Estimates of carbon stored in harvested wood products from United States Forest Service Pacific Northwest Region, 1909-2012

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Abstract

Global forests capture and store significant amounts of carbon through photosynthesis. When carbon is removed from forests through harvest, a portion of the harvested carbon is stored in wood products, often for many decades. The United States Forest Service (USFS) and other agencies are interested in accurately accounting for carbon flux associated with harvested wood products (HWP) to meet greenhouse gas monitoring commitments and climate change adaptation and mitigation objectives. National-level forest carbon accounting has been in place for over a decade, but there is an increasing need for accounting for smaller scale administrative units, including USFS National Forest System regions and individual National Forests. This paper uses the Intergovernmental Panel on Climate Change (IPCC) production accounting approach to estimate HWP carbon storage from 1909 to 2012 from harvests on the national forests in the USFS Pacific Northwest Region. For the Pacific Northwest Region as a whole, carbon stocks in the HWP pool were increasing at over 1 million megagrams of carbon (MgC) per year between the late 1940's and the early 1990's, with peak cumulative storage between 143 million and 144 million MgC spanning 1992-1995. Net positive flux into the HWP pool over this period is primarily attributable to high harvest levels during the 1960's through the 1980's. In the years between the late 1960s and 1990 timber harvest were at high but volatile levels, with harvests exceeding 10.6 million ccf (8 million MgC) twice during this period. Harvest levels from national forests have since declined to less than 1.3 million ccf (1 million MgC) per year, resulting in less carbon entering the HWP pool. Since 1995, emissions from HWP at solid waste disposal sites have exceeded additions from harvesting, resulting in a decline in the total amount of carbon stored in the HWP pool. The Pacific Northwest Region's HWP pool is now in a period of negative net annual stock change because the decay of products harvested between 1909 and 2012 exceeds additions of carbon to the HWP pool through harvest. Together with estimates of ecosystem carbon, which are also being developed through the Forest Management Carbon Framework (ForCaMF), Regional level estimates of HWP carbon flux can be used to inform management decisions and guide climate change adaptation and mitigation efforts by the agency. Though our emphasis is on the Pacific Northwest Region as a whole, this accounting method can be applied more broadly at smaller land management units, such as National Forests.

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Cover: (Vicinity of Olympia, WA) Cable yarding and log loading operation in second-growth Douglas-fir stands courtesy of Dr. Han-Sup Han, Professor, Forest Operation and Engineering, Humboldt State University.

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Background

Recent estimates of net annual storage (flux) indicate that the world's forests are an important carbon sink, removing more carbon dioxide (CO_2) from the atmosphere through photosynthesis than they emit through combustion and decay (Pan et al. 2011). The forest sector of the United States (US) currently stores about 45 billion megagrams of carbon (MgC), or the equivalent of about 24 years of total US emissions at the 2010 rate (US EPA 2012). Nationally, net additions to ecosystem and harvested wood products (HWP) pools have been estimated at 251.4 million MgC yr^{-1} (US EPA 2012), with US forests offsetting about 13.5% of the country's annual fossil fuel emissions. About 5.5% of total US forest sector carbon stocks and 7.1% of the annual flux is attributable to carbon in HWP. Increasing social and managerial interest in mitigating rising atmospheric CO_2 concentrations and the resulting impacts on climate has focused attention on the ecosystem service of forest carbon storage, including storage in HWP.

As defined by the Intergovernmental Panel on Climate Change (IPCC), HWP are products made from wood including lumber, panels, paper, paperboard, and wood used for fuel (Skog 2008). The HWP carbon pool includes both products in use and products that have been discarded to solid waste disposal sites (SWDS). Additions to the HWP pool are made through harvesting, and emissions result from decay and combustion of wood products. Forest management can affect the quantity of carbon stored in both ecosystems and forest products over time, and management activities in the US frequently include silvicultural treatments that produce HWP. Credible information on forest ecosystem and HWP carbon stocks and fluxes can inform forest managers and the public of the tradeoffs between carbon storage and other forest management objectives, and between the short and long-term carbon consequences of alternative forest management strategies (Ryan et al. 2010, McKinley et al. 2011, Galik and Jackson 2009). Though the HWP fraction of the pool is small compared to ecosystem carbon, it is an important component of national level carbon accounting and reporting.

There is growing interest among forest managers in monitoring and managing forests for sequestration of carbon as an ecosystem service. For example, during 2010, the US Forest Service (USFS) developed a climate change scorecard that will be completed annually for each of the 155 National Forests and grasslands managed by the agency (USFS 2011). The scorecard includes four categories of scored elements: organizational capacity, engagement, adaptation, and mitigation and sustainable consumption. Elements under mitigation and sustainable consumption direct individual National Forests to develop a baseline assessment of carbon stocks, as well as an assessment of the influence of disturbance and management activities on these stocks. These assessments are meant to guide mitigation actions and monitoring. Managers are expected to begin integrating carbon stewardship with management of their forest for traditional multiple uses and other ecosystem services (USFS 2011). Consequently, these requirements necessitate robust and accessible monitoring systems that provide quantitative metrics to gauge progress.

HWP carbon monitoring systems have been implemented at the national level (US EPA 2012, Skog 2008, IPCC 2006, Smith et al. 2006). Robust inventory-based methods for estimating carbon stocks and flux in forest ecosystems are well established in the US and several tools are available to forest managers (Smith et al. 2006, 2004, Zheng et al. 2010, Galik et al. 2009). However, many of the tools used to estimate carbon stored in forests do not provide estimates of HWP carbon (e.g., U.S. Forest Carbon Calculation Tool, Smith et al. 2007) while others are restricted to national level HWP accounting (e.g., WOODCARB II, Skog 2008). Neither model independently serves national forest managers who need accessible and practical tools for estimating and monitoring carbon stocks and flux in HWP, which were harvested since the inception of their units, at the regional or national forest levels (Ingerson 2011, Stockmann et al. 2012).

Objectives

There is a clear need to develop the means to monitor the contribution of HWP to carbon pools and greenhouse gas mitigation resulting from national forest harvests both at the regional and forest levels. Our objectives are to:

1) Use an established accounting approach to make estimates of HWP carbon stocks and fluxes for the USFS Pacific Northwest Region;
2) Provide a framework with clear metrics and estimation methods that can be applied to other land management units, including individual National Forests.

We do not develop a system for evaluating the future impacts of specific management actions, nor do we advocate any particular course of action to improve carbon stewardship.

Regional Description

The USFS Pacific Northwest Region is located almost entirely in Washington and Oregon. This region includes the Colville, Deschutes, Fremont-Winema, Gifford Pinchot, Malheur, Mt. Baker-Snoqualmie, Mt. Hood, Ochoco, Okanogan-Wenatchee, Olympic, Rogue River-Siskiyou, Siuslaw, Umatilla, Umpqua, Wallowa-Whitman, and Willamette National Forests, and represent 24.6 million acres (approximately 13.1%) of all National Forest System (NFS) lands (USFS 2012).

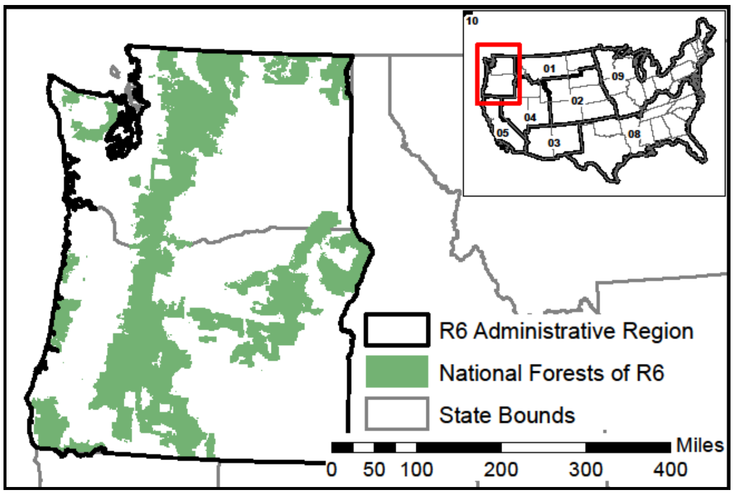

Figure 1. Map of the Pacific Northwest Region (also known as R6).

Historical Pacific Northwest Region land base changes

Forestland included in many Forest Service Regions has changed over time. In cases where administrative boundaries between Regions have changed, we used forest-specific data to standardize Regional harvest totals. A few changes through time did occur to the Regional boundary at the northeastern border regarding the Colville National Forest and at the southwestern border in the vicinity of coastal California regarding present day Six Rivers and Rogue River-Siskiyou National Forests (Davis 1983). Where these changes occurred, inclusion or exclusion of harvest volumes in this report were supported by details in cut-and-sold reports. Administrative boundary changes among national forests within the Region do not affect the estimates presented here and would only be relevant to produce HWP carbon stocks and flux estimates for individual national forests. More than forty administrative Forests have combined administratively into the current seventeen National Forests of the Pacific Northwest Region. However, records indicate that most of these changes occurred before 1920 when total harvest volumes were relatively low (Davis 1983).

