Estimates of carbon stored in harvested wood products from United States Forest Service's Sierra Nevada Bio-Regional Assessment Area of the Pacific Southwest 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 for the USFS Sierra Nevada Bio-Regional Assessment Area (Assessment Area) of the Pacific Southwest Region. For the Assessment Area as a whole, carbon stocks in the HWP pool were increasing at just above 0.5 million megagrams of carbon (MgC) per year beginning in the late 1940's until the early 1990's, with peak cumulative storage to date of 32 million MgC occurring in 1999. Net positive flux into the HWP pool over this period is primarily attributable to high harvest levels during the 1960's through 1980's. In the years between the late 1960s and 1990 timber harvest were at high but volatile levels, with high harvests of over 2.5 million ccf (1.8 million MgC) occurring six times during this period, harvest levels from National Forests have since declined to less than 0.7 million ccf (0.5 million MgC) per year, resulting in less carbon entering the HWP pool. Since 2000, 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 Assessment Area'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 Assessment Area, this accounting method can be applied more broadly at smaller land management units, such as National Forests.

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Cover: White Fir Lumber, Sierra Forest Products, Terra Bella, California from the white fir roadside hazard tree removal, Sierra National Forest. Courtesy of Larry Swan, USFS, Region 5 State and Private Forestry.

Contents

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 Sierra Nevada Bio-Regional Assessment Area of the Pacific Southwest Region (Assessment Area);
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.

Assessment Area Description

The Assessment Area is located almost entirely in California. National Forests in this region include Eldorado, Inyo, Lassen, Modoc, Plumas, Sequoia, Sierra, Stanislaus, Tahoe National Forests, and the Lake Tahoe Basin Management Unit, and represent 10.8 million acres (approximately 5.6%) of all National Forest System (NFS) lands (USFS 2012).

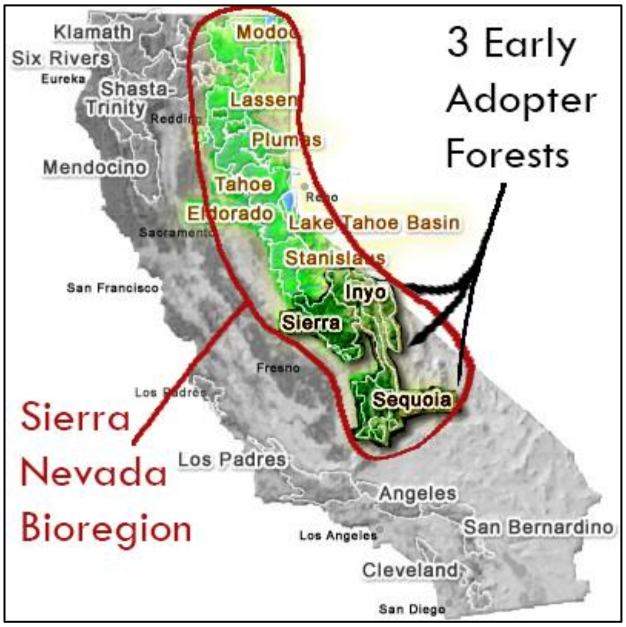

Figure 1. Map of the Sierra Nevada Bioregion of the Pacific Southwest Region (Assessment Area).

Historical Assessment Area 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 Assessment Area at the eastern border in the vicinity of Mono Lake, California regarding present day Inyo National Forest of the Pacific Southwest Region and Humboldt-Toiyabe National Forest of the Intermountain Region. Where these changes occurred, inclusion or exclusion of harvest volumes in this report were supported by details in national level reports. Another Regional boundary change occurred at the eastern border regarding present day Humboldt-Toiyabe of the Intermountain Region and Lake Tahoe Basin Management Unit of the Pacific Southwest Region (Davis 1983). Where this change 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 thirteen administrative Forests have combined administratively into the current nine National Forests and the Lake Tahoe Basin Management unit in the Assessment Area of the Pacific Southwest 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 Assessment Area 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 Assessment Area (Figure 2). In the IPCC/EPA approach, the annual carbon stock change for the Assessment Area'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 Assessment Area's forest sector, NEE is the annual net ecosystem exchange between the atmosphere and the Assessment Area's forests from all ecosystem processes including photosynthesis, decay, and natural and anthropogenic fire, H is the annual harvest of wood from the Assessment Area's forests for products, and ΔC_R is the annual change in carbon stored in HWP that were made from wood harvested from the Assessment Area'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).

