Estimates of carbon stored in harvested wood products from United States Forest Service Intermountain Region, 1911-2012

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April, 2014

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 1911 to 2012 for the USFS Intermountain Region. For the Intermountain Region as a whole, carbon stocks in the HWP pool were increasing at approximately 200,000 megagrams of carbon (MgC) per year in the late 1950s through the early 1990s, with peak cumulative storage of 9.8 million MgC occurring in 1999. Net positive flux into the HWP pool over this period is primarily attributable to high harvest levels in the early1950s through the 1990s. In the years between the mid-1960s and 1990 timber harvests were at high, volatile levels, with high harvests of over 850,000 ccf (620,000 MgC) occurring five times during this period. Harvest levels from National Forests of the Intermountain Region have since declined to less than 200,000 ccf (160,000 MgC) per year, resulting in less carbon entering the HWP pool. Since 2001, emissions from HWP at solid waste disposal sites exceeded additions from harvesting, resulting in a decline in the total amount of carbon stored in the HWP pool. The Intermountain Region's HWP pool is now in a period of negative net annual stock change because the decay of products harvested between 1911 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 Intermountain 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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Acknowledgements

The authors wish to acknowledge funding from the USFS Climate Change Office, Office of Forest Management, and the Rocky Mountain Research Station and Forest Inventory and Analysis. The authors thank Carin Clay, National Forest Service Library and U.S. West Research, Inc. for providing critical data.

Cover: Scaling logs on the Hallack and Howard Timber Sale on Boise National Forest, September 1, 1938. Photo courtesy of W. H. Shaffer (http://fsweb.r4.fs.fed.us/e/slides/BW402-1/IMG0038.jpg).

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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 Intermountain 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 US Forest Service Intermountain Region currently administers approximately 31.9 million acres of National Forest fragmented across six states located in and around the Great Basin, representing approximately 16.9% of total US National Forest System lands (USFS 2012). The Intermountain Region includes the Ashley, Boise, Bridger-Teton, Dixie, Fishlake, Manti-LaSal, Payette, Salmon-Challis, Sawtooth, Caribou-Targhee, Humboldt-Toiyabe, and Uinta-Wasatch-Cache National Forests.

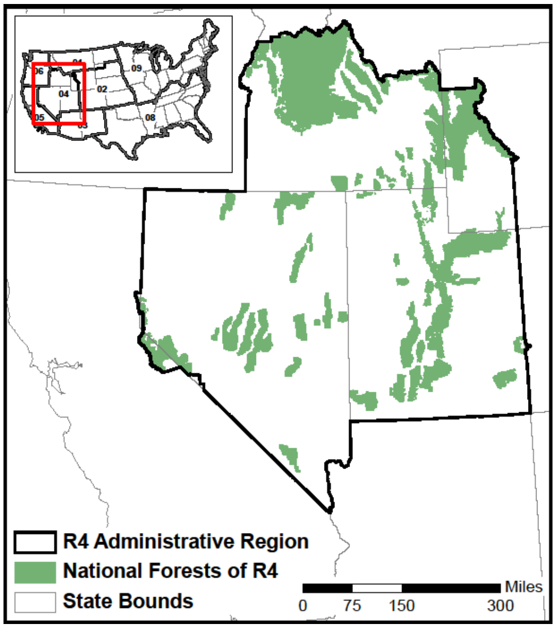

Figure 1. Map of the Intermountain Region (also known as R4).

Historical Intermountain 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 Intermountain Regional boundary. One change occurred at the western border of the Intermountain Region in the vicinity of Mono Lake, California regarding present day Humboldt-Toiyabe National Forest of the Intermountain Region and Inyo National Forest of the Pacific Southwest Region. Where this change occurred, inclusion or exclusion of harvest volumes in this report were supported by details in national level reports. Other Regional boundary changes occurred at the western border regarding present day Humboldt-Toiyabe of the Intermountain Region and Lake Tahoe Basin Management Unit of the Pacific Southwest Region, and at the northeast border regarding present day Bridger-Teton National Forest of the Intermountain Region and Shoshone National Forest of the Rocky Mountain Region concerning the Bonneville National Forest, which was discontinued in 1917 (Davis 1983). Where these changes occurred, inclusion or exclusion of harvest volumes did not take place and cannot be supported by details in national level 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 thirty eight administrative Forests have combined administratively into the current twelve National Forests of the Intermountain Region. However, records indicate that most of these changes relative to discontinued National Forests occurred before 1920 when total harvest volumes were relatively low (Davis 1983).

