Estimates of carbon stored in harvested wood products from United States Forest Service Alaska Region, 1910-2012

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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 1910 to 2012 for the USFS Alaska Region. For the Alaska Region as a whole, carbon stocks in the HWP pool were increasing at nearly one-half million megagrams of carbon (MgC) per year in the late 1960s and early 1970s, with peak cumulative storage of 13.5 million MgC occurring in 1996. Net positive flux into the HWP pool over this period is primarily attributable to high harvest levels in the mid-1950s through the 1990s. Harvest levels declined after 1990, resulting in less carbon entering the HWP pool. Since 2005, emissions from HWP at solid waste disposal sites have exceeded additions from harvesting, resulting in a decline in the total amount of carbon stored in the HWP pool. The Alaska Region HWP pool is now in a period of negative net annual stock change because the decay of products harvested between 1910 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 Alaska 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: Alaska yellow-cedar boardwalk on Prince of Wales Island over a karst viewing area, built from locally harvested trees. Photo courtesy of Dr. Susan Alexander, Regional Economist, Region 10 (Alaska Region).

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 Alaska 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 Alaska Region currently administers approximately 22 million acres of National Forest in the state of Alaska, or 11.7% of total US National Forest System lands (USFS 2012). Approximately 45% of the Alaska Region is forested (9.9 million acres) and 26% is designated wilderness. The Tongass National Forest is the largest in the National Forest System, with 16.8 million acres and the Tongass Land Management Plan identifies 176,000 acres for timber harvest in the coming century. The Chugach National Forest is the second largest in the US, and is managed almost entirely as fish and wildlife habitat (http://www.akforest.org).

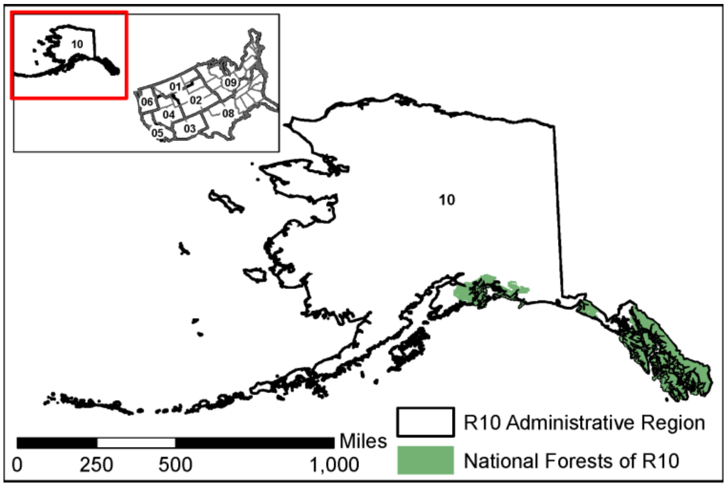

Figure 1. Map of the Alaska Region (also known as R10).

Historical Alaska 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. Although National Forest boundaries within the Alaska Region have changed, the Alaska Region boundary itself has not changed from 1910 so no standardization of Alaska Region timber harvests were necessary with no changes in Regional land base. Estimates of Alaska Region HWP carbon include timber harvested from National Forest land within the Region's current administrative boundary from 1910 to 2012. 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.

Methods

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

Accounting Approach

We use the IPCC production accounting approach, which has been adopted by the US Environmental Protection Agency (EPA; hereafter referred to as the IPCC/EPA approach) to estimate annual changes in HWP pools from the Region (Figure 2). In the IPCC/EPA approach, the annual carbon stock change for the Region's forest sector is a function of carbon flow among the atmosphere, forest ecosystems, and HWP, and is calculated as:

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

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

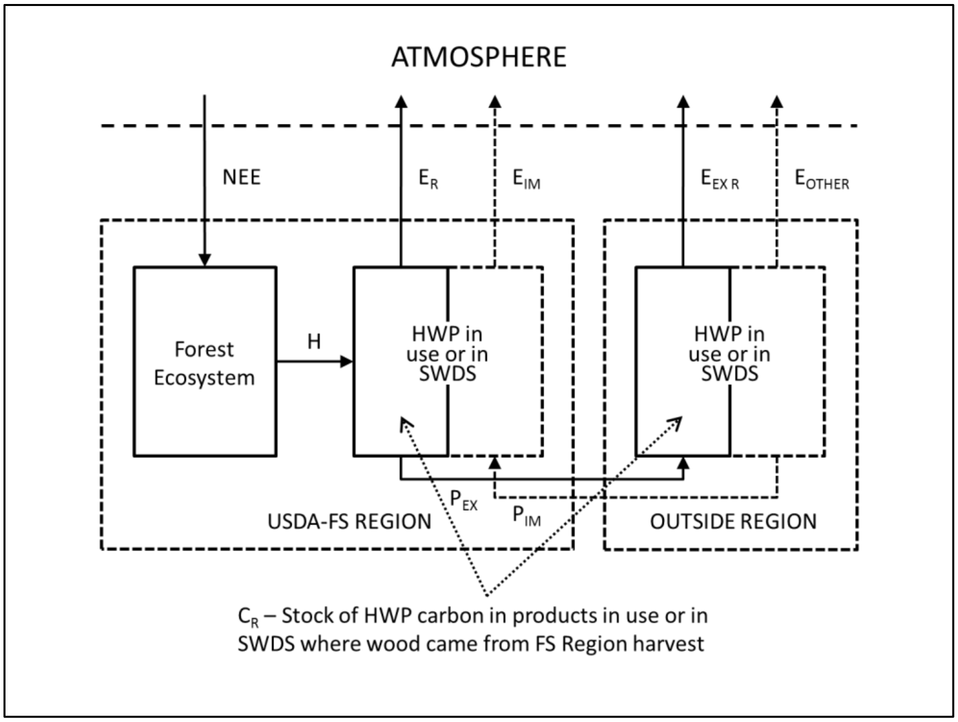

Figure 2. Carbon flows and stocks associated with forest ecosystems and harvested wood products (HWP) to illustrate the IPCC/EPA production accounting approach (adapted from Skog 2008).

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

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

System boundaries

Most people are familiar with imports and exports in the context of international trade, but the concept can be applied to understand the treatment of carbon imports and exports in the IPCC/EPA approach. In this case the terms export and import refer to the border of the Alaska 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
2.1443	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.

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[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 1910 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).

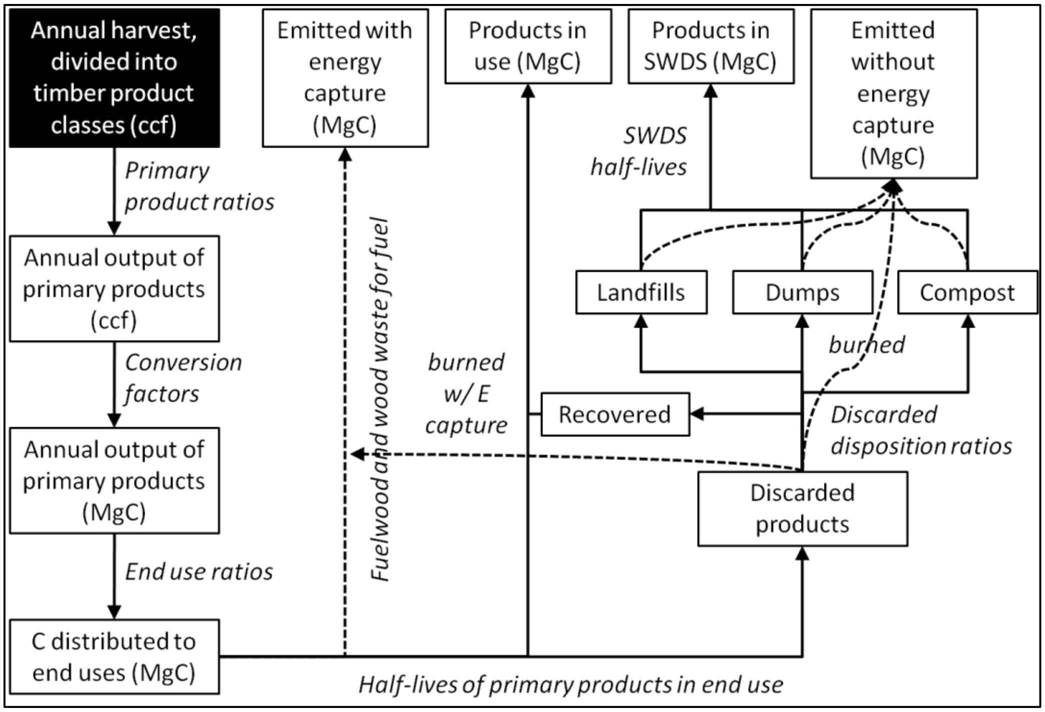

Figure 3. A schematic of calculations to quantify HWP storage and emissions. These calculations quantify HWP products in use, products in SWDS, emissions with energy capture, and emissions without energy capture using the IPCC/EPA approach.