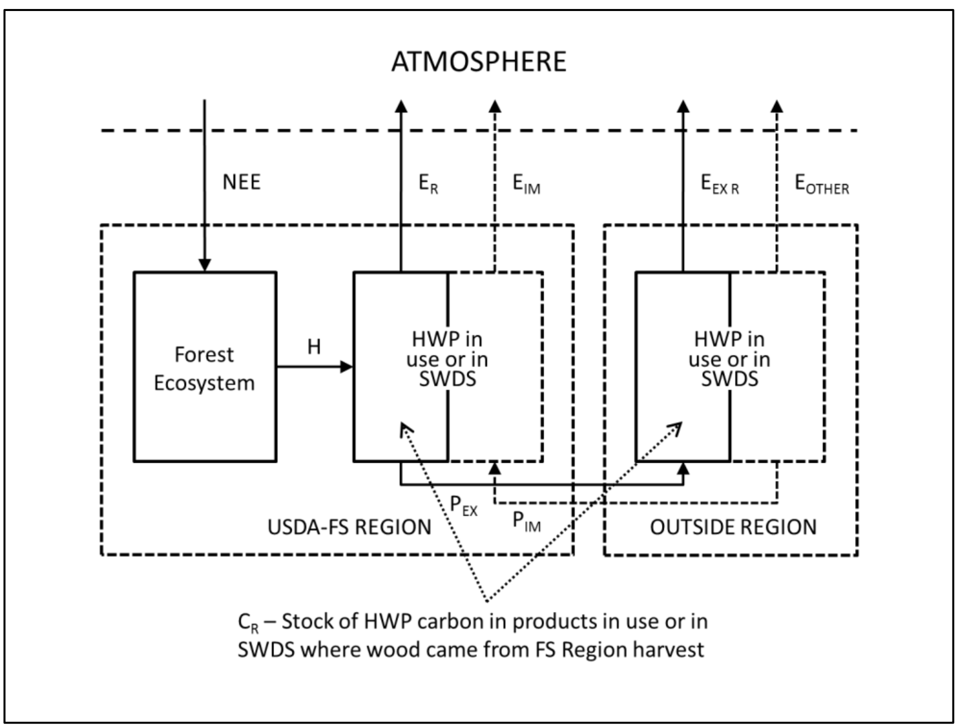

Figure 2. Carbon flows and stocks associated with forest ecosystems and harvested wood products (HWP) to illustrate the IPCC/EPA production accounting approach (adapted from Skog 2008).

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 Assessment Area from products made from wood harvested in the Assessment Area.
E_{IM}	Annual emission of carbon to the atmosphere in the Assessment Area from products made from wood harvested outside of the Assessment Area and imported into the Assessment Area.
P_{EX}	Annual exports of wood and paper products out of the Assessment Area, including roundwood, chips, residue, pulp and recovered (recycled) products.
P_{IM}	Annual imports of wood and paper products into the Assessment Area, including roundwood, chips, residue, pulp and recovered (recycled) products.
$E_{EX\ R}$	Annual emission of carbon to the atmosphere in areas outside of the Assessment Area from products made from wood harvested in the Assessment Area.
E_{OTHER}	Annual emission of carbon to the atmosphere in areas outside of the Assessment Area from products made from wood harvested outside the Assessment Area.
C_R	Stock of harvested wood products carbon in use or at solid waste disposal sites where products used wood from the Assessment Area.
$\Delta C_{IU\ R}$	Annual change in carbon stored in harvested wood products in use where products used wood from the Assessment Area.
$\Delta C_{SWDS\ R}$	Annual change in carbon stored in harvested wood products at solid waste disposal sites where products used wood from the Assessment Area.
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 Assessment Area.

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 Assessment Area. 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 Assessment Area of the Region (indicated with solid boxes) include both emissions to the atmosphere from wood products harvested and used within the Assessment Area of the Region (E_R) and emissions to the atmosphere from wood products harvested in the Assessment Area of the Region that were exported outside the Assessment Area of 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 Assessment Area of 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 Assessment Area 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 this Assessment Area.

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 2009, 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
2.0264	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).

