Estimates of carbon stored in harvested wood products from United States Forest Service Northern Region, 1906-2012

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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 1906 to 2012 for the USFS Northern Region. For the Northern Region as a whole, carbon stocks in the HWP pool were increasing at approximately 680,000 megagrams of carbon (MgC) per year in the early1950s through the mid-1990s, with peak cumulative storage of 34.1 million MgC occurring in 1995. Net positive flux into the HWP pool over this period is primarily attributable to high harvest levels in the early1960s through the early 1990s. In the years between the early-1960s and the late 1970s timber harvests were at high levels and experienced moderate variability, with high harvests of over 3.1 million ccf (2.3 million MgC) occurring four times during this period. Harvest levels from National Forests of the Northern Region have since declined to less than 450,000 ccf (340,000 MgC) per year, resulting in less carbon entering the HWP pool. Since 1996, 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 Northern Region's HWP pool is now in a period of negative net annual stock change because the decay of products harvested between 1906 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 Northern Region as a whole, this accounting method can be applied more broadly at smaller land management units, such as National Forests.

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Cover: Tracked log loader handles recently processed sawlogs in a Ponderosa pine stand on the Bitterroot National Forest in western Montana. Photo courtesy of Dan Loeffler (Rocky Mountain Research Station, Missoula, MT).

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 Northern 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 Northern Region currently administers approximately 24.4 million acres of National Forest spanning across five states located in and around the Northern Rocky Mountains and the northern portion of the American Great Plains, representing approximately 12.9% of total US National Forest System lands (USFS 2012). The Northern Region includes the Beaverhead-Deerlodge, Bitterroot, Custer, Flathead, Gallatin, Helena, Idaho Panhandle, Kootenai, Lewis and Clark, Lolo, and Nez Perce-Clearwater National Forests.

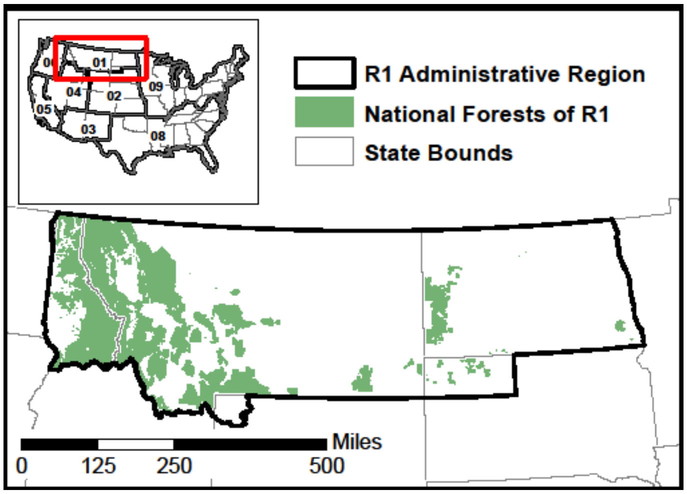

Figure 1. Map of the Northern Region (also known as R1).

Historical Northern 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 Northern Regional boundary. One change occurred at the western border of the Northern Region concerning the Colville National Forest of the Pacific Northwest Region, which has been reported with the Northern Region at points in the past. Where this change occurred, inclusion or exclusion of harvest volumes in this report were 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 administrative Forests have combined into the current eleven National Forests administered by the Northern 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 Northern 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).