Methods

The method used to estimate carbon stored in HWP for the Pacific Northwest Region is discussed here in four parts: accounting approach, computational methods, data sources, and uncertainty analysis. The first part provides a general overview of the framework used for carbon accounting, including defining the scope of analysis, relevant carbon pools, and associated fluxes. The second part provides detailed information about the data we used in our calculations that transform harvest data into carbon accounting metrics. Then we describe the origins of the data used in this analysis, with an emphasis on understanding what inputs are required and how data quality can vary over time. Lastly, the quantitative treatment of uncertainty is discussed in light of limitations of the approach used, computational methods, and data.

Accounting Approach

We use the IPCC production accounting approach, which has been adopted by the US Environmental Protection Agency (EPA; hereafter referred to as the IPCC/EPA approach) to estimate annual changes in HWP pools from the Region (Figure 1). In the IPCC/EPA approach, the annual carbon stock change for the Region's forest sector is a function of carbon flow among the atmosphere, forest ecosystems, and HWP, and is calculated as:

$$\Delta S = (NEE - H) + (\Delta C_R)$$

In this equation ΔS is the annual stock change for the Region's forest sector, NEE is the annual net ecosystem exchange between the atmosphere and the Region's forests from all ecosystem processes including photosynthesis, decay, and natural and anthropogenic fire, H is the annual harvest of wood from the Region's forests for products, and ΔC_R is the annual change in carbon stored in HWP that were made from wood harvested from the Region's national forests (Table 1, Figure2). In the IPCC/EPA approach, the annual change in carbon stored in HWP (ΔC_R) is the sum of the net change in carbon stored in products in use ($\Delta C_{IU\ R}$) and the net change in carbon stored in products at solid waste disposal sites ($\Delta C_{SWDS\ R}$) (Table 1). By estimating stocks and emissions for regional HWP carbon on an annual basis, we can calculate the annual stock change in the HWP carbon pool (ΔC_R), which is the relevant metric for this accounting approach. HWP carbon stock and flux estimates presented here are part of a larger Forest Carbon Management Framework (ForCaMF) intended to address carbon storage in the entire forest system (ΔS).

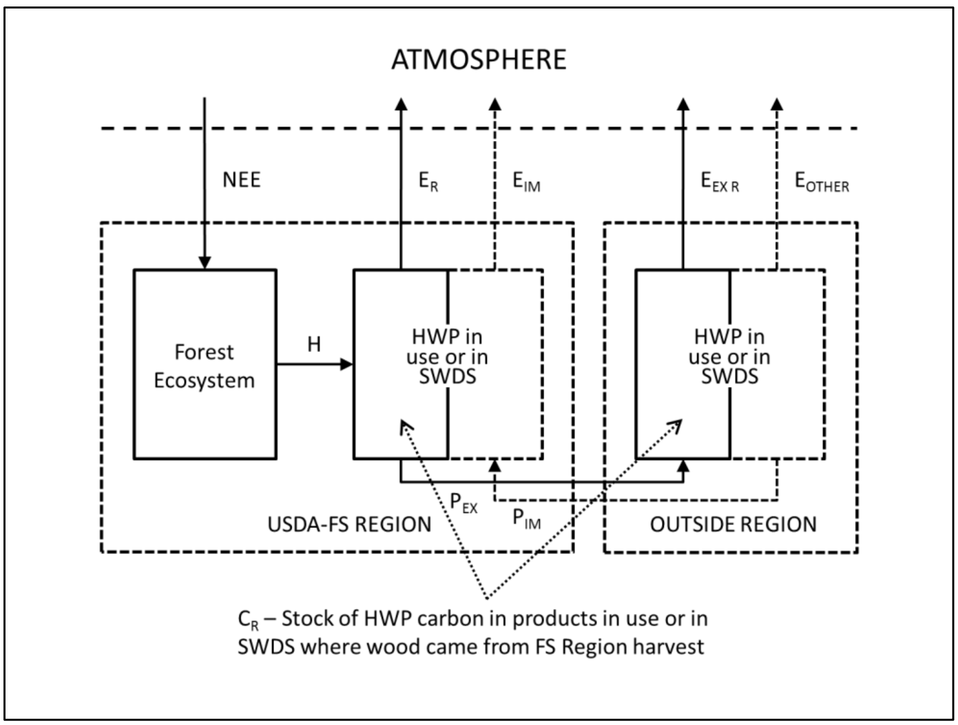

Figure 2. Carbon flows and stocks associated with forest ecosystems and harvested wood products (HWP) to illustrate the IPCC/EPA production accounting approach (adapted from Skog 2008).

Table 1. Variable definitions for the IPCC/EPA production accounting approach shown in Figure 2 (Skog 2008). Units for all variables are MgC yr^{-1}.

Variable	Definition
ΔS	Annual carbon stock change, which is calculated as $\Delta S=(NEE-H)+(\Delta C_{R1})$ in the production accounting approach.
NEE	Annual net ecosystem carbon exchange, the annual net carbon that moves from the atmosphere to forests.
H	Annual harvest of wood for products, which includes wood and residues removed from harvest sites, but excludes resides left at harvest sites.
HWP	Harvested wood products in use or at solid waste disposal sites.
E_R	Annual emission of carbon to the atmosphere in the Region from products made from wood harvested in the Region.
E_{IM}	Annual emission of carbon to the atmosphere in the Region from products made from wood harvested outside of the Region and imported into the Region.
P_{EX}	Annual exports of wood and paper products out of the Region, including roundwood, chips, residue, pulp and recovered (recycled) products.
P_{IM}	Annual imports of wood and paper products into the Region, including roundwood, chips, residue, pulp and recovered (recycled) products.
$E_{EX\ R}$	Annual emission of carbon to the atmosphere in areas outside of the Region from products made from wood harvested in the Region.
E_{OTHER}	Annual emission of carbon to the atmosphere in areas outside of the Region from products made from wood harvested outside the Region.
C_R	Stock of harvested wood products carbon in use or at solid waste disposal sites where products used wood from the Region.
$\Delta C_{IU\ R}$	Annual change in carbon stored in harvested wood products in use where products used wood from the Region.
$\Delta C_{SWDS\ R}$	Annual change in carbon stored in harvested wood products at solid waste disposal sites where products used wood from the Region.
ΔC_R	Annual change in carbon stored in harvested wood products in use and at solid waste disposal sites where products used wood from the Region.

System boundaries

Most people are familiar with imports and exports in the context of international trade, but the concept can be applied to understand the treatment of carbon imports and exports in the IPCC/EPA approach. In this case the terms export and import refer to the border of the Pacific Northwest Region. For example, HWP manufactured in a USFS Region may be used locally by consumers inside the Region or exported from the local area for use elsewhere. Similarly, HWP produced outside the Region may be imported for use within the Region. Figure 2 shows that carbon emissions attributed to HWP from the Region (indicated with solid boxes) include both emissions to the atmosphere from wood products harvested and used within the Region (E_R) and emissions to the atmosphere from wood products harvested in the Region that were exported outside the Region ($E_{EX\ R}$). Emissions (E_R and $E_{EX\ R}$) are further categorized as emitted with energy capture (e.g. fuelwood) and emitted without energy capture (e.g. decomposition and burning for waste disposal). Exports (P_{EX}) include wood and paper products, as well as roundwood, chips, residue, pulp and recovered (recycled) products from wood harvested in the Region. Under the IPCC/EPA approach, imports from elsewhere (indicated with dotted lines around the right side of both HWP boxes) are not included in regional accounting because the emphasis is on the location of harvest (H).

Additionally, this approach does not account for all emissions associated with HWP. For example, carbon emissions from fossil fuels used in harvest, transportation and manufacture of HWP are not deducted from the HWP pool. Similarly, although HWP emissions with energy capture are quantified in the IPCC/EPA approach, they are not assumed to substitute for an equivalent amount of fossil fuel carbon, potentially reducing fossil fuel emissions in some scenarios (Jones et al. 2010). Furthermore, this approach does not incorporate carbon fluxes associated with product substitution, such as the substitution of HWP for metal or concrete (or vice versa) in building applications, and the associated land use changes that may ensue.

Though these types of emissions tradeoffs are outside the scope and purpose of the approach applied in this report, there are well-developed methods of life cycle assessment (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). The IPCC/EPA approach provides information that can be used in an LCA, but in general an LCA is used to address different questions.