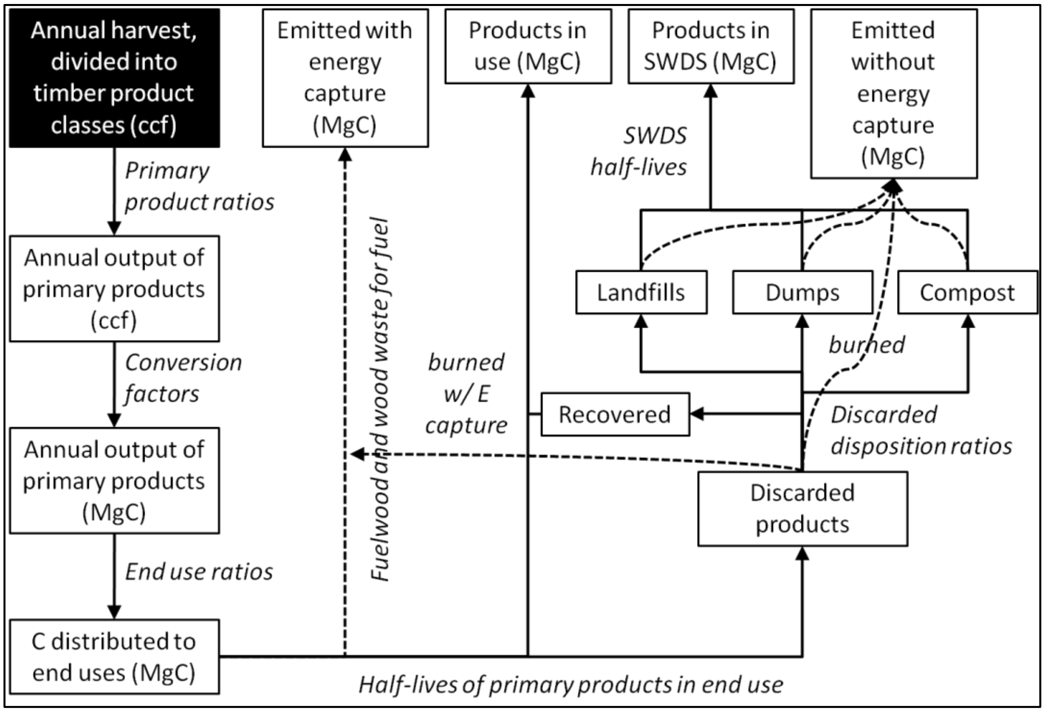

Figure 3. A schematic of calculations to quantify HWP storage and emissions. These calculations quantify HWP products in use, products in SWDS, emissions with energy capture, and emissions without energy capture using the IPCC/EPA approach.

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 Southwest Regional Office. Throughout the harvest record, data were available at the National Forest level and at the Region level, with no instances of 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 Assessment Area harvest totals in most cases. One exception occurred along the eastern boundary of the Assessment Area, where harvests from the discontinued Mono National Forest were split between the Inyo National Forest of the Assessment Area and the Humboldt-Toiyabe National Forest of Intermountain Region (Davis 1983). Where this change occurred, inclusion or exclusion of harvest volumes in this report were supported by details in national level reports. 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 the Assessment Area of the Pacific Southwest Region reported in mbf were converted to ccf using a conversion factor of 2.0264 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 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

The Assessment Area harvest records from 1909 through 1950 do not partition the harvest among different timber product classes; they report only total annual harvest. To estimate the proportion of total Assessment Area harvest that went into each timber product class, we applied Pacific Southwest Region 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 in the Pacific Southwest Region (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, explains why we include timber and primary product ratios in our uncertainty analysis.

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

Product class	Mean	Std. Error
Sawtimber, softwood	0.86	0.022
Fuelwood, softwood	0.05	0.008
Misc.-conv., softwood	0.04	0.008
Non-sawtimber, softwood	0.02	0.007
Cull logs, softwood	0.02	0.003
Other	0.02	0.003

Historical primary product data

The carbon in HWP from timber products from the Assessment Area 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 Southwest Region. The tool we built to facilitate calculations for Regional and National Forest-level analyses provides defaults for the state of California, which closely resembles the boundaries of Pacific Southwest Region. However, our modeling for this report is based on aggregated harvests for the entire Assessment Area, instead of an aggregation of calculations for individual National Forests.