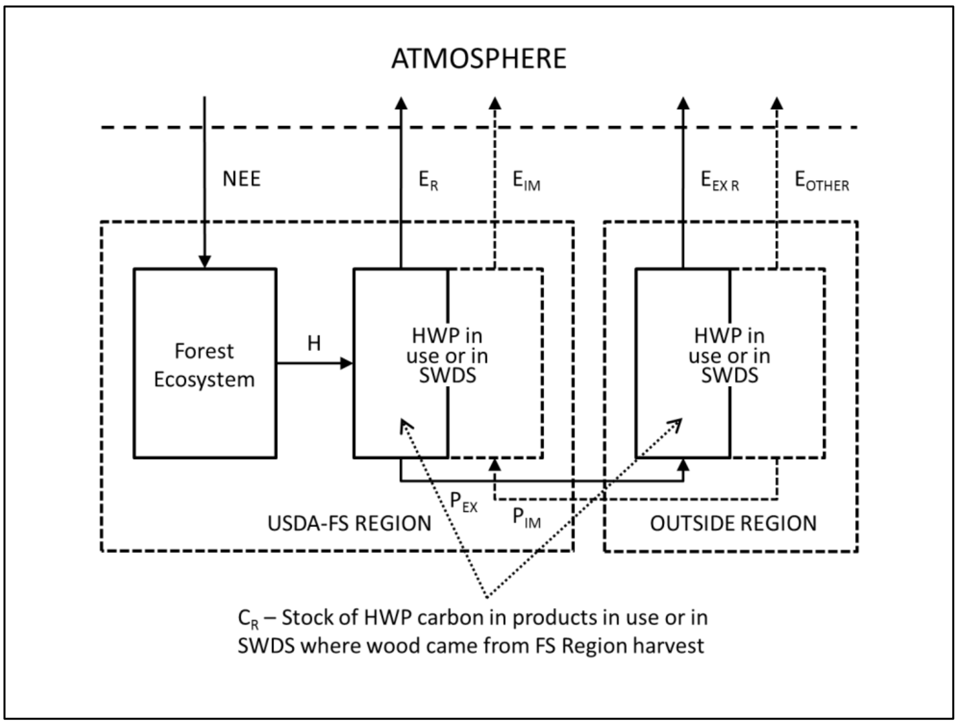

Figure 2. Carbon flows and stocks associated with forest ecosystems and harvested wood products (HWP) to illustrate the IPCC/EPA production accounting approach (adapted from Skog 2008).

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 ΔS=(NEE-H)+(ΔC_{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 Northern 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
2.2	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 1906 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).

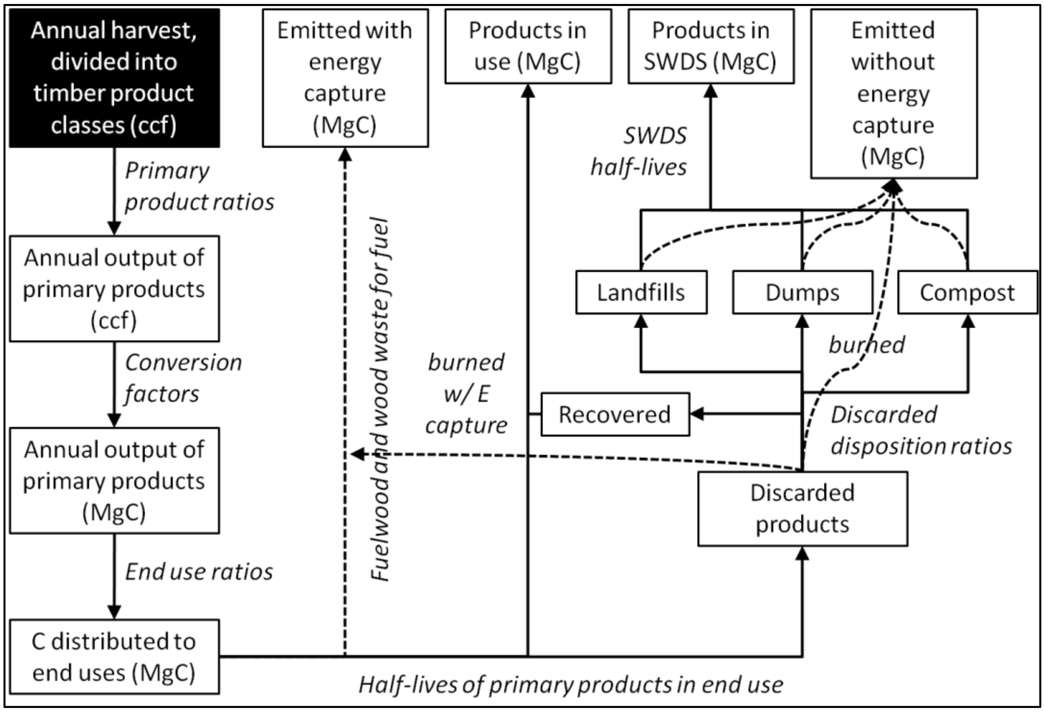

Figure 3. A schematic of calculations to quantify HWP storage and emissions. These calculations quantify HWP products in use, products in SWDS, emissions with energy capture, and emissions without energy capture using the IPCC/EPA approach.