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 1910 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 Alaska Region, annual harvest data from 1910 to present was supplied by the Regional Office. All results in this report are based mainly upon fiscal year harvests. However, Alaska Region harvest data for fiscal years 1920 through 1951 were missing from the data provided, yet calendar year harvest data was available for all years. For ease of reporting, harvest data from 1910 through 1951 were based upon calendar year harvest data while years 1952 to present were based upon fiscal year harvest data. Also, because calendar year 1951 spanned January 1 to December 31, and fiscal year 1952 spanned July 1, 1951 to June 30, 1952, harvests recorded in calendar year 1951 were reduced by half with the assumption that harvests recorded in fiscal year 1952 (which included half of calendar year 1951) is approximately equal to reduction of calendar year 1951 harvests. 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 1910 and 2000 volumes were reported in mbf only. For this period annual harvest totals for Alaska Region reported in mbf were converted to ccf using a conversion factor of 2.1443 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

Alaska Region harvest records from 1910 through 1976 do not partition the harvest among different timber product classes; they report only total annual harvest. To estimate the proportion of total Alaska 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 1910 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 Alaska Region harvests distributed to timber product classes between 1910 and 1976 (n=36).

Product class	Mean	Std. Error
Sawtimber, softwood	0.86	0.01
Pulpwood, softwood	0.13	0.009
Small rnd wd, softwood	0.007	0.004
Fuelwood, softwood	0.005	0.001
Other products	0.0006	0.0001

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). For the Alaska Region the proportion of volume in each timber product class (e.g. softwood sawlogs) allocated to primary wood products (e.g. softwood lumber, softwood plywood, etc.) are not described by Smith et al. To estimate primary wood product allocation for Alaska Region, we began by using the nearest Region's primary product allocation – the Pacific Northwest, West – from Smith et al, and adjusted the allocations according to the presence or absence of primary product industries in Alaska Region. For example, due to the plywood industry existing within Alaska Region for only years 1953 through 1959, for all other years the fraction of harvested timber products allocated to plywood primary product was added to the lumber primary product. Similarly, a lack of a non-structural panel industry within the Region resulted in that fraction of harvested timber products being allocated to other industrial products.

We were also required to make simple assumptions regarding the allocation of pulplogs to primary product categories in the years when Alaska Region had no pulp industry; pulping occurred in the Region from 1921 to 1925 and then from 1954 through 1997 (Halbrook et al. 2009). For years 1910 to 1920 and 1926 to 1954 we split equally the proportion of timber product allocated to pulp primary product to other industrial products and fuelwood. Following 1998 all pulplogs were allocated to lumber. Although we made assumptions about a few primary product classes based on historical information, in general we had a strong set of historical data to use in our calculations.

Historical end use data

The historical end use data used for the Alaska 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 1910 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 Alaska Region

Between 1910 and 1943 the annual timber harvests in Alaska Region remained below 100,000 MgC yr^{-1} and were relatively low during the early 1920's, and then again during the Great Depression in the 1930's (Table 5, Figure 4). During this time period, harvests were highest toward the end of World War II. From 1944 to 1955 annual harvest levels remained around 100,000 MgC and then increased rapidly, to maximum harvest levels in the early 1970's. At its peak in 1973, the annual timber harvest in the Region exceeded 940,000 MgC. Then in the mid-1970's annual harvests began to decrease, with a particularly steep decrease during the economic recession of the early 1980's. Between 1986 and 1990 the harvest level rose sharply, but then fell nearly every year from 1991 to 1998. Slight increases in harvest occurred from 1999 to 2001 and harvest levels since 2002 have been below 80,000 MgC yr^{-1}, which is similar to the harvest levels of the early twentieth century (Table 5, Figure 4).

Table 5. Annual timber product output in the Alaska 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	40,349	29,857
1920	108,164	80,039
1930	96,402	71,336
1940	70,473	52,149
1950	128,378	94,998
1960	690,354	510,874
1970	1,063,797	787,228
1980	1,032,489	764,097
1990	1,011,491	748,630
1995	478,371	353,995
2000	315,457	233,426
2005	104,936	77,661
2006	89,597	66,313
2007	41,451	30,672
2008	58,031	42,943
2009	61,464	45,485
2010	78,015	57,728
2011	73,615	54,478
2012	46,904	34,708

The cumulative carbon stored in the Alaska Region HWP peaked in 1996 at just slightly more than 13.5 million MgC (Figure 5, Table 6, Appendix B). For reference, this is equivalent to 49.5 million $MgCO_2$, the CO_2 equivalent annual emissions from 9.5 million passenger vehicles, 115 million barrels of oil, or the CO_2 equivalent emissions from 258,000 railcars of coal. Since 1996, carbon stocks in the HWP pool for the Alaska Region have been in a fairly slow decline (Figure 5), with slight increases in 2000 and 2001. The 2012 HWP pool is estimated to have been around 12.6 million MgC (Figure 5, Table 6).