Historical end use data

The historical end use data used for the Assessment Area 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 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 Sierra Nevada Bio-Regional Assessment Area of the Pacific Southwest Region

From 1909 to 1930 the annual timber harvests in the Region remained below 0.66 million MgC yr^{-1} (0.9 million ccf yr^{-1}). This was followed by a harvesting decrease during the Great Depression in the 1930's, when levels decreased 82% from the 1930 harvest and from 1934 onward harvests grew slowly (Table 5, Figure 4). World War II invigorated harvests further, up to 0.7 million MgC by 1944. Harvests receded during a two-year term following World War II falling to 0.54 million MgC in 1946 before beginning a rapid rate of increase in the 1950's and 1960's, peaking in 1968 at 1.85 million MgC. This was followed by a decade of prevailing declines in harvests, falling to 0.86 million MgC in 1982. Thereafter, harvests immediately rose sharply to roughly the same level as the previous 2 decades, peaking in 1988 at 1.92 million MgC. The years 1989 and 1990 showed a decline that foreshadowed large harvest declines of the 1990s. Harvest fell to 0.45 million MgC by 2000 and to the lowest harvest since the 1930s of 0.17 million MgC by 2009 and harvests have remained below 0.33 million MgC since. However, since 2009 harvests have been slowly increasing (Table 5, Figure 4).

Table 5. Annual timber product output in the Assessment Area of the Pacific Southwest 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	90,470	66,442
1920	202,333	148,594
1930	896,449	658,356
1940	536,671	394,133
1950	703,572	516,706
1960	1,677,645	1,239,350
1970	2,292,427	1,691,864
1980	1,742,890	1,281,621
1990	2,252,748	1,665,017
1995	767,083	567,742
2000	609,676	450,704
2005	380,544	282,036
2006	602,567	446,387
2007	456,357	338,674
2008	368,576	273,593
2009	234,011	174,348
2010	348,575	259,490
2011	337,504	251,839
2012	437,689	325,972

The cumulative carbon stored in the Assessment Area of the Pacific Southwest Region HWP peaked in 1999 at approximately 32 million MgC (Figure 5, Table 6, Appendix B). For reference, this is equivalent to 117 million $MgCO_2$, the CO_2 equivalent annual emissions from 22.4 million passenger vehicles, 273 million barrels of oil, or 612,700 railcars of coal. Since 1999, 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 31 million MgC, levels not seen since the early 1990's (Figure 5, Table 6).

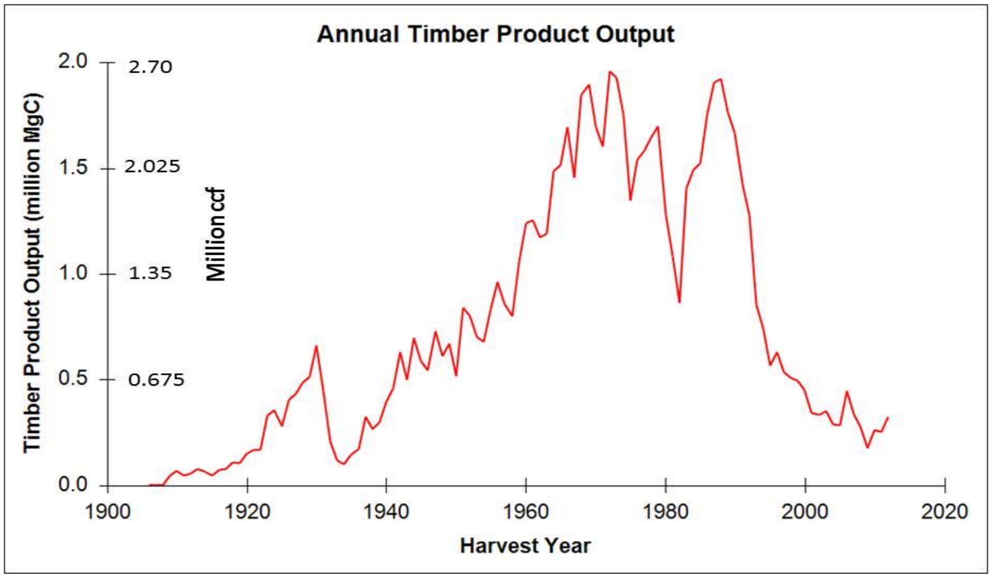

Figure 4. Annual timber product output in the Assessment Area of the Pacific Southwest Region, 1909 to 2012. Harvest estimates are based on data collected from USDA Forest Service Archives and Cut/Sold reports.