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 1906 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 Northern Region, annual harvest data from 1906 through 1976 were supplied by the Northern Regional Office. Throughout the harvest record, data were available at either the national forest level or at the Region level, with no instances of concurrent voids in both harvest data sets. In instances when lands administered within current national forest or regional boundaries were formerly administered within neighboring national forests or regions, timber volumes were reapportioned based on available details but had no bearing on Regional harvest totals in most cases. One exception occurred at the western border of the Northern Region concerning the Colville National Forest of the Pacific Northwest Region, which has been reported with the Northern Region at points in the past. 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 mainly upon fiscal year harvests. However, Northern Region harvest data for years 1921 through 1933 were reported for calendar years only, as opposed to the most conventional reporting style of fiscal years. To avoid overestimating harvest in calendar year 1933, harvest data from this year was reduced by half. This is because calendar year 1933 spanned January 1, 1933 to December 31, 1933 and fiscal year 1934 spanned July 1, 1933 to June 30, 1934; therefore, harvests recorded in calendar year 1933 were reduced by half with the assumption that half of the harvest recorded in calendar year 1933 (which included half of fiscal year 1934) is approximately equal to harvests from the first half of fiscal year 1934. Also, harvest data from July 1, 1920 through December 31, 1920 is not included in this analysis given the transition from fiscal year 1920 to calendar year 1921. 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 1906 and 2000 volumes were reported in mbf only. For this period annual harvest totals for Northern Region reported in mbf were converted to ccf using a conversion factor of 2.2 ccf per mbf in use by the Region (Table 2). No conversion was necessary for years 2001 and later since ccf is provided in the harvest data.

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

Northern Region harvest records from 1906 through 1976 do not partition the harvest among different timber product classes; they report only total annual harvest. To estimate the proportion of total Northern 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 1906 through 1976 (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 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.

Table 3. The average annual proportion of 1977 through 2012 Northern Region harvests distributed to timber product classes between 1906 and 1976 (n=36).

Product class	Mean	Std. Error
Sawtimber, softwood	0.75	0.023
Fuelwood, softwood	0.11	0.015
Pulpwood, softwood	0.06	0.007
Non-Sawtimber, softwood	0.04	0.012
Other products	0.04	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 Northern Region with the exceptions of north-eastern Washington and north-western South Dakota, which contains part of the Idaho Panhandle and Custer National Forests and of the Northern Region, respectively. 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 Northern Region. However, our modeling for this report is based on aggregated harvests for the entire Northern 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 Northern 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 1906 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 Northern Region

Between 1906 and 1929 the annual timber harvests in Northern Region remained below 325,000 MgC yr^{-1}, followed by relatively low harvests during the Great Depression of the early 1930s (Table 5, Figure 4). Beginning in 1940, harvests surpassed 225,000 MgC yr^{-1} and began to increase steadily through the early mid-1960s. From the mid-1960s to the early1990s annual harvest levels remained between 887,000 and 2.42 million MgC yr^{-1}, peaking in 1968 where annual timber harvest in the Region exceeded 2.42 million MgC. Starting in the early1990s harvest volumes experienced a steep decline to a low in 2007 of less than 245,000 MgC, the lowest harvest since 1942. Slight increases in timber harvests have occurred since 2007, but have remained below 335,000 MgC yr^{-1} (Table 5, Figure 4).

Table 5. Annual timber product output in the Northern 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	219,538	162,333
1920	279,675	206,801
1930	226,318	167,347
1940	305,631	225,993
1950	633,376	468,338
1960	2,198,313	1,625,544
1970	3,149,714	2,329,064
1980	1,838,864	1,359,785
1990	2,234,204	1,652,549
1995	770,724	569,963
2000	566,825	419,183
2005	489,137	361,731
2006	349,366	258,374
2007	324,751	240,209
2008	349,292	258,354
2009	391,472	289,630
2010	396,664	293,449
2011	415,984	307,754
2012	446,486	330,307

The cumulative carbon stored in the Northern Region HWP began to accelerate substantially around 1955 and continued to increase at a steady rate until peaking in 1995 with just over 34.1 million MgC in storage (Figure 5, Table 6, Appendix B). For reference, this is equivalent to nearly 125 million $MgCO_2$, the CO_2 equivalent annual emissions from 23.9 million passenger vehicles, 290.8 million barrels of oil, or the CO_2 equivalent emissions from 652,900 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 32.2 million MgC, levels not seen since 1991 (Figure 5, Table 6).