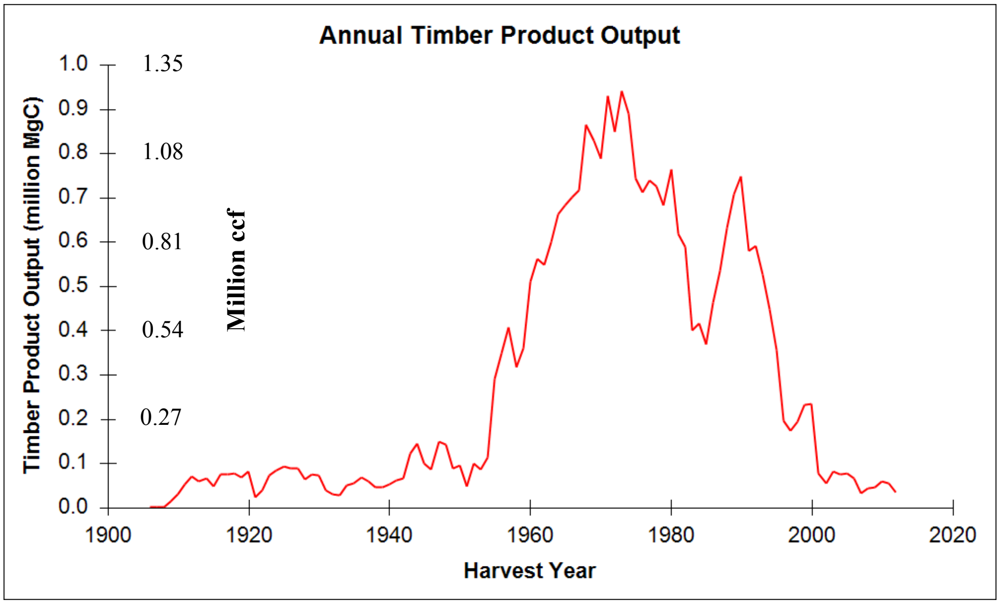

Figure 4. Annual timber product output in the Alaska Region, 1910 to 2012. Harvest estimates are based on data collected from USDA Forest Service Archives and Cut/Sold reports.

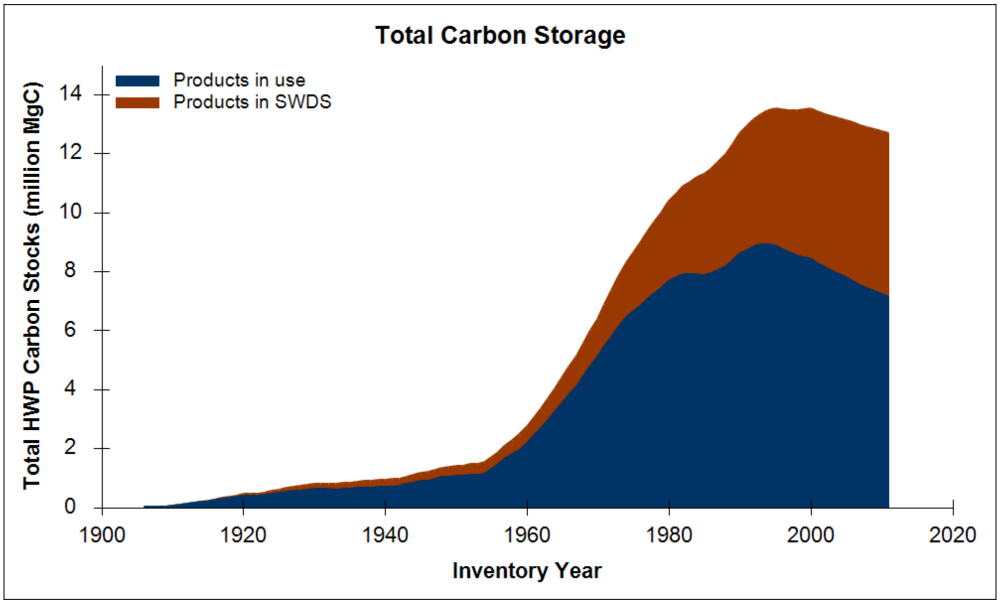

Figure 5. Cumulative total carbon stored in HWP manufactured from Alaska Region timber using the IPCC/EPA approach. Carbon in HWP includes both products that are still in use and carbon stored at solid waste disposal sites (SWDS), including landfills and dumps.