Methods

The method used to estimate carbon stored in HWP for the Intermountain 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 2). 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).

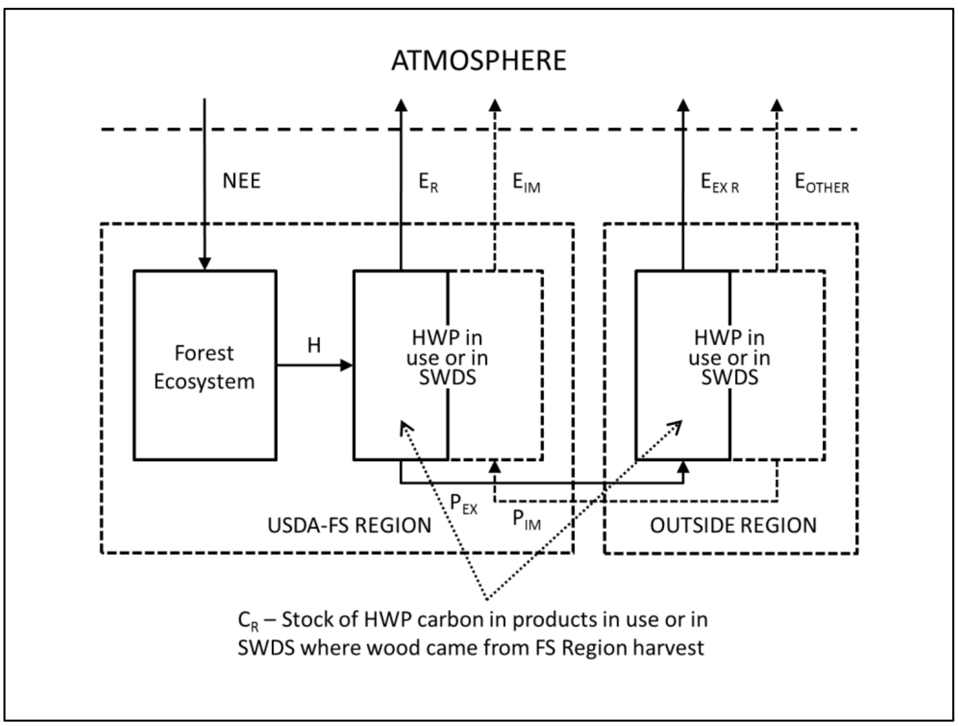

Figure 2. Carbon flows and stocks associated with forest ecosystems and harvested wood products (HWP) to illustrate the IPCC/EPA production accounting approach (adapted from Skog 2008).

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 Intermountain 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
1.8616	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 1911 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).