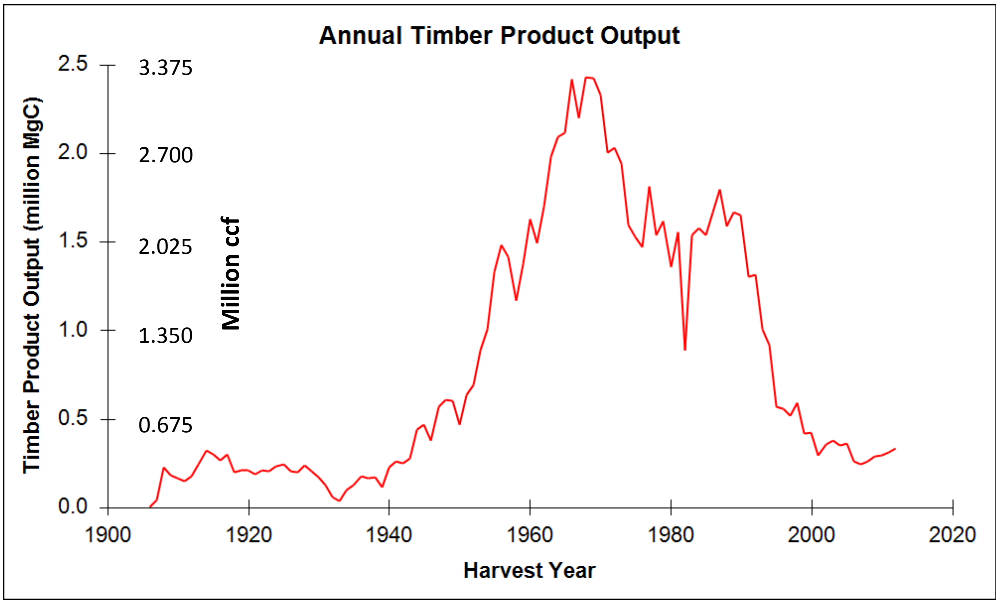

Figure 4. Annual timber product output in the Northern Region, 1906 to 2012. Harvest estimates are based on data collected from USDA Forest Service Archives and Cut/Sold reports.