If management decisions require information about harvesting, transportation and processing emissions, product substitutions, or other trade components not included in the approach used here, a consequential LCA is appropriate. However, for sub-national carbon accounting, the IPCC/EPA approach has several benefits over LCA. It is relatively easy to apply and congruent with US national carbon accounting standards, which is particularly important in developing tools that can be used by USFS managers to meet carbon monitoring goals.

Computational Methods

Figure 3 provides a flow chart of the computational methods used to calculate annual stock changes and emissions from HWP for the IPCC/EPA production accounting approach. This approach does not apply simple storage ratios to the harvest; rather it tracks carbon through the product life cycle from harvest to timber products to primary wood products to end use to disposal, applying best estimates for product ratios and half-lives at each stage.

When possible, harvest records are used to distribute annual cut volumes among specific timber product classes (e.g., softwood ties, softwood sawlogs, softwood pulpwood, softwood poles, softwood fuel wood, softwood non-saw, etc.). For periods of time when timber product classes were not recorded, ratios available from a more recent time period were used. Timber products are further distributed to specific primary wood products (e.g. softwood lumber, softwood plywood, softwood mill residue used for non-structural panels, etc.) using default average primary product ratios from national level accounting that describe primary products output according to regional forest industry structure (Smith et al. 2006, Appendix A). Mill residues are included as primary wood products with some entering solid waste disposal immediately and some getting converted into products that rely on mill residues as raw material, such as particleboard and paper. The timber product to primary wood product ratios vary by region and in most cases the geography of the regions used in national level accounting does not match perfectly the boundaries of Forest Service administrative regions. Therefore, applying default ratios for part or all of the accounting time period requires some judgment in selecting the appropriate ratios and the ratios for national regions are sometimes modified. Primary wood product outputs are converted from their reporting units to MgC using standard conversion factors for primary wood products (Smith et al. 2006, Table 2). The ratios from Smith et al. (2006) are applied to the entire time period, but are adjusted with consideration of the timing of manufacturing capacity in each region.

The recalcitrance of carbon in HWP is highly dependent on the end use of those products. For example, carbon in lumber used in new single family home construction has a longer duration than carbon in lumber used for shipping containers, which is released into the atmosphere more quickly through combustion and decay. For years 1950 through 2012, annual primary wood product output was distributed to specific end uses according to annual wood product consumption estimates in McKeever (2009, 2011).

Table 2. Conversion factors used in this analysis.

Conversion	Units
1.9231	ccf per mbf, timber harvest prior to 2000[1]
33 to 42	lbs per cubic foot, primary products
2204.6	lbs per Mg
0.95 to 1.0	Mg wood fiber per Mg product
0.5	Mg carbon per dry Mg wood fiber
0.711 to 0.919	MgC per ccf, primary products

For each of the 203 different possible end uses from the Region's HWP (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.) for each vintage year, the amount of carbon remaining in use at each inventory year is calculated based on the product half-life and the number of years that have passed between the year of harvest and the inventory year. The half-life value expresses the decay rate at which carbon in the products in use category passes into the discarded category, representing the transition between the two pools. The carbon remaining in HWP in use in a given inventory year is calculated for each vintage year end use based on a standard decay formula:

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

where N_t is the amount of carbon remaining in use in inventory year t, N_0 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 8% to reflect a loss when placed in use, which is assumed to enter the discarded carbon category. 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), and this waste is immediately distributed to the discarded products category. Fuelwood products are assumed to have full emissions with energy capture in the year they were produced.

For carbon of a particular vintage in a given inventory year, the balance of carbon in HWP that is not in use and not emitted with energy capture is assumed to be in the discarded products category (Figure 3). Carbon in the discarded products category is partitioned into five disposition categories: burned, recovered, composted, landfills and dumps. The proportion of discarded products that ends up in each of these five categories is different for paper and solid wood products, and has changed over time. For example, prior to 1970 wood and paper waste was generally discarded to dumps, where it was subject to higher rates of decay than in modern landfills. Since then, the proportion of discarded wood going to dumps has dropped to below 2%, while the proportion going to landfills has risen to 67%, with the remainder going to the other disposition categories (Skog 2008). Similarly, composting and recovery (i.e. recycling and reuse) have become a more prominent part of waste management systems. In 2004, approximately 50% of paper waste was recovered, compared to 17% in 1960. The disposition of carbon in paper and solid wood products to these categories is based on percentages in Skog (2008).

Carbon from burned and composted discarded products is assumed to be emitted without energy capture. Carbon in the recovered category reenters the products in use category in the year of recovery. Carbon in products discarded to landfills and dumps are subject to decay determined by their respective half-lives. The half-life value for discarded products in dumps and landfills expresses the decay rates at which carbon in these categories is emitted to the atmosphere. However, our calculations consider the fact that only a fraction of the discarded products pool in landfills is considered to be subject to decay; 77% of solid wood carbon and 44% of paper carbon in landfills is identified as fixed carbon, not subject to decay (Skog 2008). For a given vintage year, the carbon remaining in SWDS in a given inventory year is the sum of fixed carbon and the carbon remaining after decay. We do not account for the difference between methane and CO_2 emissions from landfills in terms of CO_2 equivalents, nor do we account for methane remediation that includes combustion and subsequent emissions with energy capture. All landfill and dump emissions are considered emissions without energy capture.

[1] Both mbf and ccf are available in all timber harvest reports after 2000.

These methods were used to calculate annual gross stocks and gross emissions for all inventory years 1909 through 2012. Results for each inventory year were used to calculate net change in stocks of carbon in regional HWP products in use ($\Delta C_{IU\ R}$) and SWDS ($\Delta C_{SWDS\ R}$), as well as net change in emissions from SWDS and fuelwood (E_R).

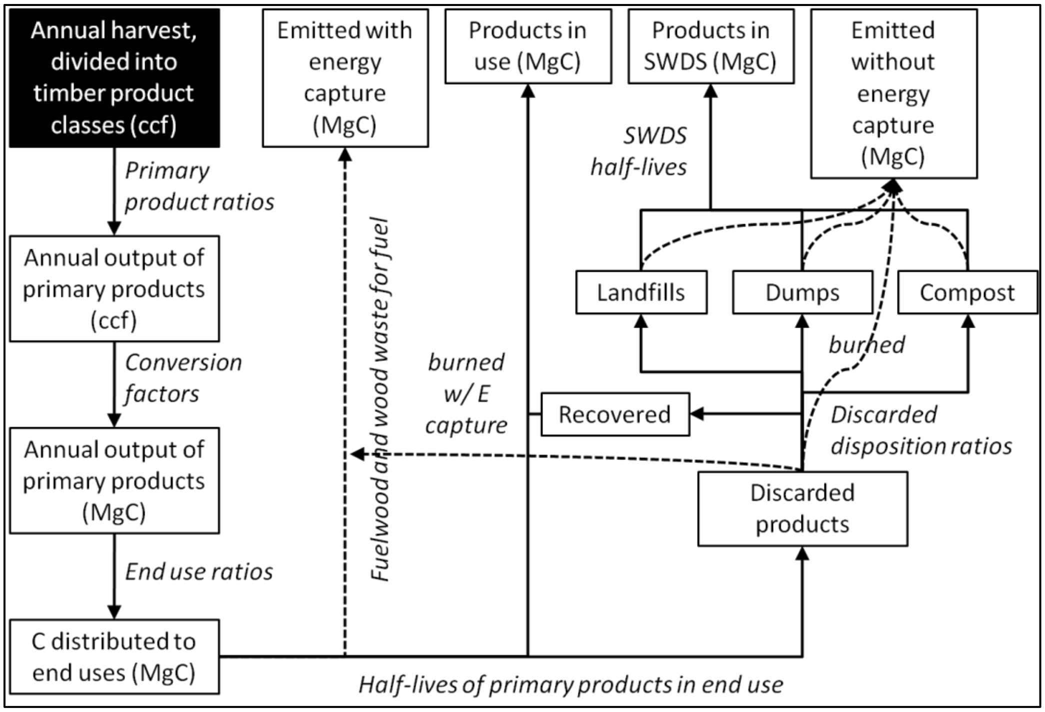

Figure 3. A schematic of calculations to quantify HWP storage and emissions. These calculations quantify HWP products in use, products in SWDS, emissions with energy capture, and emissions without energy capture using the IPCC/EPA approach.

Online Harvested Wood Products Carbon Accounting Tool

Calculations were facilitated by an online HWP carbon accounting tool developed by USFS and cooperators (USURS 2012). The tool requires two inputs: a harvest time series and a time series of timber product ratios that partition the harvest into different timber product classes, which are discussed in the following section. In addition, the user can enter primary product ratios if they are known, or use the default values from Smith et al. (2006). The option to input primary products ratios allows the user to more accurately reflect regional changes in industry structure and associated primary product manufacturing if desired. The user can also provide additional inputs to guide the Monte Carlo simulations that determine statistical confidence intervals, including random variable distributions and number of iterations, or use the default values provided. The latest version of the tool, with supporting documentation, can be found at: http://maps.gis.usu.edu/HWP.