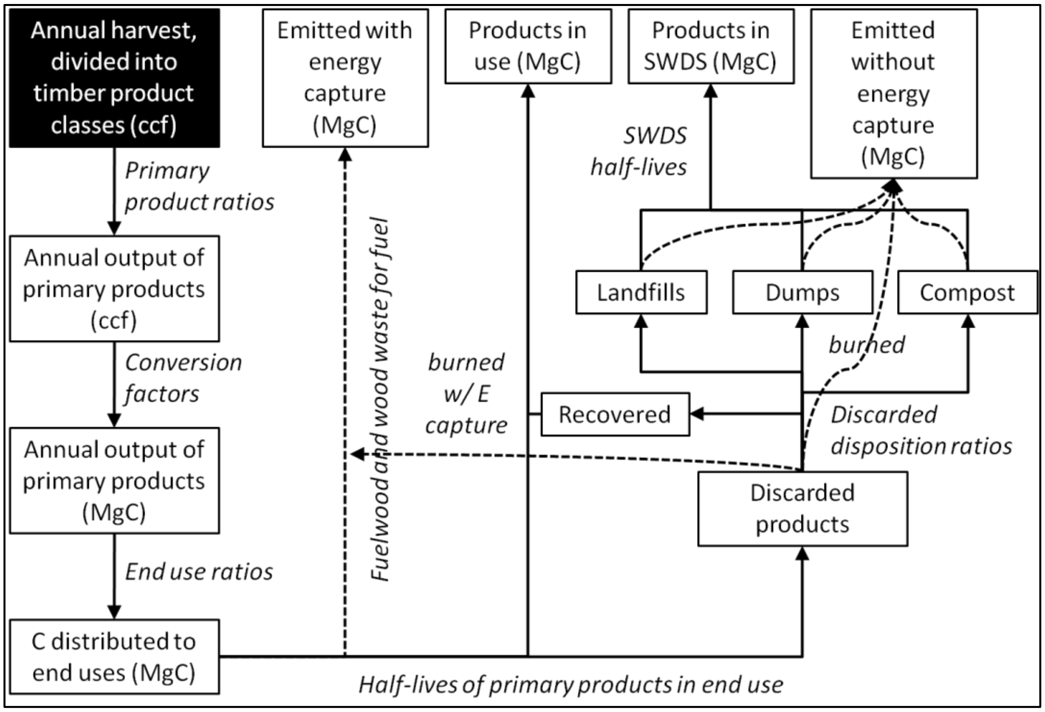

Figure 3. A schematic of calculations to quantify HWP storage and emissions. These calculations quantify HWP products in use, products in SWDS, emissions with energy capture, and emissions without energy capture using the IPCC/EPA approach.

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 1911 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; for the Intermountain Region, annual harvest data from 1911 through 1976 were not available at the Regional Office, nor was consistent harvest data available from individual National Forests. Regional Harvest data for the Intermountain Region were available in archived annual documents titled "Report of the Chief of the Forest Service" for all years from 1955 through 1976. Additional harvest data for the Intermountain Region for all years from 1928 through 1954 were retrieved from cut-and-sold reports obtained with assistance from US West Research, Inc., while harvest data from 1911 through 1927 were located in a US Forest Service Publication, FS-399 (Alexander 1987). In instances when lands administered within current National Forest boundaries were formerly administered within neighboring National Forests, timber volumes were reapportioned based on available details but had no bearing on Regional harvest totals in most cases. One exception was additional harvest data from the discontinued Mono National Forest (current day Inyo and Humboldt-Toiyabe National Forests), which was located in Pacific Southwest Region harvest data and has been apportioned and included in Intermountain Region harvest data based on present day boundaries for all years from 1911 through 1942, with the assumption that data from 1943 and 1944 already included harvests from the Mono National Forest. Other Regional boundary changes occurred at the western border regarding present day Humboldt-Toiyabe of the Intermountain Region and Lake Tahoe Basin Management Unit of the Pacific Southwest Region, and at the northeast border regarding present day Bridger-Teton National Forest of the Intermountain Region and Shoshone National Forest of the Rocky Mountain Region concerning the Bonneville National Forest, which was discontinued in 1917 (Davis 1983). Where these changes occurred, inclusion or exclusion of harvest volumes did not take place and cannot be supported by details in national level reports

All results in this report are based mainly upon fiscal year harvests. However, Intermountain Region harvest data for years 1911 through 1915, and 1922 through 1932 were reported for calendar years only, as opposed to the most conventional reporting style of fiscal years. To avoid overestimating harvests in calendar years 1915 and 1932, harvest data from these years was reduced by half. For example calendar year 1915 spanned January 1, 1915 to December 31, 1915 and fiscal year 1916 spanned July 1, 1915 to June 30, 1916; therefore, harvests recorded in calendar year 1915 were reduced by half with the assumption that half of the harvest recorded in calendar year 1915 (which included half of fiscal year 1916) is approximately equal to harvests from the first half of fiscal year 1916. Also, harvest data from July 1, 1921 through December 31, 1921 is not included in this analysis given the transition from fiscal year 1921 to calendar year 1922. 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 1911 and 2000 volumes were reported in mbf only. For this period annual harvest totals for Intermountain Region reported in mbf were converted to ccf using a conversion factor of 1.8616 ccf per mbf (Table 2), which is the mean conversion factor obtained from harvested volumes from 2001 to 2012 when harvest volumes were reported in both mbf and ccf.

There is new evidence that ccf per mbf conversion factors have changed in recent decades. For example, Keegan et al. (2010a) have found a 16% decrease in mbf per ccf conversion in California from 1970s to 2000s. This alone would suggest conversions from mbf to ccf in earlier decades overestimate the volume harvested. On the other hand, Keegan et al. (2010b) indicate that 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 (16% in California). This would suggest that estimates of carbon in products in use were underestimated in earlier decades. Assuming that the

[2] USFS 2013 (http://www.fs.fed.us/forestmanagement/products/sold-harvest/cut-sold.shtml)
[3] Many times the timber product classes recorded in cut-and-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, explains why we include timber and primary product ratios in our uncertainty analysis.

findings by Keegan et al. essentially cancel each other out, and considering we did not have adequate timber harvest data from all National Forests across the entire period, we chose not to incorporate this information into our calculations. In addition, 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

Intermountain Region harvest records from 1911 through 1976 do not partition the harvest among different timber product classes; they report only total annual harvest. To estimate the proportion of total Intermountain 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 1977 through 2012 to the annual harvest for each year 1911 through 1976 (Table 3).