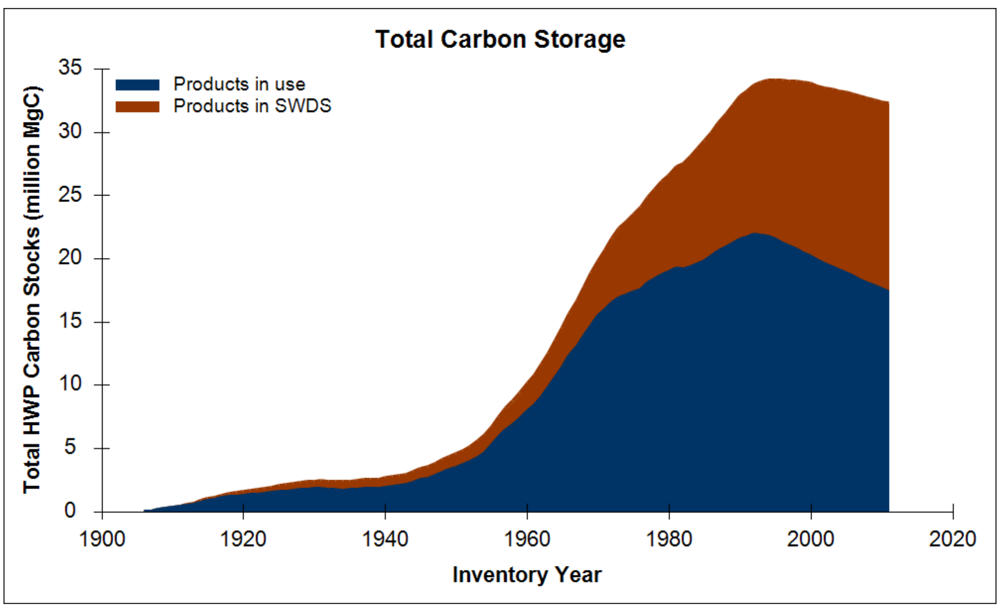

Figure 5. Cumulative total carbon stored in HWP manufactured from Northern Region timber using the IPCC/EPA approach. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposal sites (SWDS), including landfills and dumps.

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 1906 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 Northern 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	157,775	11,155	250,380	10,311	260,691
1920	979,350	243,334	1,211,582	272,383	1,483,965
1930	1,727,524	732,027	1,766,725	579,017	2,345,741
1940	2,161,449	1,315,064	1,819,082	742,526	2,561,608
1950	3,607,503	2,099,420	3,309,652	1,030,317	4,339,969
1960	7,316,858	3,676,292	7,299,759	2,042,370	9,342,129
1970	14,588,673	7,156,744	14,728,858	4,101,475	18,830,334
1980	20,611,934	11,636,470	18,742,248	7,363,803	26,106,051
1990	25,766,905	15,548,147	21,233,100	10,896,907	32,130,007
1995	27,749,215	17,852,570	21,803,312	12,344,291	34,147,603
2000	28,651,382	19,943,251	20,473,938	13,452,751	33,926,689
2005	29,297,401	21,832,667	19,125,240	14,156,204	33,281,444
2006	29,429,680	22,181,587	18,900,134	14,272,042	33,172,176
2007	29,534,202	22,519,813	18,616,583	14,385,134	33,001,718
2008	29,633,902	22,847,430	18,335,166	14,492,673	32,827,839
2009	29,751,883	23,164,505	18,067,105	14,595,933	32,663,038
2010	29,894,255	23,471,396	17,817,645	14,695,795	32,513,441
2011	30,026,507	23,768,739	17,592,008	14,793,280	32,385,289
2012	30,157,770	24,057,223	17,390,318	14,889,525	32,279,844
2013	30,292,236	24,337,584	17,214,903	14,985,470	32,200,373

[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 1940s additions to carbon stocks in HWP were growing by over 80,000 MgC yr^{-1}, increasing to over 650,000 MgC yr^{-1} in the mid-1950s; peak stock growth occurred in 1967 with the addition of slightly more than 1.14 million MgC. After 1967, additions to carbon stock in HWP began to decline with the addition of just over 260,000 MgC in 1983. Following 1983, additions to the HWP carbon pool began to increase reaching just over 783,000 MgC in 1989, before beginning to decline. In 1996, the net change moved from positive to negative, and since then the Northern HWP pool has become a net source of atmospheric carbon, with the exceptions of 1999 when just over 10,000 MgC were added to the carbon stock. The year with the largest negative net change from the Northern Region HWP carbon pool was 2002, when stocks decreased by over 185,000 MgC. However, since 2008 additions to the HWP through new harvest have grown faster than emissions from the HWP pool. Recall that these estimates relate only to HWP and do not quantify carbon fluxes in the ecosystem pool.