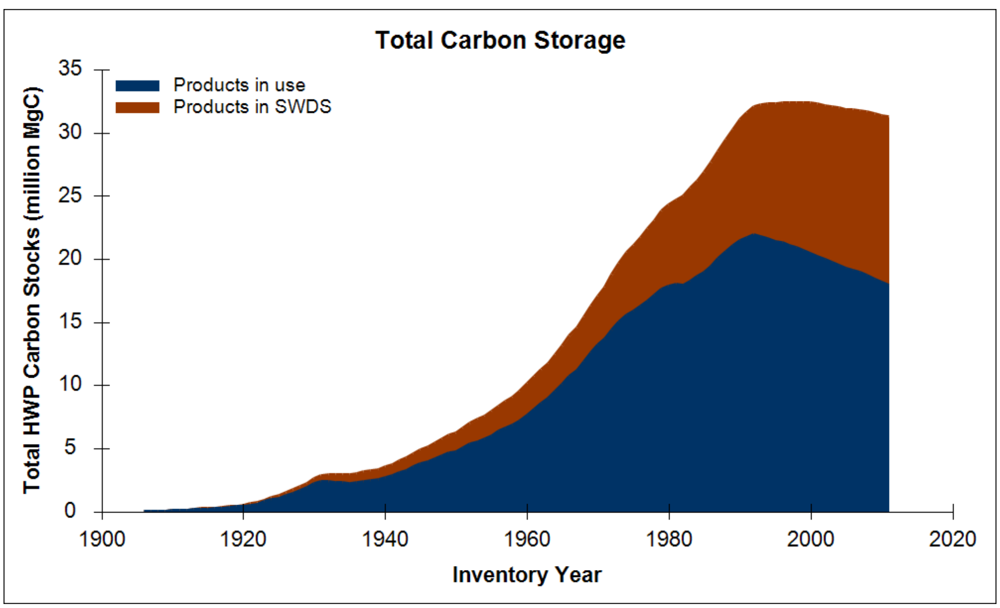

Figure 5. Cumulative total carbon stored in HWP manufactured from Assessment Area of the Pacific Southwest Region timber using the IPCC/EPA approach. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposal sites (SWDS), including landfills and dumps.

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 Assessment Area of the Pacific Southwest 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	15,360	712	28,231	-	28,231
1920	254,279	58,041	367,142	66,019	433,161
1930	1,348,409	365,410	1,879,048	365,738	2,244,786
1940	2,260,084	1,088,848	2,509,336	835,660	3,344,995
1950	4,202,002	2,215,308	4,612,869	1,409,098	6,021,966
1960	6,827,559	4,036,641	7,197,068	2,345,662	9,542,729
1970	11,621,097	7,075,839	12,606,262	3,685,757	16,292,019
1980	16,902,183	10,891,713	17,606,882	6,194,935	23,801,817
1990	21,869,495	14,304,193	21,061,179	9,236,928	30,298,107
1995	23,889,359	16,375,751	21,644,799	10,651,179	32,295,978
2000	24,750,616	18,245,399	20,674,846	11,718,630	32,393,476
2005	25,335,480	19,944,978	19,492,526	12,467,366	31,959,892
2006	25,426,451	20,258,898	19,252,306	12,595,311	31,847,616
2007	25,577,995	20,565,772	19,118,231	12,720,014	31,838,244
2008	25,696,292	20,864,602	18,919,496	12,847,528	31,767,025
2009	25,797,826	21,155,291	18,685,346	12,972,577	31,657,923
2010	25,878,853	21,436,884	18,388,716	13,094,130	31,482,846
2011	25,980,851	21,710,724	18,164,541	13,209,523	31,374,065
2012	26,076,597	21,976,891	17,947,134	13,323,709	31,270,843
2013	26,194,963	22,236,685	17,785,729	13,436,113	31,221,842

[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 late 1940's additions to carbon stocks in HWP were growing by over 0.25 million MgC yr^{-1}, increasing to over 0.6 million MgC yr^{-1} in the 1960's; peak stock growth occurred in 1973 with the addition of slightly more than 0.957 million MgC. In 2000, the net change moved from positive to negative, and since then the Assessment Area of the Pacific Southwest HWP pool has become a net source of atmospheric carbon. The year with the largest negative net change from the Assessment Area of the Pacific Southwest Region HWP carbon pool was 2010, when stocks decreased by over 0.175 million MgC. However, since 2010 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.