Table 3. The average annual proportion of 1977 through 2012 Intermountain Region harvests distributed to timber product classes between 1911 and 1976 (n=36).

Product class	Mean	Std. Error
Sawtimber, softwood	0.68	0.025
Fuelwood, softwood	0.26	0.023
Sawtimber, hardwood	0.02	0.003
Poles, softwood	0.01	0.002
Other products	0.03	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 that mostly encompasses the Intermountain Region with the exception of eastern California, which contains part of the Humboldt-Toiyabe National Forest of the Intermountain Region. The tool we built to facilitate calculations for Regional and National Forest-level analyses provides defaults for the Rocky Mountain states including Arizona, Idaho, Colorado, Montana, Nevada, New Mexico, Utah, and Wyoming, which mostly contain the Intermountain Region. However, our modeling for this report is based on aggregated harvests for the entire Intermountain Region, instead of an aggregation of harvests from individual National Forests within the states listed above.

Historical end use data

The historical end use data used for the Intermountain Region comes from McKeever (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 1911 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 Intermountain Region

Between 1911 and 1923 the annual timber harvests in Intermountain Region remained below 65,000 MgC yr^{-1} before increasing to approximately 103,000 MgC yr^{-1} in 1925, followed by relatively stable harvests during the Great Depression of the early 1930s (Table 5, Figure 4). Beginning in 1935, harvests surpassed 170,000 MgC yr^{-1} and began to increase steadily through the early 1950s. From the mid-1950s to the 1990s annual harvest levels remained between 340,000 and 660,000 MgC yr^{-1}, peaking in 1972 where annual timber harvest in the Region exceeded 658,000 MgC. Starting in the mid-1990s harvest volumes experienced a steep decline to a low in 2005 of less than 85,000 MgC, the lowest harvest since 1932. Slight increases in timber harvests have occurred since 2005, but have remained below 155,000 MgC yr^{-1} (Table 5, Figure 4).

Table 5. Annual timber product output in the Intermountain 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)
1920	70,907	51,666
1930	207,338	151,075
1940	262,474	191,249
1950	255,068	185,854
1960	667,296	486,233
1970	836,727	609,690
1980	569,962	420,490
1990	773,978	572,120
1995	387,827	286,237
2000	230,741	164,671
2005	116,245	84,916
2006	148,286	109,719
2007	172,936	126,703
2008	171,705	126,387
2009	176,700	129,715
2010	166,419	123,075
2011	200,882	148,531
2012	209,313	154,532

The cumulative carbon stored in the Intermountain Region HWP began to accelerate substantially around 1955 and continued to increase at a steady rate until peaking in 2000 with just over 9.5 million MgC in storage (Figure 5, Table 6, Appendix B). For reference, this is equivalent to nearly 35.9 million $MgCO_2$, the CO_2 equivalent annual emissions from 6.9 million passenger vehicles, 83.5 million barrels of oil, or the CO_2 equivalent emissions from

187,000 railcars of coal. Since 2000, 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 2013, the HWP pool had fallen to around 9.3 million MgC, levels not seen since 1993 (Figure 5, Table 6).