Data Sources

Data quality impacts the uncertainty and reliability of our estimates, and the data used in this analysis provide a good illustration of the challenges associated with using historical data in carbon accounting. This section is divided into four parts: first we discuss historical timber harvest data acquisition and limitations, and how those limitations were addressed. Following that we describe how the data were allocated to timber products, how timber products were allocated to primary products and finally how we allocate primary products to end use products for all Regions. By standardizing boundaries and units and partitioning the harvest among different timber and primary product classes, we created a continuous dataset spanning 1909 through 2012 that meets the criteria for estimation established by the IPCC (2006).

Historical timber harvest data

Regional harvests have been reported in detailed cut-and-sold reports and are available online from 1977 to the present[2]. These reports include the value and volume of timber sold and harvested in the region, which are reported by both fiscal and calendar year. In addition, total harvests are partitioned by sale value, timber product class[3], tree species, and national forest within the Region. Records for annual harvest prior to 1977 are generally more difficult to obtain; however, annual harvest data from 1909 to present were supplied by the Pacific Northwest Regional Office. Throughout the harvest record, there were few periods when data were not available at either the national forest level or at the Region level, but no instances with concurrent voids in both harvest data sets. In instances when lands within current national forest boundaries were formerly within neighboring national forests, timber volumes were reapportioned based on available details but had no bearing on Regional harvest totals. All results in this report are based upon fiscal year harvest reports. Additionally, the span of fiscal years changed in 1976 to run from October 1 to the following September 30; timber harvested during the period from July 1 to September 30, 1976, known as the 'transition quarter' was removed from the analysis.

Because the model developed for this purpose requires cubic foot input metrics for harvested timber, conversion factors for specific timber products were used to convert volumes from thousand board feet (mbf) to hundred cubic feet (ccf) (Table 2). Beginning in 2001, harvested volumes have been reported in both mbf and ccf. Between 1909 and 2000 volumes were reported in mbf only. For this period annual harvest totals for Pacific Northwest Region were reported in mbf and converted to ccf using a conversion factor of 1.9231 ccf per mbf in use by the Region. No conversion was necessary for years 2000 and later since ccf is provided in the harvest data (Table 2).

There is new evidence that ccf per mbf conversion factors have changed in recent decades. For example, Keegan et al. (2010a) has found 23% and 19% increases in ccf per mbf conversions in Oregon and Washington, respectively, from 1970 to 2000s. This alone would suggest our conversions from mbf to ccf in earlier decades, overestimate the volume harvested. On the other hand, Keegan et al. (2010b) indicates that the utilization represented as cubic feet of green finished lumber per cubic foot of bole wood processed has increased during the same period, by roughly the same magnitude (Oregon 24%, Washington 16%). This would suggest our estimates of carbon volume moved into products in use was underestimated in earlier decades. Given that these two essentially cancel each other out and the fact that we did not have adequate data specific to wood cut from national forests across the entire period we chose not to incorporate this information into our calculations. However, analyses similar to those found in Keegan et al (2010a, 2010b) are not available for all USFS Regions. To accommodate this type of unknown variability over time, we provide an uncertainty analysis in this report, which is discussed below.

Historical timber product data

Pacific Northwest Region harvest records prior to 1950 do not partition the harvest among different timber product classes; they report only total annual harvest. To estimate the proportion of total Pacific Northwest Region harvest that went into each timber product class, we applied the average annual proportion of the harvest represented by each timber product class from 1951 through 2012 to the annual harvest for each year 1909 through 1950. Timber product classes of "convertible biomass" have been eliminated from 1909 to 1950 because these timber product classes have only been recorded since 1998 and account for less than 0.7% of the total yearly average harvest from 1951 to 2012 (Included in "Other" Table 3).

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[2] USFS 2013 (http://www.fs.fed.us/forestmanagement/products/sold-harvest/cut-sold.shtml)

[3] Many times the timber product classes predicted and recorded in cut sold reports are not actually the products classes that are used after harvest. This reality, in addition to the lack data for these ratios for the entire data period, explain why we include timber and primary product ratios in our uncertainty analysis.

Table 3. The average annual proportion of 1951 to 2012 Pacific Northwest Region harvests distributed to timber product classes between 1909 and 1950 (n=61yrs).

Product class	Mean	Std. Error
Sawtimber, softwood	0.85	0.013
Cull logs, softwood	0.05	0.005
Non-sawtimber, softwood	0.04	0.009
Fuel., softwood	0.04	0.006
Pulp, softwood	0.01	0.003
Other	0.02	0.003

Historical primary product data

The carbon in HWP from timber products to primary products is based upon intricate disposition connections from harvested timber products to primary products to end-uses found in Smith et al. (2006). Smith et al. used a footprint very similar to the Pacific Northwest Region, but split it into east and west zones at the Cascade Mountain Range. The tool we built to facilitate calculations for regional and national forest-level analyses provides defaults for both zones. However, our modeling for this report is based on aggregated harvest for the entire Region, instead of an aggregation of individual national forest. A Western Wood Processing Facilities Map (BBER 2013) indicates that the notable majority of mills and processing capacity in the Pacific Northwest Region exist west of the Cascade Range. This, in conjunction with the information about the majority of cut volume coming from national forests west of the cascade division supports our decision to use the Pacific Northwest west-zone for primary product ratios.

Historical end use data

The historical end use data used for the Pacific Northwest Region comes from McIver (2009 and 2011). This national data set is used for all NFS regions for the distribution of primary products to end uses for all regions, with no regional variation. Estimates for 1950 were used for 1909 through 1949 and estimates for 2009 were used for 1950 through 2012. We acknowledge that this is not ideal, but no other data are available for these periods. The annual end use wood product estimates are periodically updated, which could allow better HWP storage and flux estimates in the future.

Uncertainty analysis

Interpretation of the results should be made in light of some constraints. Though we attempted to normalize annual harvests to the modern boundary of the Region using forest-specific harvest data, in actuality the annual harvest is from a land base that is somewhat variable over time. The USFS has commonly engaged in land exchanges, divestments and acquisitions in the Regions since their origin, which means that the geographic boundary for Regions has not been consistent. In addition, conversion factors (which depend on average log size, mill technology and efficiency, etc.), distribution of timber products to primary products, and the distribution of primary products to end uses have changed over time. Though we have used annual data whenever possible, there is some uncertainty associated with applying averages to the early years of the harvest series.

Uncertainty is quantified using the methods described in Skog (2008). We identified the most critical sources of uncertainty in our analysis (Table 4), developed probability distributions (using expected ranges) for each of four major sources of uncertainty (conversion factors, reported harvest, product distribution variables, and product decay parameters), and carried out Monte Carlo simulations to determine the collective effect of uncertainty in these variables on estimates of HWP stocks. We did not explore the contribution of each variable in a sensitivity analysis, but instead address collective uncertainty. Further investigation into the level of uncertainty of each random variable and its effect on confidence intervals could help managers determine where to focus improvements in reporting to reduce uncertainty in carbon storage and flux estimates. Across all variables, sensitivity analyses could be used to identify variables that have the greatest impact on carbon storage and flux, and compare alternative levels of those variables associated with different scenarios of forest management and HWP production, use and disposition.

Table 4. Sources of uncertainty and range of the triangular distribution for each random variable used in the Monte Carlo simulation.

Source of Uncertainty	Range of distribution	Years
Reported harvest in ccf	±30%	start to 1945
	±20%	1946 to 1979
	±15%	1980 to end
Timber product ratios	±30%	start to 1945
	±20%	1946 to 1979
	±15%	1980 to end
Primary product ratios	±30%	start to 1945
	±20%	1946 to 1979
	±15%	1980 to end
Conversion factors, ccf to MgC	±5%	all years
End use product ratios	±15%	all years
Product half lives	±15%	all years
Discarded disposition ratios (paper)	±15%	all years
Discarded disposition ratios (wood)	±15%	all years
Landfill decay limits (paper)	±15%	all years
Landfill decay limits (wood)	±15%	all years
Landfill half-lives (paper)	±15%	all years
Landfill half-lives (wood)	±15%	all years
Dump half-lives (paper)	±15%	all years
Dump half-lives (wood)	±15%	all years
Recovered half-lives (paper)	±15%	all years
Recovered half-lives (wood)	±15%	all years
Burned with energy capture ratio	±15%	all years

Because we apply different distributions to different time periods for some variables, the 23 distributions cover 17 different variables. Multiple time-delineated distributions are used for reported harvest, primary products ratios, and end use ratios, with time periods separated at benchmark years related to data quality. The probability distributions of these random variables were developed based on estimates in Skog (2008) and on professional judgment, and are assumed to be triangular and symmetric. A triangular error distribution was selected because without additional empirical information, we reasonably assume the error distribution to be symmetric with greater likelihood of values being centered in between the limits of the distribution than at one or both of the limits of the distribution. In addition, we can reasonably assign values to the limits. The distributions are assumed to be independent of one another.