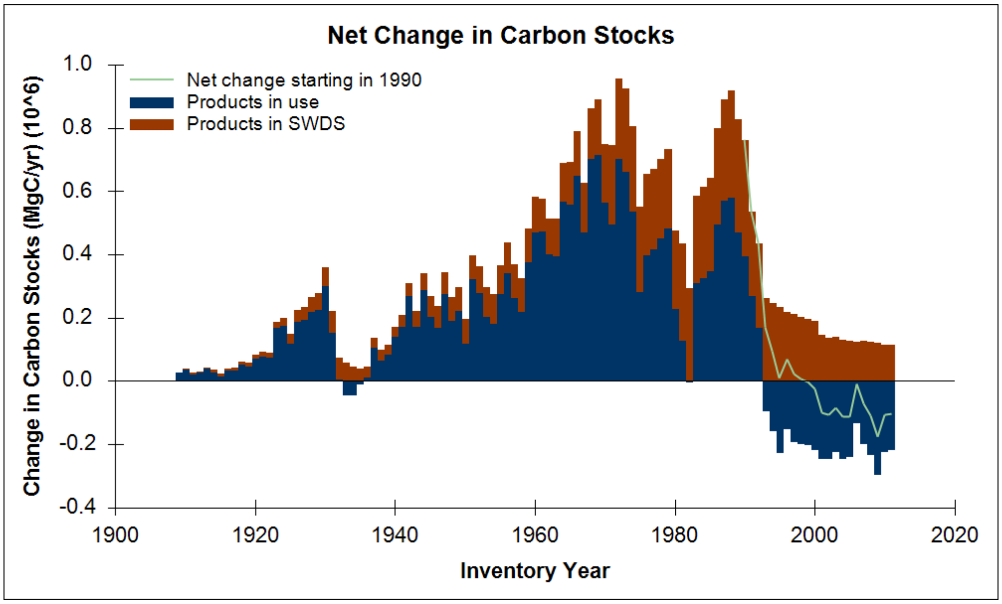

Figure 6. The net change in carbon stocks in Assessment Area HWP from the previous year using the IPCC/EPA production accounting approach. The net stock change is the sum of net change for SWDS and products in use. The total net change trend line shows a transition from net additions to carbon stocks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

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

Inventory Year	Stock change[a] ($MgC\ yr^{-1}$)
1910	28,231
1920	57,695
1930	277,809
1940	116,283
1950	298,711
1960	482,920
1970	890,815
1980	733,350
1990	830,583
1995	92,763
2000	-4,805
2005	-114,347
2006	-112,276
2007	-9,372
2008	-71,219
2009	-109,102
2010	-175,077
2011	-108,781
2012	-103,222
2013	-49,001

[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 32,370,160 MgC to 32,409,084 MgC, with a mean value of 32,389,622 MgC. This is equivalent to a ±0.06% difference from the mean.

Table 8. Confidence intervals for cumulative carbon in Assessment Area 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)	90% Confidence interval Upper limit (MgC)
1910	28,659	28,546	28,772
1920	435,994	435,426	436,562
1930	2,258,447	2,255,637	2,261,257
1940	3,365,754	3,362,314	3,369,194
1950	6,059,688	6,054,385	6,064,990
1960	9,571,159	9,563,934	9,578,383
1970	16,314,625	16,302,799	16,326,452
1980	23,812,054	23,795,868	23,828,240
1990	30,299,102	30,280,228	30,317,975
1995	32,293,392	32,273,784	32,313,001
2000	32,389,622	32,370,160	32,409,084
2005	31,955,523	31,936,244	31,974,802
2006	31,843,306	31,824,051	31,862,560
2007	31,833,671	31,814,399	31,852,943
2008	31,762,060	31,742,796	31,781,324
2009	31,652,608	31,633,363	31,671,853
2010	31,477,576	31,458,351	31,496,802
2011	31,368,651	31,349,426	31,387,875
2012	31,265,146	31,245,914	31,284,378
2013	31,215,824	31,196,573	31,235,076

Discussion of Assessment Area 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). Using the numbers for the entire Pacific Southwest Region and dividing the 2005 HWP stock estimate of 50.2 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 Southwest Region ecosystem carbon stock of 1,408 TgC, we estimate that the Pacific Southwest Region HWP carbon stocks represent roughly 3.4% of total forest carbon storage associated with National Forests in the Pacific Southwest 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 Southwest Region HWP carbon stocks represented 2.1% 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 those evaluating the Assessment Area to reasonably account for carbon

[4] Mean measurement year reported as 2005.