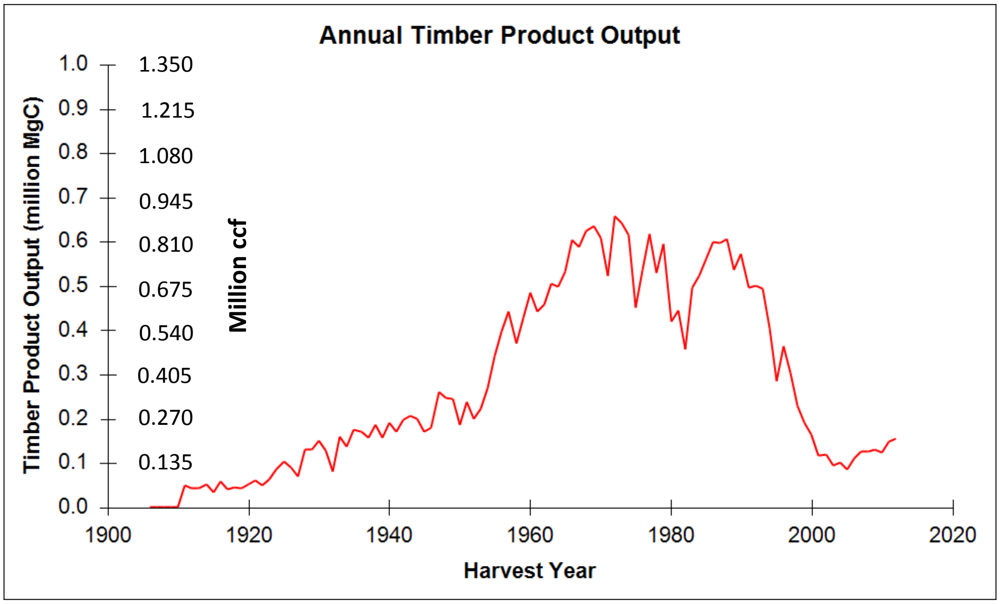

Figure 4. Annual timber product output in the Intermountain Region, 1911 to 2012. Harvest estimates are based on data collected from USDA Forest Service Archives and Cut/Sold reports.

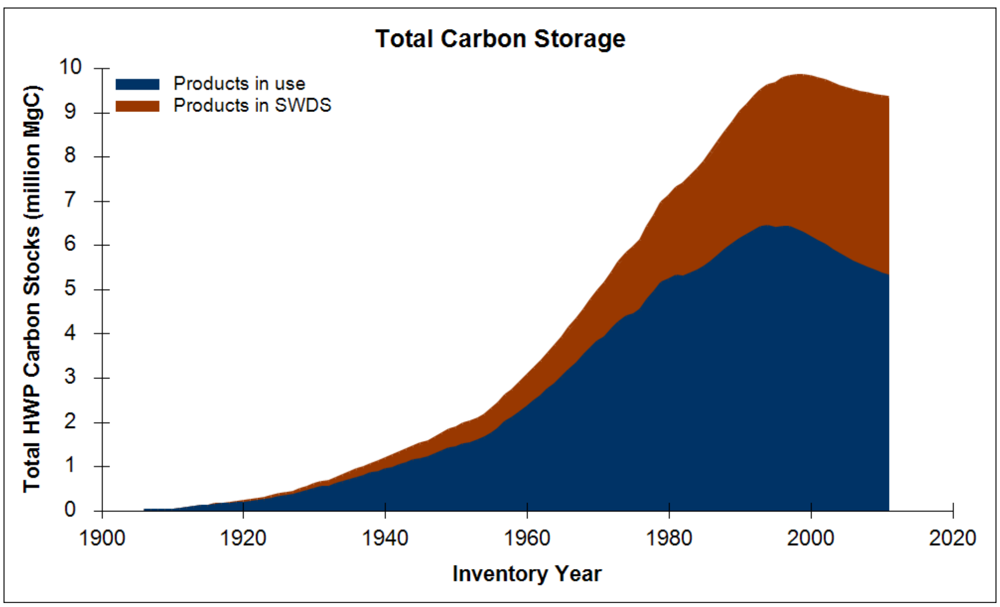

Figure 5. Cumulative total carbon stored in HWP manufactured from Intermountain Region timber using the IPCC/EPA approach. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposal sites (SWDS), including landfills and dumps.

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 1911 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 Intermountain 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)		
1920	194,157	24,101	154,201	28,948	183,149
1930	590,559	109,166	426,332	98,576	524,908
1940	1,306,453	310,708	860,327	238,946	1,099,274
1950	2,290,564	663,923	1,391,958	425,274	1,817,232
1960	3,762,601	1,193,041	2,205,961	679,084	2,885,045
1970	6,319,429	2,092,976	3,669,936	1,094,227	4,764,163
1980	8,762,332	3,190,885	5,138,388	1,815,720	6,954,108
1990	11,035,735	4,209,175	6,008,244	2,773,563	8,781,807
1995	12,068,632	4,832,242	6,420,255	3,194,722	9,614,977
2000	12,654,634	5,424,429	6,268,119	3,569,055	9,837,174
2005	12,983,399	5,967,748	5,792,469	3,806,805	9,599,274
2006	13,034,154	6,066,247	5,697,418	3,842,467	9,539,885
2007	13,097,492	6,161,381	5,618,653	3,876,016	9,494,668
2008	13,167,078	6,253,412	5,553,574	3,908,660	9,462,234
2009	13,237,675	6,342,507	5,490,231	3,940,925	9,431,157
2010	13,320,144	6,428,788	5,421,867	3,972,702	9,394,568
2011	13,399,925	6,512,372	5,353,077	4,003,760	9,356,837
2012	13,488,682	6,593,705	5,302,417	4,034,077	9,336,494
2013	13,579,187	6,672,990	5,257,526	4,064,662	9,322,188