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 1910 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 Alaska 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	3,840	215	8,542	-	8,542
1920	183,908	46,286	328,490	56,264	384,754
1930	389,294	178,820	580,303	161,514	741,817
1940	531,050	365,477	661,791	238,369	900,160
1950	825,657	609,920	1,026,421	329,677	1,356,098
1960	1,456,668	996,951	1,923,265	528,327	2,451,592
1970	3,410,263	2,069,907	4,788,761	1,207,031	5,995,793
1980	5,702,570	3,727,478	7,422,983	2,558,009	9,980,991
1990	7,322,896	5,241,633	8,366,204	3,945,680	12,311,884
1995	8,210,040	6,146,090	8,904,643	4,531,731	13,436,374
2000	8,533,080	6,992,075	8,459,892	5,011,210	13,471,103
2005	8,651,751	7,739,648	7,882,939	5,291,495	13,174,433
2006	8,667,598	7,873,427	7,774,567	5,333,325	13,107,892
2007	8,683,173	8,001,982	7,661,748	5,373,714	13,035,462
2008	8,689,885	8,125,149	7,529,938	5,412,490	12,942,428
2009	8,699,933	8,243,431	7,412,881	5,448,778	12,861,658
2010	8,710,757	8,357,097	7,302,775	5,483,859	12,786,634
2011	8,723,978	8,466,624	7,206,642	5,517,898	12,724,540
2012	8,737,232	8,572,243	7,111,557	5,551,544	12,663,100
2013	8,745,976	8,674,016	7,006,360	5,584,534	12,590,893

[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. In the late 1960s and early 1970s carbon stocks in HWP were growing by nearly one-half million MgC yr^{-1}; peak stock growth occurred in 1972 with the addition of slightly more than 500,000 MgC. In the late 1990’s, the net change moves from positive to negative, and following 2 years of net additions in 2000 and 2001, the Alaska Region HWP pool becomes a net source of atmospheric carbon. The year with the largest negative net change from the Alaska Region HWP carbon pool was 2003, when stocks decreased by nearly 98,000 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.

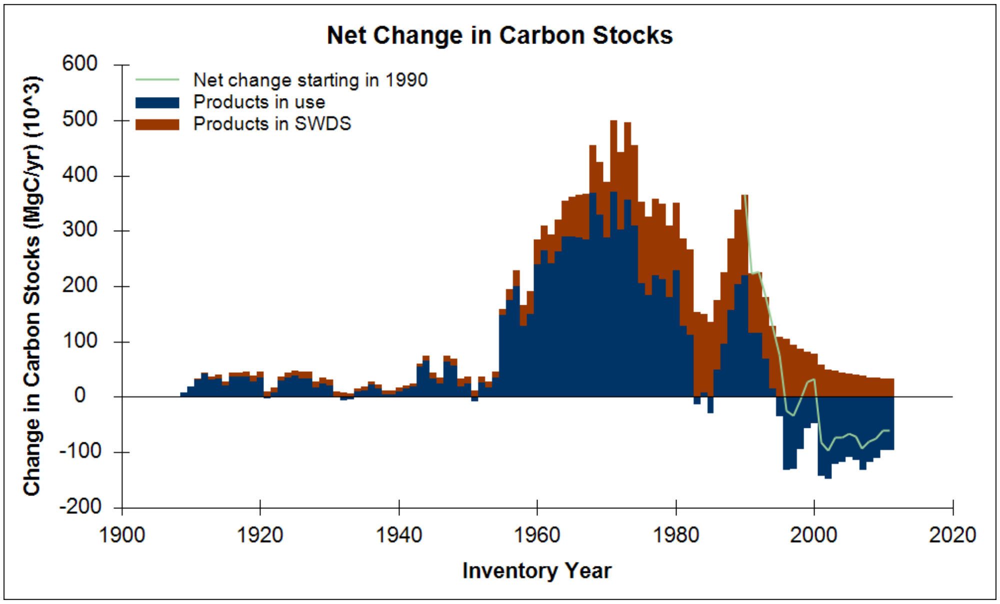

Figure 6. The net change in carbon stocks in HWP from the previous year using the IPCC/EPA production accounting approach. The net stock change is the sum of net change for SWDS and products in use. The total net change trend line shows a transition from net additions to carbon stocks in HWP to a period 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	8,542
1920	38,227
1930	35,675
1940	11,660
1950	33,145
1960	191,070
1970	424,821
1980	310,351
1990	339,209
1995	127,922
2000	26,396
2005	-73,805
2006	-66,542
2007	-72,430
2008	-93,034
2009	-80,769
2010	-75,024
2011	-62,094
2012	-61,439
2013	-72,207

[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 13,459,304 MgC to 13,476,002 MgC, with a mean value of 13,467,653 MgC. This is equivalent to a ±0.06% difference from the mean.