The effect of uncertainty in these variables on HWP carbon storage was evaluated using Monte Carlo simulation. For each simulation, a mean value and 90% confidence intervals are the results of 3,000 iterations performed to reach a stable standard deviation in the mean (Stockmann et al. 2012). In each iteration, HWP carbon stocks are calculated using values for variables drawn at random from the established distributions. Using thousands of draws, we produce a simulation mean and a distribution of values that can be used to establish the confidence intervals shown in the tables. These confidence intervals show the range of values in which 90% of all values are expected to fall.

Results for the Pacific Northwest Region

From 1909 to 1930 the annual timber harvest in the Region remained below 0.75 million MgC yr^{-1}. This was followed by a harvesting decrease during the Great Depression in the 1930's, when levels decreased 75% from the 1930 harvest and from 1934 onward harvests grew slowly (Table 5, Figure 4). World War II invigorated harvests further, up to 2.1 million MgC by 1944. Harvests receded during a two-year term following World War II falling to 1.4 million MgC in 1946 before beginning a rapid rate of increase in the 1960's and 1970's, peaking in 1973 at 8.3 million MgC. This was followed by a decade of prevailing declines in harvests, falling to 3.2 million MgC in 1982. Thereafter, harvests immediately rose sharply to roughly the same level as the previous 2 decades, with 8.1 million MgC in 1987. The years 1989 and 1990 showed a minor decline that foreshadowed large harvest declines of the early 1990s. Harvest fell to 1.1 million MgC by 1997 and to the lowest since the 1930s of 0.45 million MgC by 2001 and harvests have remained below 1 million MgC since. However, since 2006 harvests have been slowly increasing (Table 5, Figure 4).

Table 5. Annual timber product output in the Pacific Northwest Region for selected years using the IPCC/EPA production accounting approach. This table shows carbon removed from the ecosystem by harvesting.

Harvest year	Harvest (ccf)	Timber product output (MgC)
1910	93,420	69,027
1920	397,080	293,397
1930	981,760	725,410
1940	1,280,159	945,893
1950	2,899,266	2,142,230
1960	8,185,888	6,062,528
1970	9,335,658	6,920,681
1980	6,978,425	5,169,153
1990	7,460,202	5,529,212
1995	1,653,456	1,225,562
2000	786,847	582,830
2005	924,534	684,763
2006	734,365	543,881
2007	812,140	601,385
2008	801,809	593,940
2009	822,896	611,011
2010	983,019	728,598
2011	1,084,648	803,430
2012	1,157,713	857,604

The cumulative carbon stored in the Pacific Northwest Region HWP peaked in 1994 at approximately 144 million MgC (Figure 5, Table 6, Appendix B). For reference, this is equivalent to 528 million $MgCO_2$ or the CO_2 equivalent annual emissions from 101 million passenger vehicles, 1,227 million barrels of oil, or 2.75 million railcars of coal. Since 1994, carbon stocks in the HWP pool for the Region have been in a slow decline as a consequence of harvest reductions from national forests. By 2012, the HWP pool had fallen to around 131 million MgC, levels not seen since the 1980s (Figure 5, Table 6).

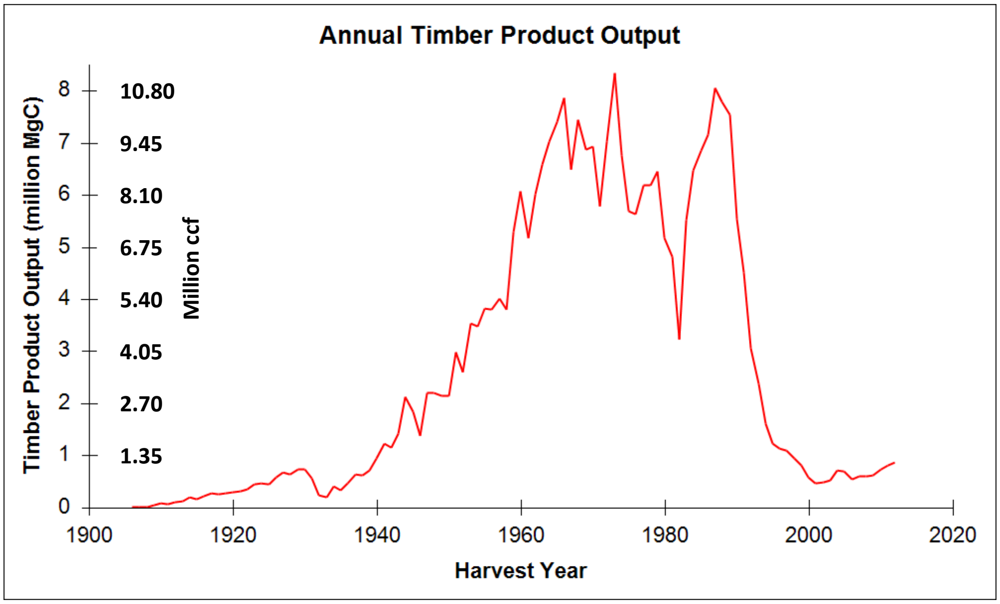

Figure 4. Annual timber product output in the Pacific Northwest Region, 1909 to 2012. Harvest estimates are based on data collected from USDA Forest Service Archives and Cut/Sold reports.

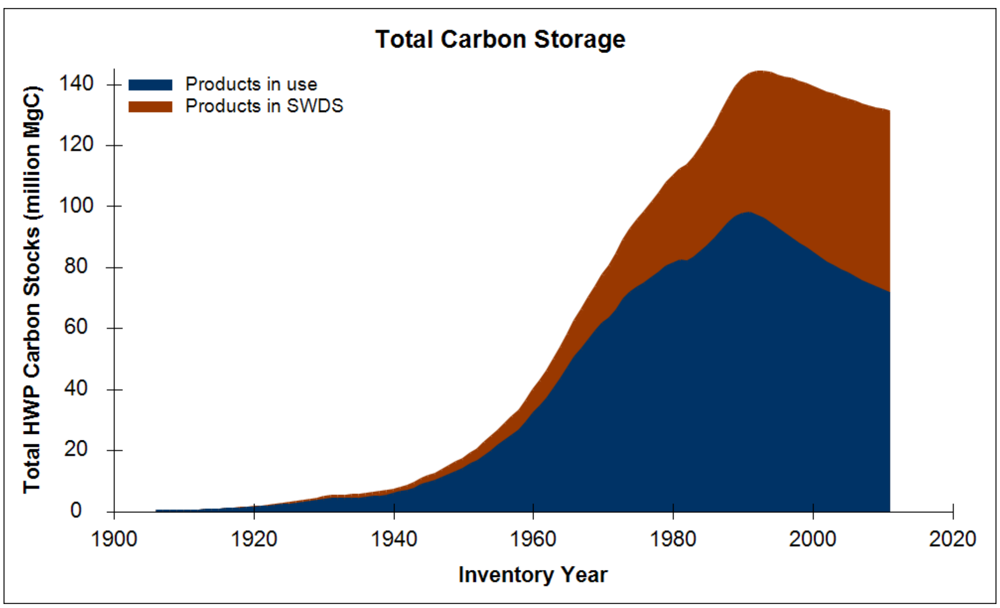

Figure 5. Cumulative total carbon stored in HWP manufactured from Pacific Northwest Region timber using the IPCC/EPA approach. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposal sites (SWDS), including landfills and dumps.

All else being equal, higher harvest levels result in more carbon removed from the ecosystem pool and added to the HWP pool (Figure 2). Figure 5 shows the cumulative carbon in both products in use and SWDS components of the HWP pool for the Region. Based on the years that match the most recent EPA report (US EPA 2012), Table 6 shows how the disposition of HWP carbon is broken into the four IPCC/EPA categories: emitted with energy capture, emitted without energy capture, products in use and products in SWDS. For each inventory year shown in the first column, the second column shows aggregate carbon emitted with energy capture (i.e. fuelwood), the third column shows aggregate carbon emitted through decay or combustion from SWDS, and the fourth and fifth columns show carbon stored in products in use and products in SWDS, respectively. The final column, the "Total in HWP pool," is the sum of products in use and carbon in SWDS. Note that the estimate for each inventory year includes the portion of HWP carbon still in use and in SWDS for all previous harvest years back to 1909 in addition to carbon harvested in the inventory year. Some of the cumulative emissions from the burned and decayed HWP (Table 6, second and third columns) are theoretically taken out of the atmosphere by regrowth on harvested sites, but this effect is accounted for in the ecosystem carbon component (NEE) of the change in carbon stock equation., not in the HWP component (H and ΔC_R).