[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 means 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 results in a transition from a positive net annual change in carbon stocks to a negative net annual change in carbon stocks. Beginning in the 1930s additions to carbon stocks in HWP were growing by over 50,000 MgC yr^{-1}, increasing to over 216,000 MgC yr^{-1} in the late 1960s; peak stock growth occurred in 1978 with the addition of slightly more than 308,000 MgC. After 1978, additions to carbon stock in HWP began to decline with the addition of just over 85,000 MgC in 1983. Following 1983, additions to the HWP carbon pool began to increase reaching just less than 250,000 MgC in 1989, before beginning to decline. In 2000, the net change moved from positive to negative, and since then the Intermountain HWP pool has become a net source of atmospheric carbon. The year with the largest negative net change from the Intermountain Region HWP carbon pool was 2004, when stocks decreased by over 61,000 MgC. However, since

2004 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.

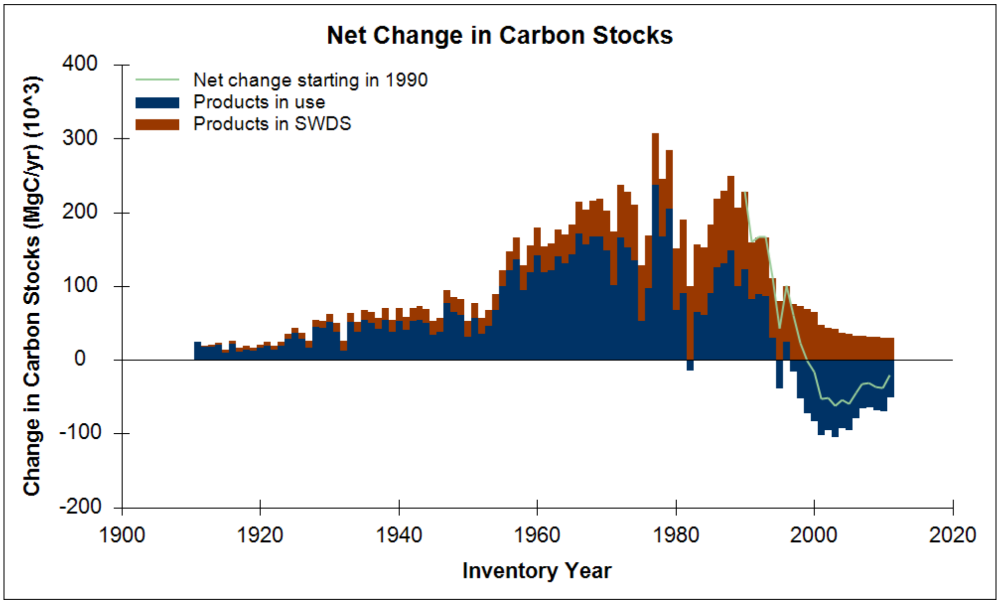

Figure 6. The net change in carbon stocks in HWP from the previous year using the IPCC/EPA production accounting approach. The net stock change is the sum of net change for SWDS and products in use. The total net change trend line shows a transition from net additions to carbon stocks in HWP to a period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

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

Inventory Year	Stock change[a] ($MgC\ yr^{-1}$)
1920	17,512
1930	53,571
1940	55,043
1950	83,371
1960	155,162
1970	219,365
1980	284,486
1990	206,306
1995	111,466
2000	-2,466
2005	-54,811
2006	-59,390
2007	-45,216
2008	-32,434
2009	-31,077
2010	-36,588
2011	-37,732
2012	-20,343
2013	-14,305