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

Inventory year	Simulation Mean (MgC)	90% Confidence interval	
		Lower limit (MgC)	Upper limit (MgC)
1910	8,532	8,498	8,565
1920	384,082	383,574	384,590
1930	741,474	740,703	742,244
1940	899,663	898,830	900,496
1950	1,355,552	1,354,405	1,356,700
1960	2,451,006	2,449,079	2,452,933
1970	5,995,807	5,991,143	6,000,470
1980	9,980,432	9,973,405	9,987,459
1990	12,309,176	12,301,276	12,317,076
1995	13,432,967	13,424,644	13,441,290
2000	13,467,653	13,459,304	13,476,002
2005	13,170,804	13,162,531	13,179,077
2006	13,104,305	13,096,049	13,112,561
2007	13,031,870	13,023,630	13,040,110
2008	12,938,880	12,930,660	12,947,100
2009	12,858,154	12,849,952	12,866,356
2010	12,783,216	12,775,025	12,791,407
2011	12,721,226	12,713,044	12,729,407
2012	12,659,794	12,651,616	12,667,972
2013	12,587,659	12,579,488	12,595,830

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 13.1 teragrams of carbon (TgC) presented in Table 6 by the sum of this stock estimate and Heath et al.'s (2011) estimated 2006[4] Alaska Region ecosystem carbon stock of 1,384 TgC, we estimate that the Alaska Region HWP carbon stocks represent roughly 0.9% of total forest carbon storage associated with National Forests in the Alaska Region as of 2006. At the national

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[4] Mean measurement year reported as 2006.2.

level, based on the EPA's total US HWP 2006 stock estimate of 2,383 TgC (US EPA 2012), the Alaska Region HWP carbon stocks represented 0.5% 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 Alaska 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 Alaska 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 Alaska 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 Alaska Region HWP pool is now in a period of negative net annual stock because the decay of products harvested between 1910 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).