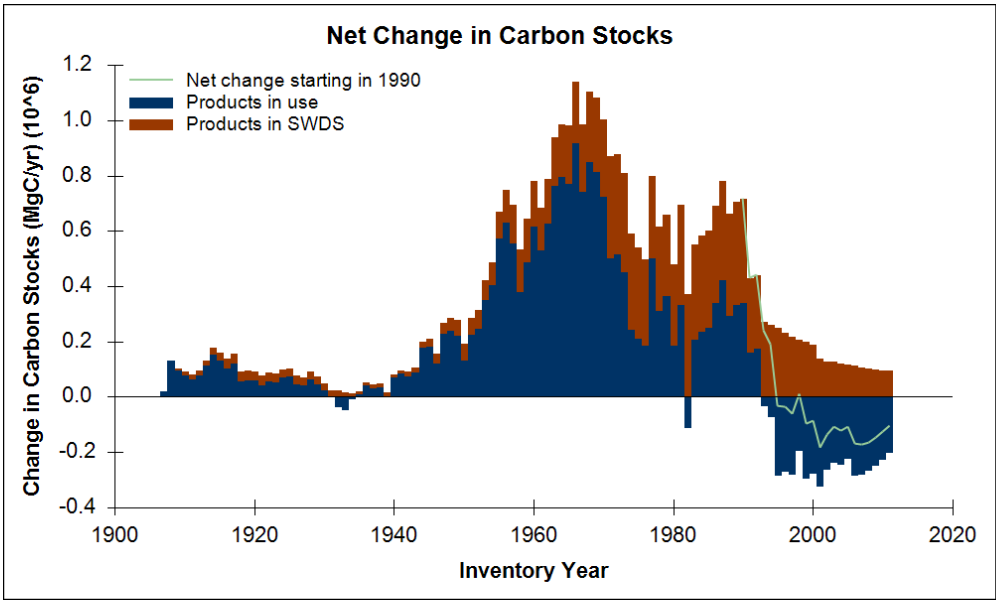

Figure 6. The net change in carbon stocks in HWP from the previous year using the IPCC/EPA production accounting approach. The net stock change is the sum of net change for SWDS and products in use. The total net change trend line shows a transition from net additions to carbon stocks in HWP to a period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

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

Inventory Year	Stock change[a] (MgC yr^{-1})
1910	104,303
1920	94,946
1930	73,375
1940	15,279
1950	277,673
1960	647,276
1970	1,084,419
1980	661,022
1990	707,464
1995	189,381
2000	-96,899
2005	-123,998
2006	-109,268
2007	-170,458
2008	-173,879
2009	-164,801
2010	-149,597
2011	-128,152
2012	-105,445
2013	-79,471

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

To quantify uncertainty, confidence intervals were estimated for HWP stock estimates using Monte Carlo simulation, representing 18 random variable distributions, with distributions determined from publications and expert opinion. Table 8 shows the resulting confidence intervals for the IPCC/EPA estimates for selected years. For 1995, the year of peak carbon stocks in Table 8, the 90% confidence interval ranges from 34,108,116 MgC to 34,145,741 MgC, with a mean value of 34,126,928 MgC. This is equivalent to a ±0.06% difference from the mean.

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

Inventory year	Simulation Mean (MgC)	90% Confidence interval Lower limit (MgC)	90% Confidence interval Upper limit (MgC)
1910	261,295	260,602	261,988
1920	1,485,521	1,483,679	1,487,362
1930	2,346,934	2,344,710	2,349,157
1940	2,561,302	2,559,084	2,563,521
1950	4,338,895	4,335,424	4,342,365
1960	9,340,640	9,333,760	9,347,520
1970	18,828,299	18,815,515	18,841,084
1980	26,094,353	26,078,070	26,110,635
1990	32,108,768	32,090,539	32,126,998
1995	34,126,928	34,108,116	34,145,741
2000	33,908,127	33,889,515	33,926,740
2005	33,264,552	33,246,143	33,282,962
2006	33,155,741	33,137,348	33,174,135
2007	32,985,736	32,967,374	33,004,098
2008	32,812,364	32,794,035	32,830,694
2009	32,648,168	32,629,866	32,666,469
2010	32,498,709	32,480,431	32,516,988
2011	32,371,379	32,353,110	32,389,649
2012	32,265,967	32,247,698	32,284,237
2013	32,186,956	32,168,670	32,205,241

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 2006 HWP stock estimate of 33.2 teragrams of carbon (TgC) presented in Table 6 by the sum of this stock estimate and Heath et al.'s (2011) estimated 2006[4] Northern Region ecosystem carbon stock of 1,530 TgC, we estimate that the Northern Region HWP carbon stocks represent roughly 2.1% of total forest carbon storage associated with National Forests in the Northern Region as of 2006. At the

[4] Mean measurement year reported as 2006.2.

national level, based on the EPA's total US HWP 2006 stock estimate of 2,383 TgC (US EPA 2012), the Northern Region HWP carbon stocks represented 1.4% 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 Northern 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.