[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 2000, the year of peak carbon stocks in Table 8, the 90% confidence interval ranges from 9,833,759 MgC to 9,844,760 MgC, with a mean value of 9,839,260 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 1920 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)	90% Confidence interval Upper limit (MgC)
1920	183,094	182,824	183,363
1930	525,115	524,506	525,724
1940	1,099,379	1,098,250	1,100,509
1950	1,816,424	1,814,862	1,817,986
1960	2,884,867	2,882,759	2,886,974
1970	4,763,325	4,760,042	4,766,609
1980	6,957,593	6,953,112	6,962,075
1990	8,785,289	8,780,163	8,790,416
1995	9,617,264	9,611,839	9,622,690
2000	9,839,260	9,833,759	9,844,760
2005	9,600,892	9,595,439	9,606,345
2006	9,541,462	9,536,020	9,546,904
2007	9,496,237	9,490,799	9,501,676
2008	9,463,761	9,458,328	9,469,195
2009	9,432,685	9,427,249	9,438,120
2010	9,395,970	9,390,531	9,401,408
2011	9,358,271	9,352,831	9,363,711
2012	9,337,958	9,332,516	9,343,401
2013	9,323,566	9,318,111	9,329,020

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 9.6 teragrams of carbon (TgC) presented in Table 6 by the sum of this stock estimate and Heath et al.'s (2011) estimated 2005[4] Intermountain Region ecosystem carbon stock of 1,213 TgC, we estimate that the Intermountain Region HWP carbon stocks represent roughly 0.8% of total forest carbon storage associated with National Forests in the Intermountain 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 Intermountain Region HWP carbon stocks represented 0.4% 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 Intermountain Region to reasonably account for carbon that was 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.

[4] Mean measurement year reported as 2004.9.

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 Intermountain 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.

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 Intermountain Region HWP pool is now in a period of negative net annual stock because the decay of products harvested between 1911 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)
1912	24,074	616	24,437	-	24,437
1913	44,152	1,742	42,966	1,435	44,401
1914	65,026	3,390	61,067	3,790	64,857
1915	89,739	5,649	81,964	6,880	88,843
1916	105,710	8,283	92,751	10,752	103,503
1917	133,281	11,576	114,932	14,701	129,634
1918	152,108	15,288	126,993	19,366	146,359
1919	173,795	19,479	141,563	24,074	165,637
1920	194,157	24,101	154,201	28,948	183,149
1921	218,720	29,245	170,680	33,863	204,543
1922	247,777	35,013	191,009	39,040	230,049
1923	271,767	41,259	205,218	44,680	249,898
1924	301,807	48,122	225,109	50,366	275,475
1925	341,986	55,846	254,404	56,413	310,817
1926	391,088	64,639	291,197	63,338	354,535
1927	434,198	74,328	319,881	71,469	391,350
1928	467,114	84,627	336,941	80,162	417,104
1929	528,637	96,245	382,706	88,631	471,338
1930	590,559	109,166	426,332	98,576	524,908
1931	662,384	123,614	477,806	109,719	587,525
1932	723,578	139,281	515,820	122,329	638,149
1933	762,113	155,554	529,352	135,412	664,764
1934	838,466	173,367	581,693	147,432	729,126
1935	903,999	192,408	620,398	160,789	781,186
1936	986,863	213,087	675,240	174,579	849,819
1937	1,068,490	235,332	726,193	189,654	915,847
1938	1,143,432	258,931	768,169	205,631	973,800
1939	1,231,825	284,189	822,392	221,839	1,044,231
1940	1,306,453	310,708	860,327	238,946	1,099,274
1941	1,397,378	339,333	913,833	255,897	1,169,729
1942	1,478,974	369,241	955,692	273,214	1,228,906
1943	1,573,484	400,733	1,009,460	290,597	1,300,056
1944	1,671,530	433,857	1,064,710	308,711	1,373,421
1945	1,766,727	468,492	1,114,933	327,572	1,442,505
1946	1,847,641	504,213	1,148,988	346,788	1,495,776