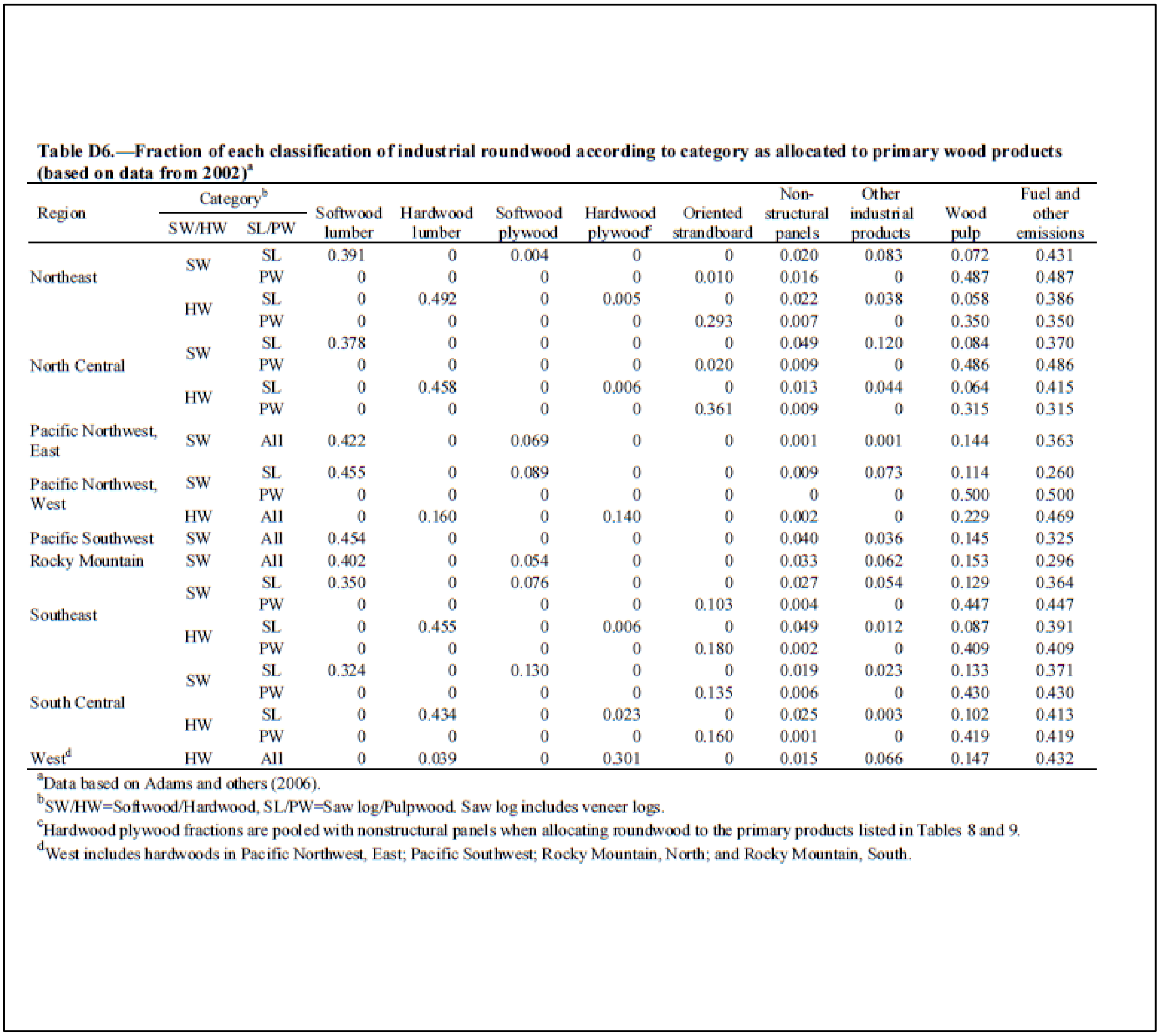

Table D6.—Fraction of each classification of industrial roundwood according to category as allocated to primary wood products (based on data from 2002)[a]

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

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

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

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

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

Appendix B

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

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1910	3,840	215	8,542	-	8,542
1911	12,576	891	27,417	503	27,920
1912	27,488	2,335	58,844	1,994	60,838
1913	48,015	4,812	100,853	5,009	105,862
1914	64,982	8,074	132,483	9,881	142,364
1915	83,967	12,250	166,990	15,674	182,664
1916	98,001	17,035	188,773	22,500	211,273
1917	119,631	22,878	226,656	29,460	256,117
1918	141,611	29,725	263,477	37,579	301,056
1919	164,198	37,589	299,975	46,552	346,527
1920	183,908	46,286	328,490	56,264	384,754
1921	207,328	56,026	364,250	66,161	430,411
1922	213,974	65,819	361,238	76,712	437,950
1923	225,091	76,096	369,032	85,516	454,548
1924	245,911	87,394	398,305	93,875	492,180
1925	270,304	99,919	433,675	103,150	536,826
1926	297,012	113,783	472,014	113,652	585,667
1927	322,901	128,910	506,295	125,359	631,654
1928	348,573	144,961	539,291	137,837	677,129
1929	367,258	161,525	555,962	150,180	706,142
1930	389,294	178,820	580,303	161,514	741,817
1931	410,167	196,737	601,649	172,584	774,233
1932	421,296	214,721	601,047	183,250	784,297
1933	429,694	232,679	595,464	192,331	787,795
1934	437,930	250,610	590,770	199,917	790,687
1935	452,274	268,849	600,697	206,326	807,023
1936	467,911	287,416	613,462	212,594	826,055
1937	487,835	306,538	635,512	218,825	854,336
1938	505,181	326,034	650,973	225,550	876,523
1939	518,119	345,671	656,248	232,252	888,500
1940	531,050	365,477	661,791	238,369	900,160
1941	546,308	385,836	672,727	244,057	916,784
1942	563,938	406,562	688,762	249,475	938,237
1943	582,868	427,709	707,178	255,144	962,322
1944	618,488	450,230	762,074	261,135	1,023,208

