distribution).

$$Triangular\ Random\ Variable = \begin{cases} if\ 0 < U < F(c), & a + \sqrt{U(b-a)(c-a)} \\ else, & b - \sqrt{(1-U)(b-a)(c-a)} \end{cases}$$

In this equation *U* is the random uniform variable (the LHS draw), $F(c) = (c-a)/(b-a)$, *a* is the minimum value for the triangular distribution, *b* is the maximum value, and *c* is the mode.

Note that the specifications require 90% confidence intervals and do not state what the endpoints for the triangular distributions should be. Endpoint values that corresponded with the desired 90% confidence intervals (Table 3b) were derived through simulation and trial and error.

Table 3b. Translation of 90% Confidence Intervals to endpoints for triangular distributions

90% Confidence Interval Range	Endpoints Used
0.7, 1.3	0.57, 1.43
0.8, 1.2	0.71, 1.29
0.85, 1.15	0.78, 1.22
0.95, 1.05	0.93, 1.07

Each random draw from a triangular distribution was used to adjust an MC parameter for all years in a single iteration. The next iteration would use the subsequent random draw. The only exception occurs when the 90% confidence intervals changed within the year set for an iteration. In those instances (i.e., for Harvest, timber production ratios, and primary production ratios) we simulate random draws for three random variables. For each iteration we use the appropriate random triangular variable draw for the given year set (e.g., 1906 to 1945).

Some random variables should be correlated with one another (e.g., Stockmann et al. 2012). For instance, there are three parameters for Harvest each to account for three changes in confidence interval values during the time series. There is a separate random variable for each of those three sets of years because the intervals are assumed to have been constructed in similar ways and therefore would have been correlated. Therefore, a correlation among the three Harvest variables was created. Timber Product Ratios and End Use Product Ratios each have sets of three correlated variables and pairs of correlated random triangular variables for all paper/wood discard disposition ratios and decay limits were created.

Pearson's correlation of 0.5 were used for all correlations. This value was also used by Anderson et al. (2013) and Stockmann et al. (2012). A Pearson's correlation matrix was created, with the number of columns and rows corresponding to the number of random variables to correlate. For a three-variable correlation the following matrix was used and a Choleski decomposition was created from it:

$$Pearson's\ Correlation\ Matrix = \begin{bmatrix} 1 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{bmatrix}$$

$$Choleski\ Decomposition = \begin{bmatrix} 1 & 0.5 & 0.5 \\ 0 & 0.866 & 0.289 \\ 0 & 0 & 0.816 \end{bmatrix}$$

Linear multiplication of a vector containing the three variables against the Choleski decomposition matrix alters the second and third variables such that they are correlated to the first. The correlated triangular random variables were generated by first transforming an iteration's three LHS random uniform variables into values from a standard normal distribution by treating the random uniform variables as probability quantiles from a standard normal distribution. The three standard normal values are then altered and become correlated by linearly multiplying them by the Choleski decomposition. The values return to those from a standard uniform distribution by finding the cumulative distribution function values of the three (now normally distributed and correlated) random variables. These random values are then ready to be processed as described above into draws from a triangular distribution and remain correlated.

Sampling and the HWP Program

The goal of the MC simulation was to produce estimates and confidence intervals for overall values for SWDS, PIU, EWOEC, EEC, and their combinations. Before entering the MC loop, the program performs all LHS draws, forces correlations among specific variables, and transforms the random draws into draws from triangular distributions.

A description of how each parameter was altered is provided below.

<u>CCF to MgC Conversion Factors</u>

Within a single iteration, one random triangular variable value is multiplied across the CCF to MgC conversion factor values for all years.

<u>Harvest</u>

For Harvest three correlated random variables for every MC iteration was used. Each random variable is used to adjust its corresponding range of years (Table 3a). Subsequent iterations use a different draw of three correlated random variables. The matrix of random triangular variables, with years = rows, iterations = columns, is multiplied by a vector of the harvest volume per year. For each iteration in the MC loop a different vector of these altered values is used.

<u>Timber Product Ratios</u>

This parameter is more complicated than Harvest because the values within a year must sum to one. It relies on three correlated random variables which are processed as described above. For each iteration, the code examines all 40 proportion values and determines which one, for a given year, is the maximum value. It finds the product of the random triangular variable value and the maximum proportion. If the resulting value is ≥ 1 then the maximum proportion is set to 1.0 and all the other 39 values are set to 0.0. If it is < 1 then the code calculates the ratio of (1 – new maximum proportion) / (1 – old maximum proportion) and multiplies this proportion against all the remaining proportions. All 40 altered values should sum to 1.0.

The result is that for each year there are 40 altered TPR values. When the MTC variable is calculated for each iteration, the altered values are effectively propagated across all PPR and EUR categories per year. This MC sum-to-one approach does have some substantial drawbacks. For instance, Timber Product Ratio 2 is Softwood Sawtimber. It accounts for 77% to 97% of harvest in a given year. Multiplying the triangular distribution value by Timber Product Ratio 2 frequently results in values that are ≥ 1.0. Therefore, the alteration of this variable frequently results in the same value, and the distribution of Timber Product Ratio 2 is triangular until the distribution crosses the 1.0 boundary, at which point the remainder of the distribution is stacked at 1.0.

Primary Product Ratios

Three correlated random variables were used to alter PPR for each MC iteration, as was done for TPR. The 64 Primary Product Ratios (PPRs) differ from the TPR values in that they sum to 40, instead of 1, for each year in the time series. However, subsets of PPR ratios sum to 1 but 36 of primary products are not part of a subset of a timber product. The PPRs were altered in the same fashion as TPR values with one difference. The code found, for each PPR set with more than one value, the maximum proportion and then adjusted that proportion with the random triangular parameter value. It adjusted the remainder of the values in the PPR set as described for TPR. If there was only one value in the set, it was always equal to 1.0 and the code never adjusted it. These 1.0 values allowed the TPR value to be carried through PPR. Similarly, if the maximum ratio in a set was already 1.0, no alteration occurred. These values are propagated across all EUR categories per year so that they may be multiplied against other values in the eu_ratio matrix to create the altered MTC values.

End Use Product Ratios

End Use Product ratios were altered as described for PPRs. One difference is that the EUR alterations only used one random triangular variable value for all years in an iteration (i.e., not three correlated variables) because the triangular distribution confidence intervals were held constant across years. EUR values for a given year summed to 64. The code therefore examined sets of EUR values for each PPR category.

Product Half Lives

There are 224 half-life values, one per EUR and the same random triangular random variable value was multiplied by all 224 values per iteration. Each iteration of the MC loop used a different vector of those 224 values in the decay function that is used to determine PIU over time.

Decay and Half-Life Limits for Landfills, Dumps, and Recovered Pools

Description of these parameters is combined because they relied on the same process. Each one has two correlated random triangular variables, for paper and wood. A function inputs the original 224 ratios for each, where most of the 224 ratios are for wood and a few are for paper. The function also obtains the two vectors of correlated random variables. Each iteration has a single random variable value multiplied by the paper ratio and another for the wood ratio. The altered vectors are then combined into a matrix. When the MC loop runs, each iteration obtains a differently altered vector of 224 values to enter into the decay function.

Discarded Disposition Ratios for Wood and Paper

These ratios control what fraction of waste ends up as burned, burned with energy capture, recycled, composted, placed in a landfill, or sent to a dump (the six fates). The values can differ by year and a function was created that operated on the ratios for wood and paper separately. The function performed the sum-to-one approach on the six ratios for either wood or paper.