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.

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 Assessment Area, we believe the same trend is likely to hold for most areas. 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 Sierra Nevada Bio-Regional Assessment Area 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 Assessment Area 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 Assessment Area 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	15,360	712	28,231	-	28,231
1911	37,523	2,432	66,870	1,658	68,529
1912	52,513	4,812	89,638	5,364	95,002
1913	70,466	7,984	116,567	9,882	126,448
1914	95,989	12,280	155,891	15,316	171,207
1915	117,117	17,469	184,791	22,271	207,062
1916	132,360	23,261	201,463	29,925	231,389
1917	156,585	30,056	234,204	37,455	271,660
1918	182,675	37,907	268,717	45,827	314,543
1919	219,043	47,266	320,417	55,050	375,466
1920	254,279	58,041	367,142	66,019	433,161
1921	303,847	70,864	437,866	78,210	516,076
1922	359,502	85,967	515,779	92,852	608,631
1923	415,021	103,293	589,162	110,039	699,202
1924	524,915	125,311	758,811	129,141	887,951
1925	643,871	152,321	934,479	155,536	1,090,015
1926	736,734	183,020	1,051,893	188,600	1,240,493
1927	871,444	219,279	1,240,954	223,919	1,464,873
1928	1,015,151	261,362	1,436,156	265,336	1,701,492
1929	1,177,033	309,978	1,654,554	312,423	1,966,977
1930	1,348,409	365,410	1,879,048	365,738	2,244,786
1931	1,568,020	429,730	2,181,024	424,782	2,605,806
1932	1,716,118	499,396	2,335,207	493,313	2,828,521
1933	1,785,861	570,670	2,340,994	561,370	2,902,364
1934	1,824,878	642,047	2,296,816	620,229	2,917,045
1935	1,858,094	713,166	2,251,132	668,313	2,919,445
1936	1,906,136	784,631	2,240,778	707,236	2,948,014
1937	1,963,842	856,813	2,252,659	740,538	2,993,197
1938	2,072,009	931,998	2,359,537	770,447	3,129,984
1939	2,160,787	1,009,189	2,425,645	803,068	3,228,713
1940	2,260,084	1,088,848	2,509,336	835,660	3,344,995
1941	2,391,556	1,173,634	2,649,138	869,159	3,518,297
1942	2,544,932	1,263,130	2,822,140	905,689	3,727,829
1943	2,755,326	1,359,949	3,090,894	947,736	4,038,630
1944	2,921,054	1,461,744	3,262,014	1,000,038	4,262,051