Table 6. Cumulative disposition of Pacific Northwest Region HWP carbon for selected years using the IPCC/EPA production accounting approach. This table shows the fate of all carbon removed from the ecosystem by harvesting.

(1) Inventory year	(2) Emitted with energy capture	(3) Emitted without energy capture	(4) Products in use	(5) SWDS	(6) Total in HWP Pool[a]
	(MgC)				
1910	12,117	782	30,992	-	30,992
1920	457,760	113,882	977,603	138,648	1,116,251
1930	1,759,012	674,926	3,403,606	680,134	4,083,740
1940	3,036,403	1,839,797	5,007,849	1,434,392	6,442,241
1950	7,426,840	4,270,982	12,833,517	3,097,666	15,931,183
1960	16,593,181	9,860,101	28,878,679	7,194,053	36,072,732
1970	32,918,241	22,008,529	58,840,978	14,872,180	73,713,158
1980	48,097,367	37,564,346	80,171,099	27,200,560	107,371,659
1990	64,371,327	51,570,990	96,484,408	42,504,151	138,988,559
1995	69,083,599	60,285,482	94,131,891	49,307,148	143,439,039
2000	70,470,230	68,012,239	86,205,644	53,843,765	140,049,409
2005	71,292,642	74,858,282	78,900,865	56,638,264	135,539,129
2006	71,499,021	76,106,209	77,720,296	57,091,148	134,811,444
2007	71,663,610	77,314,787	76,498,953	57,527,902	134,026,855
2008	71,843,662	78,486,742	75,367,695	57,946,266	133,313,962
2009	72,034,679	79,623,232	74,264,432	58,352,139	132,616,571
2010	72,226,278	80,726,405	73,219,350	58,745,420	131,964,770
2011	72,441,011	81,799,410	72,300,859	59,129,036	131,429,895
2012	72,686,903	82,844,359	71,454,825	59,508,549	130,963,373
2013	72,946,190	83,863,701	70,675,030	59,884,830	130,559,859

[a] Sum of Products in use and SWDS.

Figure 6 and Table 7 present the trend in terms of net annual change in HWP carbon stocks. Negative net annual change in HWP carbon stocks values in Figure 6 mean that total carbon stored in the HWP pool in the inventory year is lower than in the previous year. In other words, a decline in the HWP pool (as seen in Figure 5) results in a transition from a positive net annual change in carbon stocks to a negative net annual change in carbon stocks in Figure 6. Beginning in the late 1940s carbon stocks in HWP were growing by over 1 million MgC yr^{-1}; peak stock growth occurred in 1974 with the addition of slightly less than 4.75 million MgC. In the mid-1990's, the net change moved from positive to negative, and since then the Pacific Northwest HWP pool has become a net source of atmospheric carbon. The year with the largest negative net change from the Pacific Northwest Region HWP carbon pool was 2002, when stocks decreased by just over 1 million MgC. However, since 2007 additions to the HWP through new harvest have grown faster than emissions from the HWP pool. Recall that these estimates relate only to HWP and do not quantify carbon fluxes in the ecosystem pool.

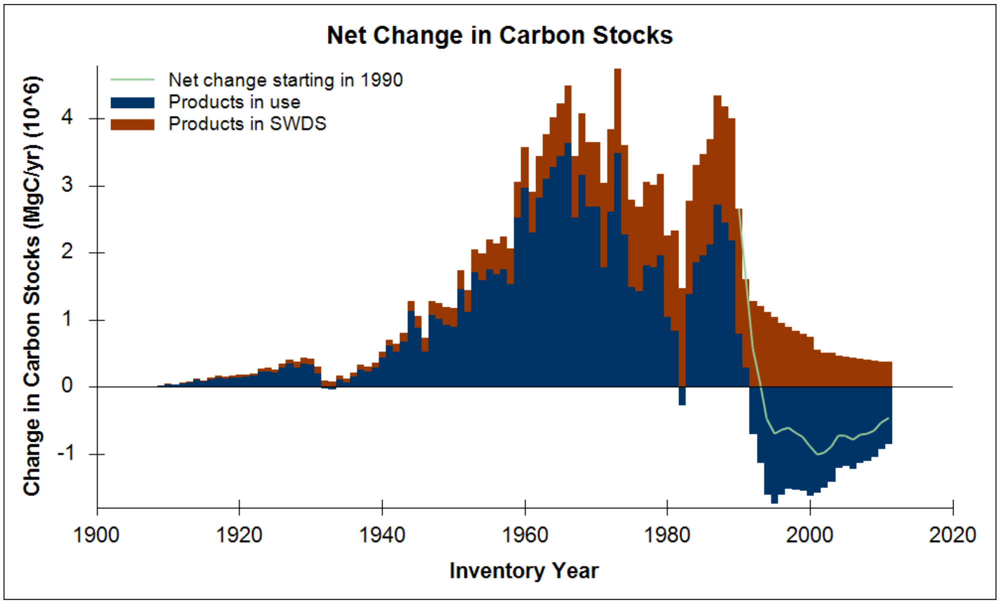

Figure 6. The net change in carbon stocks in HWP from the previous year using the IPCC/EPA production accounting approach. The net stock change is the sum of net change for SWDS and products in use. The total net change trend line shows a transition from net additions to carbon stocks in HWP to a period of net loss in HWP.

Table 7. Annual net change in HWP carbon stocks for selected years for harvests.

Inventory Year	Stock change[a] (MgC yr^{-1})
1910	30,992
1920	173,214
1930	433,379
1940	370,012
1950	1,189,886
1960	3,068,399
1970	3,650,361
1980	3,175,506
1990	4,008,126
1995	-473,944
2000	-748,307
2005	-737,871
2006	-727,685
2007	-784,589
2008	-712,893
2009	-697,391
2010	-651,801
2011	-534,875
2012	-466,522
2013	-403,514

[a]Net annual change in C in products in use and SWDS.

To quantify uncertainty, confidence intervals were estimated for HWP stock estimates using Monte Carlo simulation, representing 18 random variable distributions, with distributions determined from publications and expert opinion. Table 8 shows the resulting confidence intervals for the IPCC/EPA estimates for selected years. For 1995, the year of peak carbon stocks in Table 8, the 90% confidence interval ranges from 143,263,436 MgC to 143,423,563 MgC, with a mean value of 143,343,500 MgC. This is equivalent to a ±0.06% difference from the mean.

Table 8. Confidence intervals for cumulative carbon in HWP for selected years for harvests beginning in 1910 using the IPCC/EPA production accounting approach. Means and confidence intervals were calculated using Monte Carlo simulation (3,000 iterations).

Inventory year	Simulation Mean (MgC)	90% Confidence interval Lower limit (MgC)	Upper limit (MgC)
1910	31,092	30,973	31,210
1920	1,118,800	1,117,312	1,120,287
1930	4,093,311	4,088,793	4,097,829
1940	6,459,954	6,453,999	6,465,908
1950	15,987,116	15,973,344	16,000,889
1960	36,119,950	36,093,452	36,146,449
1970	73,717,506	73,666,543	73,768,469
1980	107,294,394	107,226,173	107,362,615
1990	138,899,539	138,820,659	138,978,420
1995	143,343,500	143,263,436	143,423,563
2000	139,955,865	139,876,951	140,034,779
2005	135,445,580	135,367,737	135,523,423
2006	134,719,081	134,641,338	134,796,823
2007	133,934,274	133,856,605	134,011,944
2008	133,221,772	133,144,185	133,299,360
2009	132,525,019	132,447,470	132,602,568
2010	131,873,807	131,796,282	131,951,332
2011	131,339,883	131,262,348	131,417,417
2012	130,873,955	130,796,380	130,951,531
2013	130,470,976	130,393,318	130,548,634

Discussion of Regional-level Estimates

National context

Although these results rely on numerous calculations, the time series of annual harvest volume (Figure 4) is at the root of the trends in carbon stocks and flux for the regional HWP pool. Several recent publications help put these HWP carbon estimates in the context of the total forest carbon, including both ecosystem carbon and HWP carbon (Heath et al. 2011, US EPA 2012). By dividing the 2005 HWP stock estimate of 135.5 teragrams of carbon (TgC) presented in Table 6 by the sum of this stock estimate and Heath et al.'s (2011) estimated 2005[4] Pacific Northwest Region ecosystem carbon stock of 2,493 TgC, we estimate that the Pacific Northwest Region HWP carbon stocks represent roughly 5.2% of total forest carbon storage associated with national forests in the Pacific Northwest Region as of 2005. At the national level, based on the EPA's total US HWP 2005 stock estimate of 2,354 TgC (US EPA 2012), the Pacific Northwest Region HWP carbon stocks represented 5.8% of total US HWP carbon stocks.