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1945	660,599	474,355	828,421	269,504	1,097,924
1946	689,872	499,265	862,702	280,364	1,143,066
1947	715,124	524,813	886,850	291,432	1,178,282
1948	758,606	552,071	951,044	302,285	1,253,329
1949	800,061	580,750	1,007,594	315,359	1,322,953
1950	825,657	609,920	1,026,421	329,677	1,356,098
1951	853,453	639,813	1,050,264	342,930	1,393,194
1952	867,079	669,501	1,042,286	355,871	1,398,157
1953	895,814	699,988	1,069,567	366,689	1,436,256
1954	920,586	730,930	1,087,109	377,988	1,465,097
1955	953,218	762,800	1,121,891	388,998	1,510,889
1956	1,037,942	798,872	1,270,096	400,807	1,670,903
1957	1,139,776	840,170	1,445,135	420,526	1,865,661
1958	1,258,683	887,732	1,645,336	448,999	2,094,335
1959	1,351,474	939,878	1,773,744	486,777	2,260,522
1960	1,456,668	996,951	1,923,265	528,327	2,451,592
1961	1,606,141	1,062,606	2,163,497	573,596	2,737,093
1962	1,770,570	1,137,565	2,428,699	619,000	3,047,699
1963	1,931,007	1,221,055	2,670,106	672,478	3,342,583
1964	2,106,292	1,313,414	2,932,766	731,438	3,664,204
1965	2,300,083	1,415,217	3,223,828	796,202	4,020,030
1966	2,500,053	1,526,522	3,514,285	867,377	4,381,662
1967	2,705,255	1,647,113	3,803,297	944,319	4,747,616
1968	2,914,902	1,777,099	4,088,941	1,026,021	5,114,962
1969	3,167,570	1,918,399	4,458,570	1,112,402	5,570,972
1970	3,410,263	2,069,907	4,788,761	1,207,031	5,995,793
1971	3,640,593	2,203,401	5,078,279	1,306,258	6,384,537
1972	3,912,697	2,346,023	5,448,708	1,436,897	6,885,605
1973	4,161,122	2,496,286	5,752,177	1,576,097	7,328,275
1974	4,436,651	2,654,933	6,108,600	1,717,103	7,825,703
1975	4,697,121	2,821,318	6,419,075	1,862,560	8,281,635
1976	4,914,820	2,993,699	6,624,945	2,009,737	8,634,682
1977	5,123,218	3,171,234	6,808,856	2,152,926	8,961,782
1978	5,317,363	3,353,990	7,029,787	2,291,445	9,321,232
1979	5,513,898	3,539,577	7,242,166	2,428,474	9,670,640
1980	5,702,570	3,727,478	7,422,983	2,558,009	9,980,991
1981	5,921,252	3,881,015	7,651,731	2,681,044	10,332,775
1982	6,100,290	4,035,156	7,780,685	2,838,170	10,618,855

Inventory year	Emitted with energy capture (MgC)	Emitted without energy capture (MgC)	Products in use (MgC)	SWDS (MgC)	Total in HWP Pool (MgC)
1983	6,269,984	4,189,759	7,892,785	2,992,761	10,885,546
1984	6,386,082	4,343,528	7,880,528	3,145,998	11,026,526
1985	6,507,310	4,496,099	7,888,214	3,289,094	11,177,308
1986	6,629,569	4,646,692	7,858,672	3,424,990	11,283,662
1987	6,764,739	4,796,246	7,908,304	3,551,535	11,459,839
1988	6,924,235	4,944,728	8,005,241	3,680,422	11,685,663
1989	7,112,897	5,092,923	8,162,745	3,809,929	11,972,675
1990	7,322,896	5,241,633	8,366,204	3,945,680	12,311,884
1991	7,545,474	5,419,043	8,587,326	4,090,136	12,677,462
1992	7,720,785	5,599,197	8,703,011	4,197,604	12,900,615
1993	7,901,930	5,781,450	8,820,014	4,306,754	13,126,768
1994	8,065,322	5,964,297	8,889,388	4,419,064	13,308,452
1995	8,210,040	6,146,090	8,904,643	4,531,731	13,436,374
1996	8,318,849	6,325,518	8,869,359	4,641,427	13,510,786
1997	8,380,939	6,500,348	8,738,467	4,746,509	13,484,977
1998	8,431,934	6,669,811	8,609,443	4,841,866	13,451,309
1999	8,477,629	6,833,734	8,515,581	4,929,126	13,444,706
2000	8,533,080	6,992,075	8,459,892	5,011,210	13,471,103
2001	8,588,600	7,152,760	8,412,877	5,089,925	13,502,802
2002	8,605,370	7,308,110	8,270,894	5,148,646	13,419,540
2003	8,618,325	7,456,223	8,122,395	5,199,221	13,321,617
2004	8,636,345	7,600,645	8,000,787	5,247,452	13,248,238
2005	8,651,751	7,739,648	7,882,939	5,291,495	13,174,433
2006	8,667,598	7,873,427	7,774,567	5,333,325	13,107,892
2007	8,683,173	8,001,982	7,661,748	5,373,714	13,035,462
2008	8,689,885	8,125,149	7,529,938	5,412,490	12,942,428
2009	8,699,933	8,243,431	7,412,881	5,448,778	12,861,658
2010	8,710,757	8,357,097	7,302,775	5,483,859	12,786,634
2011	8,723,978	8,466,624	7,206,642	5,517,898	12,724,540
2012	8,737,232	8,572,243	7,111,557	5,551,544	12,663,100
2013	8,745,976	8,674,016	7,006,360	5,584,534	12,590,893