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1945	3,153,797	1,571,638	3,549,151	1,055,482	4,604,633
1946	3,350,061	1,687,630	3,753,772	1,120,226	4,873,998
1947	3,531,579	1,808,876	3,922,968	1,188,250	5,111,219
1948	3,774,294	1,938,165	4,199,261	1,256,957	5,456,219
1949	3,978,117	2,073,369	4,390,764	1,332,491	5,723,255
1950	4,202,002	2,215,308	4,612,869	1,409,098	6,021,966
1951	4,374,361	2,361,301	4,731,792	1,488,357	6,220,149
1952	4,647,457	2,516,173	5,053,471	1,564,376	6,617,847
1953	4,907,320	2,679,721	5,331,660	1,649,392	6,981,052
1954	5,135,903	2,850,065	5,536,838	1,741,619	7,278,456
1955	5,356,696	3,026,484	5,719,839	1,835,394	7,555,233
1956	5,627,629	3,210,944	5,994,854	1,928,779	7,923,633
1957	5,940,149	3,405,121	6,337,807	2,026,328	8,364,135
1958	6,220,221	3,607,538	6,602,226	2,131,216	8,733,441
1959	6,481,162	3,816,796	6,820,929	2,238,880	9,059,810
1960	6,827,559	4,036,641	7,197,068	2,345,662	9,542,729
1961	7,231,218	4,273,355	7,666,736	2,460,171	10,126,907
1962	7,640,594	4,525,878	8,139,909	2,564,227	10,704,136
1963	8,023,574	4,791,369	8,540,126	2,678,100	11,218,226
1964	8,412,887	5,068,925	8,936,693	2,796,130	11,732,823
1965	8,897,511	5,362,395	9,505,492	2,917,691	12,423,183
1966	9,392,121	5,671,481	10,065,399	3,051,507	13,116,906
1967	9,942,841	5,998,227	10,713,924	3,195,255	13,909,180
1968	10,417,309	6,338,489	11,185,421	3,351,994	14,537,415
1969	11,016,696	6,697,744	11,889,739	3,511,465	15,401,204
1970	11,621,097	7,075,839	12,606,262	3,685,757	16,292,019
1971	12,156,480	7,409,070	13,171,737	3,872,000	17,043,737
1972	12,658,897	7,753,542	13,667,524	4,124,842	17,792,366
1973	13,280,711	8,111,999	14,371,008	4,378,723	18,749,732
1974	13,891,138	8,483,277	15,033,222	4,644,676	19,677,898
1975	14,444,954	8,865,724	15,568,720	4,916,445	20,485,165
1976	14,858,797	9,255,088	15,851,518	5,187,210	21,038,729
1977	15,342,999	9,652,602	16,251,225	5,443,821	21,695,046
1978	15,842,537	10,057,767	16,669,750	5,696,534	22,366,284
1979	16,367,431	10,470,607	17,122,015	5,946,451	23,068,466
1980	16,902,183	10,891,713	17,606,882	6,194,935	23,801,817
1981	17,289,765	11,236,804	17,835,587	6,444,552	24,280,139
1982	17,608,546	11,581,588	17,963,983	6,753,284	24,717,268

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1983	17,863,437	11,923,727	17,959,005	7,049,289	25,008,294
1984	18,337,731	12,264,371	18,268,375	7,327,294	25,595,669
1985	18,868,621	12,603,123	18,595,279	7,614,710	26,209,990
1986	19,402,019	12,940,572	18,942,952	7,910,244	26,853,196
1987	19,998,898	13,278,357	19,439,771	8,213,858	27,653,630
1988	20,652,028	13,617,619	20,010,784	8,535,419	28,546,203
1989	21,289,672	13,959,576	20,591,090	8,876,435	29,467,525
1990	21,869,495	14,304,193	21,061,179	9,236,928	30,298,107
1991	22,417,283	14,716,822	21,456,091	9,606,123	31,062,214
1992	22,891,692	15,134,858	21,726,554	9,870,999	31,597,553
1993	23,324,771	15,554,334	21,895,761	10,137,241	32,033,002
1994	23,618,994	15,968,911	21,801,248	10,401,968	32,203,216
1995	23,889,359	16,375,751	21,644,799	10,651,179	32,295,978
1996	24,080,912	16,772,121	21,417,572	10,886,089	32,303,661
1997	24,271,852	17,158,119	21,267,298	11,105,781	32,373,079
1998	24,430,167	17,532,341	21,075,316	11,318,451	32,393,766
1999	24,586,596	17,894,691	20,876,123	11,522,158	32,398,281
2000	24,750,616	18,245,399	20,674,846	11,718,630	32,393,476
2001	24,902,544	18,603,400	20,457,834	11,909,122	32,366,956
2002	25,011,225	18,953,218	20,211,050	12,056,312	32,267,361
2003	25,124,712	19,289,881	19,963,764	12,195,519	32,159,283
2004	25,244,024	19,622,009	19,738,971	12,335,268	32,074,239
2005	25,335,480	19,944,978	19,492,526	12,467,366	31,959,892
2006	25,426,451	20,258,898	19,252,306	12,595,311	31,847,616
2007	25,577,995	20,565,772	19,118,231	12,720,014	31,838,244
2008	25,696,292	20,864,602	18,919,496	12,847,528	31,767,025
2009	25,797,826	21,155,291	18,685,346	12,972,577	31,657,923
2010	25,878,853	21,436,884	18,388,716	13,094,130	31,482,846
2011	25,980,851	21,710,724	18,164,541	13,209,523	31,374,065
2012	26,076,597	21,976,891	17,947,134	13,323,709	31,270,843
2013	26,194,963	22,236,685	17,785,729	13,436,113	31,221,842