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 Northern 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 Northern Region HWP pool is now in a period of negative net annual stock because the decay of products harvested between 1906 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)
1907	303	13	506	-	506
1908	13,627	587	22,743	30	22,773
1909	93,784	4,537	155,026	1,362	156,388
1910	157,775	11,155	250,380	10,311	260,691
1911	215,397	20,140	328,837	23,799	352,636
1912	266,893	31,187	392,540	40,056	432,596
1913	329,518	44,711	471,725	57,781	529,507
1914	414,774	61,607	584,570	77,666	662,236
1915	528,636	83,013	738,716	101,439	840,154
1916	635,173	108,539	871,357	131,051	1,002,408
1917	728,980	137,555	975,697	164,490	1,140,187
1918	835,147	170,487	1,096,197	199,509	1,295,707
1919	906,091	205,745	1,152,202	236,817	1,389,019
1920	979,350	243,334	1,211,582	272,383	1,483,965
1921	1,052,757	283,168	1,270,217	306,588	1,576,805
1922	1,118,003	324,820	1,314,107	339,671	1,653,778
1923	1,191,558	368,564	1,371,768	370,986	1,742,754
1924	1,263,613	414,268	1,425,551	401,619	1,827,169
1925	1,345,620	462,286	1,494,826	431,506	1,926,332
1926	1,431,947	512,736	1,568,918	461,683	2,030,601
1927	1,502,997	564,910	1,614,742	492,435	2,107,178
1928	1,572,322	618,675	1,657,169	522,033	2,179,202
1929	1,655,261	674,550	1,721,972	550,394	2,272,366
1930	1,727,524	732,027	1,766,725	579,017	2,345,741
1931	1,786,926	790,513	1,789,343	606,735	2,396,078
1932	1,831,835	849,352	1,788,691	632,333	2,421,024
1933	1,852,720	907,494	1,750,389	654,709	2,405,099
1934	1,864,846	964,546	1,702,486	672,080	2,374,566
1935	1,898,378	1,021,403	1,695,622	684,540	2,380,162
1936	1,941,693	1,078,476	1,706,759	695,200	2,401,958
1937	2,003,142	1,136,531	1,748,354	705,442	2,453,796
1938	2,060,823	1,195,407	1,781,484	717,104	2,498,589
1939	2,120,630	1,255,188	1,816,846	729,484	2,546,330
1940	2,161,449	1,315,064	1,819,082	742,526	2,561,608
1941	2,241,668	1,377,451	1,888,426	754,144	2,642,571

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1942	2,332,736	1,441,950	1,971,911	767,747	2,739,658
1943	2,420,890	1,508,396	2,045,782	784,599	2,830,381
1944	2,519,527	1,577,207	2,133,536	803,658	2,937,194
1945	2,676,145	1,650,859	2,313,759	825,362	3,139,121
1946	2,840,904	1,729,610	2,496,390	854,708	3,351,098
1947	2,975,449	1,812,026	2,617,974	890,901	3,508,874
1948	3,177,810	1,900,961	2,847,753	929,386	3,777,139
1949	3,393,316	1,996,836	3,086,301	975,994	4,062,296
1950	3,607,503	2,099,420	3,309,652	1,030,317	4,339,969
1951	3,773,747	2,206,440	3,441,800	1,090,388	4,532,188
1952	3,998,473	2,320,009	3,668,181	1,150,385	4,818,566
1953	4,243,043	2,440,989	3,916,276	1,215,717	5,131,993
1954	4,557,557	2,572,234	4,268,680	1,287,656	5,556,336
1955	4,914,506	2,715,372	4,671,972	1,371,526	6,043,499
1956	5,386,297	2,874,816	5,245,397	1,469,061	6,714,458
1957	5,912,264	3,052,346	5,876,412	1,587,774	7,464,186
1958	6,414,351	3,246,884	6,430,790	1,728,078	8,158,868
1959	6,829,275	3,454,027	6,811,082	1,883,772	8,694,853
1960	7,316,858	3,676,292	7,299,759	2,042,370	9,342,129
1961	7,893,854	3,921,463	7,916,655	2,209,148	10,125,803
1962	8,424,448	4,185,947	8,445,703	2,363,827	10,809,529
1963	9,027,723	4,471,381	9,073,153	2,526,274	11,599,427
1964	9,730,567	4,780,685	9,837,718	2,701,447	12,539,165
1965	10,473,643	5,114,198	10,632,576	2,895,021	13,527,596
1966	11,225,405	5,471,556	11,404,547	3,105,605	14,510,152
1967	12,084,108	5,856,341	12,321,940	3,330,668	15,652,607
1968	12,864,730	6,264,569	13,063,823	3,576,330	16,640,153
1969	13,726,885	6,698,511	13,914,227	3,831,688	17,745,915
1970	14,588,673	7,156,744	14,728,858	4,101,475	18,830,334
1971	15,415,385	7,558,322	15,453,437	4,381,322	19,834,759
1972	16,127,123	7,974,258	15,956,374	4,749,812	20,706,186
1973	16,849,474	8,403,655	16,471,674	5,112,822	21,584,497
1974	17,538,497	8,844,464	16,924,390	5,470,762	22,395,152
1975	18,104,503	9,292,689	17,166,934	5,819,780	22,986,715
1976	18,646,815	9,747,353	17,377,701	6,149,679	23,527,380
1977	19,169,705	10,207,130	17,563,765	6,463,547	24,027,313
1978	19,695,641	10,676,905	18,066,699	6,762,416	24,829,115
1979	20,142,404	11,152,910	18,377,259	7,067,770	25,445,029