Estimates of forest ecosystem flux in the western US exist (Healey et al. 2009, Heath et al. 2011, Van Deusen and Heath 2007) and others in development. However, long-term data collection requirements will delay reporting until the USFS Forest Inventory and Analysis Program completes its second cycle of plot measurements. However, our calculations of HWP carbon flux will allow the Pacific Northwest Region to reasonably account for carbon that was

[4] Mean measurement year reported as 2005.2.

harvested from national forests over the study period. Ideally, when changes in forest ecosystem carbon are quantified in subsequent research they can be linked with the HWP estimates described here.

Applications of this approach by forest managers

The methods presented here for estimating the HWP carbon pool will allow resource managers and the public to develop a more complete understanding of the dynamics of HWP as a component of total forest carbon pool, and may allow the evaluation of the effect of alternative harvesting intensities on carbon stocks and fluxes. Furthermore, a benefit may be realized by evaluating the feasibility, utility, uncertainty, and limitations of the metrics and estimation methods that could be used to meet carbon monitoring objectives.

The IPCC/EPA approach requires harvest information for many prior years to make an estimate of net change to carbon stocks each inventory year over time. We recommend that all applications of the IPCC/EPA approach consider the quality of the data and adjust their uncertainty analysis accordingly, particularly with regards to the distributions of random variables (e.g. Table 4). However, though carbon of older vintages may be associated with higher uncertainty, it is also likely to have a smaller impact on current stocks and fluxes than more recent harvests. For example, the importance of the early harvests for the Northern Region – which spans northern Idaho, Montana, North Dakota, South Dakota, and eastern Washington – was estimated by Stockmann et al. (2012) by quantifying the portion of the current HWP pool that is attributable to carbon harvested prior to 1950. In 1950 the Northern Region HWP carbon pool was 4.5 million MgC. By inventory year 2010, only 1.7 million MgC of the carbon harvested before 1950 remained in products in use and SWDS, which accounted for 6.6% of the total stocks of 25.8 million MgC in 2010. Although we do not provide a similar estimate for the Pacific Northwest Region, we believe the same trend is likely to hold for most regions. This small contribution to current stocks is a result of two factors. First, there was greater harvesting activity for the period after than before 1950. Second, following the passage of the Resource Conservation and Recovery Act of 1976 (RCRA, 42 USC 6901) and after a short lag, a much larger portion of discarded HWP goes into modern landfills where it is subject to lower rates of decay than in aerobic dumps or disposal by open burning, which were the dominant disposal methods prior to RCRA.

Obtaining historical information may present a challenge for some National Forests. It may be particularly difficult to reconstruct harvest data prior to the mid-1940s, though regression of trends after the period might be appropriate for extrapolation to earlier periods. Alternatively, regions could base their carbon accounting on national level parameters, making the assumption that national-level numbers are adequate for regional and sub-regional analysis. If national level values represent the best available data, the IPCC/EPA method requires only harvest volume information from the user. Many regional and forest type-specific default dynamics and decay functions are supplied by national level efforts (Skog 2008, Smith et al. 2006). The simplicity associated with using national data in calculations may make the system functional and effective in meeting monitoring needs for forest managers both within and outside the USFS, regardless of data quality. If superior information exists for smaller scale units, it may be possible to substitute these ratios and conversion factors into the modeling effort. However, one needs to be mindful that the results of tailored analyses might not match up with results across the country and NFS. This could be a source of interesting future research.

We successfully applied the methods described by Skog (2008) to estimate the uncertainty associated with our HWP carbon stock estimates (Table 8). However, it is unclear how the magnitude of this uncertainty would change, if at all, if the analysis were done on smaller management units (e.g. the individual National Forest level). The change in uncertainty would, in large part, depend on assumptions made about the distributions of random variables used in the analysis. In some cases, a regional analysis may be sufficient to inform forest-level land management planning, forest management practices, and planning of long-term (programmatic) timber harvest levels and associated effects on carbon flux. A detailed sub-regional analysis may be needed where there are significant within-region differences in ecosystems and disturbance processes and harvest levels (e.g., western Washington compared to eastern Washington).

Conclusions

HWP is an important carbon pool that should be considered in decision making associated with carbon monitoring and climate change adaptation and mitigation. However, as $\Delta S = (NEE - H) + (\Delta C_R)$ shows, total forest carbon is a function of both HWP and ecosystem carbon, which may have increased over the study period. This report fits into a larger effort to address this entire system, the Forest Carbon Management Framework, which is currently under development. Together with accounting and modeling methods that quantify ecosystem forest carbon, the approaches used in this study provide a powerful tool to monitor carbon stocks, stock change, as well as the ability to assess the possible outcomes of management actions intended to reduce the vulnerability of forest resources to climate change.

Though our analysis is at the Regional level, we provide a framework by which the IPCC/EPA method can be applied broadly at other administrative units and forests to estimate harvest (H) and the resulting change in HWP carbon stocks for the region (ΔC_R). We estimated ΔC_R each year by summing our estimates for the change of carbon stored in products in use from wood harvested in the region ($\Delta C_{IU\ R}$) and the change of carbon stored in solid waste disposal systems from wood harvested in the region ($\Delta C_{SWDS\ R}$). Although we did not have access to detailed recent information about wood harvest in agency cut-and-sold reports, we were fortunate to have archived historic harvest volume records. As expected, records for the partitioning of the harvest to timber and primary product classes improved markedly as our records approached the present time. Although we applied timber product distributions, primary product distributions, and end use product distributions from the more recent years to earlier years of harvest and we made adjustments to primary product distributions to reflect the manufacturing onset for several primary product classes based on historical information, in general we had a strong set of historical data to use in our calculations.

The Pacific Northwest Region HWP pool is now in a period of negative net annual stock because the decay of products harvested between 1909 and 2012 exceeds additions of carbon to the HWP pool through harvest (Tables 6 and 7). The IPCC/EPA production accounting approach is data intensive because it includes past harvest and product disposition data for each inventory year, but it provides estimates of total stocks and stock change making it congruent with national accounting and reporting protocols.

The IPCC/EPA approach could be used to predict changes to the HWP component of the forest carbon pool resulting from planned or potential change in the amount of wood harvested. Quantifying uncertainty is an important component regardless of the analytical approach used because it quantifies the confidence we have in estimates of carbon stocks. We believe further research is necessary to help policy makers and managers better understand the implications of alternative forest management strategies on forest carbon stocks and stock change. An integrated approach might include consequential LCA that evaluates changes in harvest activity on carbon emissions including all sources of emissions and product substitutions.

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Appendix A

Distribution of timber products to primary wood products for regions of the US (Smith et al. 2006).

Table D6.—Fraction of each classification of industrial roundwood according to category as allocated to primary wood products (based on data from 2002)[a]

Region	Category[b] SW/HW	Category[b] SL/PW	Softwood lumber	Hardwood lumber	Softwood plywood	Hardwood plywood[c]	Oriented strandboard	Non-structural panels	Other industrial products	Wood pulp	Fuel and other emissions
Northeast	SW	SL	0.391	0	0.004	0	0	0.020	0.083	0.072	0.431
		PW	0	0	0	0	0.010	0.016	0	0.487	0.487
	HW	SL	0	0.492	0	0.005	0	0.022	0.038	0.058	0.386
		PW	0	0	0	0	0.293	0.007	0	0.350	0.350
North Central	SW	SL	0.378	0	0	0	0	0.049	0.120	0.084	0.370
		PW	0	0	0	0	0.020	0.009	0	0.486	0.486
	HW	SL	0	0.458	0	0.006	0	0.013	0.044	0.064	0.415
		PW	0	0	0	0	0.361	0.009	0	0.315	0.315
Pacific Northwest, East	SW	All	0.422	0	0.069	0	0	0.001	0.001	0.144	0.363
Pacific Northwest, West	SW	SL	0.455	0	0.089	0	0	0.009	0.073	0.114	0.260
		PW	0	0	0	0	0	0	0	0.500	0.500
	HW	All	0	0.160	0	0.140	0	0.002	0	0.229	0.469
Pacific Southwest	SW	All	0.454	0	0	0	0	0.040	0.036	0.145	0.325
Rocky Mountain	SW	All	0.402	0	0.054	0	0	0.033	0.062	0.153	0.296
Southeast	SW	SL	0.350	0	0.076	0	0	0.027	0.054	0.129	0.364
		PW	0	0	0	0	0.103	0.004	0	0.447	0.447
	HW	SL	0	0.455	0	0.006	0	0.049	0.012	0.087	0.391
		PW	0	0	0	0	0.180	0.002	0	0.409	0.409
South Central	SW	SL	0.324	0	0.130	0	0	0.019	0.023	0.133	0.371
		PW	0	0	0	0	0.135	0.006	0	0.430	0.430
	HW	SL	0	0.434	0	0.023	0	0.025	0.003	0.102	0.413
		PW	0	0	0	0	0.160	0.001	0	0.419	0.419
West[d]	HW	All	0	0.039	0	0.301	0	0.015	0.066	0.147	0.432

[a]Data based on Adams and others (2006).