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1947	1,933,116	541,103	1,187,262	365,367	1,552,629
1948	2,057,561	580,157	1,264,286	383,625	1,647,911
1949	2,174,571	621,124	1,329,979	403,882	1,733,861
1950	2,290,564	663,923	1,391,958	425,274	1,817,232
1951	2,378,924	707,770	1,423,614	447,382	1,870,996
1952	2,492,035	753,167	1,480,506	468,447	1,948,953
1953	2,586,658	799,645	1,516,471	490,045	2,006,516
1954	2,692,104	847,446	1,562,946	511,116	2,074,062
1955	2,820,630	897,151	1,631,487	532,305	2,163,793
1956	2,982,959	949,545	1,731,506	554,944	2,286,450
1957	3,172,418	1,005,239	1,854,109	580,565	2,434,674
1958	3,382,300	1,064,799	1,990,745	610,024	2,600,769
1959	3,558,578	1,127,207	2,086,003	643,881	2,729,883
1960	3,762,601	1,193,041	2,205,961	679,084	2,885,045
1961	3,993,762	1,264,051	2,348,255	716,641	3,064,896
1962	4,204,417	1,339,278	2,468,235	750,596	3,218,831
1963	4,422,329	1,418,516	2,590,729	786,123	3,376,852
1964	4,662,508	1,502,006	2,731,008	823,265	3,554,273
1965	4,899,625	1,589,324	2,862,429	862,799	3,725,228
1966	5,153,075	1,680,759	3,005,533	903,817	3,909,350
1967	5,440,019	1,776,951	3,177,179	947,032	4,124,211
1968	5,720,252	1,877,657	3,334,285	993,627	4,327,912
1969	6,016,766	1,983,030	3,502,149	1,042,650	4,544,799
1970	6,319,429	2,092,976	3,669,936	1,094,227	4,764,163
1971	6,609,284	2,189,738	3,818,725	1,147,893	4,966,619
1972	6,858,001	2,289,040	3,920,074	1,220,911	5,140,985
1973	7,171,129	2,391,824	4,086,385	1,292,585	5,378,970
1974	7,476,684	2,497,713	4,239,970	1,366,909	5,606,879
1975	7,768,814	2,606,532	4,375,857	1,442,150	5,818,007
1976	7,982,946	2,716,871	4,429,218	1,517,532	5,946,751
1977	8,238,686	2,829,373	4,527,434	1,588,348	6,115,783
1978	8,421,172	2,946,353	4,765,396	1,658,446	6,423,842
1979	8,581,796	3,066,552	4,933,165	1,736,456	6,669,622
1980	8,762,332	3,190,885	5,138,388	1,815,720	6,954,108
1981	8,908,320	3,292,160	5,206,639	1,898,765	7,105,404
1982	9,060,330	3,394,425	5,297,218	1,999,354	7,296,571
1983	9,239,524	3,496,471	5,282,734	2,099,398	7,382,133
1984	9,478,091	3,598,486	5,347,834	2,191,905	7,539,739

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1985	9,748,036	3,700,072	5,408,792	2,284,437	7,693,229
1986	10,024,154	3,801,396	5,500,248	2,376,364	7,876,611
1987	10,298,655	3,902,752	5,626,278	2,469,930	8,096,209
1988	10,560,841	4,004,337	5,758,373	2,567,283	8,325,656
1989	10,808,959	4,106,537	5,907,421	2,668,080	8,575,500
1990	11,035,735	4,209,175	6,008,244	2,773,563	8,781,807
1991	11,272,557	4,331,767	6,131,112	2,879,493	9,010,605
1992	11,485,790	4,456,012	6,213,856	2,956,188	9,170,044
1993	11,694,463	4,581,373	6,303,485	3,033,712	9,337,197
1994	11,896,290	4,707,217	6,390,229	3,113,281	9,503,511
1995	12,068,632	4,832,242	6,420,255	3,194,722	9,614,977
1996	12,197,741	4,955,096	6,382,452	3,274,595	9,657,047
1997	12,342,060	5,076,443	6,407,606	3,349,741	9,757,347
1998	12,469,806	5,195,468	6,391,997	3,425,432	9,817,429
1999	12,567,882	5,311,616	6,340,641	3,499,000	9,839,640
2000	12,654,634	5,424,429	6,268,119	3,569,055	9,837,174
2001	12,733,582	5,539,569	6,185,748	3,634,935	9,820,683
2002	12,799,024	5,651,958	6,084,549	3,683,405	9,767,954
2003	12,866,958	5,759,929	5,989,186	3,726,839	9,716,025
2004	12,924,925	5,865,586	5,884,991	3,769,094	9,654,085
2005	12,983,399	5,967,748	5,792,469	3,806,805	9,599,274
2006	13,034,154	6,066,247	5,697,418	3,842,467	9,539,885
2007	13,097,492	6,161,381	5,618,653	3,876,016	9,494,668
2008	13,167,078	6,253,412	5,553,574	3,908,660	9,462,234
2009	13,237,675	6,342,507	5,490,231	3,940,925	9,431,157
2010	13,320,144	6,428,788	5,421,867	3,972,702	9,394,568
2011	13,399,925	6,512,372	5,353,077	4,003,760	9,356,837
2012	13,488,682	6,593,705	5,302,417	4,034,077	9,336,494
2013	13,579,187	6,672,990	5,257,526	4,064,662	9,322,188