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1980	20,611,934	11,636,470	18,742,248	7,363,803	26,106,051
1981	21,013,677	12,031,886	18,928,704	7,656,044	26,584,748
1982	21,470,325	12,428,554	19,261,013	8,020,692	27,281,705
1983	21,732,786	12,822,547	19,150,246	8,391,687	27,541,933
1984	22,329,074	13,215,358	19,358,593	8,737,261	28,095,854
1985	22,929,519	13,606,212	19,593,843	9,085,702	28,679,546
1986	23,473,658	13,995,291	19,845,872	9,436,599	29,282,471
1987	24,054,488	14,383,416	20,184,336	9,789,602	29,973,938
1988	24,667,448	14,771,533	20,607,192	10,150,152	30,757,344
1989	25,201,989	15,159,498	20,900,020	10,522,523	31,422,543
1990	25,766,905	15,548,147	21,233,100	10,896,907	32,130,007
1991	26,303,845	16,007,991	21,571,980	11,276,477	32,848,457
1992	26,721,499	16,471,643	21,732,081	11,545,598	33,277,678
1993	27,134,827	16,936,794	21,906,593	11,813,339	33,719,932
1994	27,459,901	17,397,900	21,874,564	12,083,658	33,958,222
1995	27,749,215	17,852,570	21,803,312	12,344,291	34,147,603
1996	27,942,433	18,295,963	21,517,373	12,596,216	34,113,589
1997	28,134,710	18,727,154	21,246,720	12,828,549	34,075,269
1998	28,318,282	19,145,153	20,966,670	13,046,707	34,013,377
1999	28,507,915	19,551,033	20,771,219	13,252,369	34,023,588
2000	28,651,382	19,943,251	20,473,938	13,452,751	33,926,689
2001	28,797,866	20,342,143	20,196,984	13,641,527	33,838,511
2002	28,909,432	20,730,925	19,872,009	13,780,747	33,652,757
2003	29,037,498	21,105,318	19,607,589	13,907,942	33,515,531
2004	29,171,225	21,474,044	19,369,140	14,036,302	33,405,442
2005	29,297,401	21,832,667	19,125,240	14,156,204	33,281,444
2006	29,429,680	22,181,587	18,900,134	14,272,042	33,172,176
2007	29,534,202	22,519,813	18,616,583	14,385,134	33,001,718
2008	29,633,902	22,847,430	18,335,166	14,492,673	32,827,839
2009	29,751,883	23,164,505	18,067,105	14,595,933	32,663,038
2010	29,894,255	23,471,396	17,817,645	14,695,795	32,513,441
2011	30,026,507	23,768,739	17,592,008	14,793,280	32,385,289
2012	30,157,770	24,057,223	17,390,318	14,889,525	32,279,844
2013	30,292,236	24,337,584	17,214,903	14,985,470	32,200,373