[b]SW/HW=Softwood/Hardwood, SL/PW=Saw log/Pulpwood. Saw log includes veneer logs.

[c]Hardwood plywood fractions are pooled with nonstructural panels when allocating roundwood to the primary products listed in Tables 8 and 9.

[d]West includes hardwoods in Pacific Northwest, East; Pacific Southwest; Rocky Mountain, North; and Rocky Mountain, South.

Appendix B

Disposition of HWP carbon for all years. This table shows the fate of all carbon removed from the ecosystem by harvesting.

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1910	12,117	782	30,992	-	30,992
1911	30,377	2,628	75,699	1,824	77,523
1912	48,233	5,454	116,656	5,821	122,476
1913	73,219	9,714	173,580	11,366	184,946
1914	103,676	15,683	241,352	19,204	260,556
1915	153,928	24,569	356,124	29,553	385,676
1916	193,841	35,499	438,013	44,764	482,777
1917	249,550	49,554	556,440	61,924	618,364
1918	319,196	67,449	704,478	83,136	787,614
1919	384,438	88,723	833,667	109,370	943,037
1920	457,760	113,882	977,603	138,648	1,116,251
1921	535,374	143,063	1,125,928	171,568	1,297,496
1922	616,235	176,366	1,276,003	207,835	1,483,837
1923	706,155	214,266	1,442,863	247,108	1,689,971
1924	825,118	258,472	1,676,799	290,003	1,966,802
1925	949,256	308,958	1,912,742	339,914	2,252,656
1926	1,067,494	365,194	2,122,855	395,598	2,518,453
1927	1,219,749	429,316	2,411,432	454,762	2,866,194
1928	1,399,061	502,632	2,755,915	521,774	3,277,689
1929	1,565,779	583,943	3,051,963	598,397	3,650,361
1930	1,759,012	674,926	3,403,606	680,134	4,083,740
1931	1,950,909	775,080	3,736,486	769,931	4,506,417
1932	2,098,154	881,359	3,941,725	865,300	4,807,025
1933	2,157,276	988,304	3,916,855	958,170	4,875,025
1934	2,206,319	1,095,897	3,876,077	1,036,307	4,912,384
1935	2,311,471	1,207,696	3,988,294	1,102,506	5,090,800
1936	2,398,173	1,321,873	4,051,703	1,167,736	5,219,439
1937	2,520,008	1,440,762	4,206,325	1,228,363	5,434,688
1938	2,687,828	1,566,912	4,473,634	1,290,715	5,764,350
1939	2,848,901	1,699,369	4,711,648	1,360,581	6,072,229
1940	3,036,403	1,839,797	5,007,849	1,434,392	6,442,241
1941	3,286,625	1,994,394	5,451,765	1,515,138	6,966,903
1942	3,610,939	2,164,657	6,063,645	1,608,038	7,671,683
1943	3,914,311	2,348,227	6,590,940	1,722,159	8,313,099
1944	4,287,613	2,549,706	7,273,555	1,848,555	9,122,110

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1945	4,849,185	2,780,659	8,405,383	1,995,112	10,400,495
1946	5,334,366	3,033,714	9,282,358	2,184,261	11,466,619
1947	5,698,926	3,301,086	9,811,712	2,392,503	12,204,215
1948	6,282,429	3,598,121	10,886,303	2,598,710	13,485,013
1949	6,863,274	3,921,986	11,903,896	2,837,400	14,741,296
1950	7,426,840	4,270,982	12,833,517	3,097,666	15,931,183
1951	7,993,536	4,644,896	13,735,022	3,372,012	17,107,034
1952	8,758,829	5,057,283	15,189,461	3,658,869	18,848,330
1953	9,428,016	5,499,244	16,306,523	3,989,395	20,295,918
1954	10,339,812	5,987,389	18,015,210	4,337,223	22,352,432
1955	11,240,400	6,517,831	19,612,115	4,736,137	24,348,252
1956	12,228,459	7,093,943	21,374,244	5,169,768	26,544,012
1957	13,214,400	7,712,657	23,050,743	5,639,710	28,690,453
1958	14,257,667	8,378,560	24,804,571	6,133,400	30,937,971
1959	15,250,133	9,085,808	26,347,039	6,657,294	33,004,333
1960	16,593,181	9,860,101	28,878,679	7,194,053	36,072,732
1961	18,120,536	10,725,223	31,849,615	7,799,476	39,649,091
1962	19,391,228	11,655,795	34,162,539	8,397,104	42,559,644
1963	20,865,881	12,664,718	36,981,950	9,017,370	45,999,320
1964	22,482,176	13,754,664	40,084,828	9,693,380	49,778,208
1965	24,213,839	14,927,435	43,373,876	10,428,094	53,801,971
1966	26,015,753	16,187,651	46,818,516	11,220,432	58,038,948
1967	27,922,111	17,538,568	50,462,694	12,074,838	62,537,532
1968	29,510,252	18,952,573	52,985,445	12,992,160	65,977,605
1969	31,297,486	20,448,589	56,153,792	13,909,005	70,062,798
1970	32,918,241	22,008,529	58,840,978	14,872,180	73,713,158
1971	34,507,227	23,367,758	61,526,688	15,841,251	77,367,939
1972	35,844,084	24,765,643	63,311,174	17,105,731	80,416,905
1973	37,500,684	26,215,552	65,925,807	18,340,846	84,266,653
1974	39,468,279	27,728,800	69,409,359	19,606,850	89,016,209
1975	41,034,472	29,283,903	71,687,909	20,941,448	92,629,357
1976	42,350,593	30,872,108	73,173,381	22,253,976	95,427,357
1977	43,667,837	32,492,754	74,600,571	23,520,574	98,121,145
1978	45,115,019	34,149,988	76,421,894	24,755,534	101,177,428
1979	46,576,251	35,839,321	78,209,825	25,986,327	104,196,153
1980	48,097,367	37,564,346	80,171,099	27,200,560	107,371,659
1981	49,290,153	38,958,183	81,219,032	28,414,663	109,633,695
1982	50,412,918	40,352,207	82,054,643	29,915,663	111,970,306

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1983	51,154,483	41,735,875	81,784,263	31,391,731	113,175,994
1984	52,456,619	43,120,019	83,174,757	32,776,430	115,951,187
1985	54,168,388	44,504,573	85,036,549	34,223,938	119,260,487
1986	56,106,366	45,891,687	87,000,157	35,735,639	122,735,796
1987	58,088,889	47,286,771	89,133,443	37,302,373	126,435,815
1988	60,260,380	48,697,533	91,847,514	38,940,814	130,788,327
1989	62,337,748	50,125,310	94,294,631	40,685,803	134,980,434
1990	64,371,327	51,570,990	96,484,408	42,504,151	138,988,559
1991	65,819,805	53,323,683	97,282,517	44,369,749	141,652,265
1992	67,033,204	55,093,804	97,569,643	45,692,091	143,261,734
1993	67,872,272	56,854,389	96,860,819	46,975,420	143,836,239
1994	68,563,480	58,589,572	95,732,115	48,180,868	143,912,983
1995	69,083,599	60,285,482	94,131,891	49,307,148	143,439,039
1996	69,487,010	61,934,286	92,394,823	50,346,706	142,741,529
1997	69,769,881	63,534,297	90,786,353	51,306,247	142,092,600
1998	70,034,749	65,081,297	89,273,887	52,207,410	141,481,297
1999	70,261,992	66,574,000	87,746,266	53,051,450	140,797,716
2000	70,470,230	68,012,239	86,205,644	53,843,765	140,049,409
2001	70,631,385	69,472,124	84,586,206	54,587,642	139,173,848
2002	70,764,889	70,888,337	83,008,516	55,146,012	138,154,528
2003	70,920,231	72,242,770	81,511,298	55,663,595	137,174,893
2004	71,084,092	73,570,634	80,105,198	56,171,802	136,277,000
2005	71,292,642	74,858,282	78,900,865	56,638,264	135,539,129
2006	71,499,021	76,106,209	77,720,296	57,091,148	134,811,444
2007	71,663,610	77,314,787	76,498,953	57,527,902	134,026,855
2008	71,843,662	78,486,742	75,367,695	57,946,266	133,313,962
2009	72,034,679	79,623,232	74,264,432	58,352,139	132,616,571
2010	72,226,278	80,726,405	73,219,350	58,745,420	131,964,770
2011	72,441,011	81,799,410	72,300,859	59,129,036	131,429,895
2012	72,686,903	82,844,359	71,454,825	59,508,549	130,963,373
2013	72,946,190	83,863,701	70,675,030	59,884,830	130,559,859