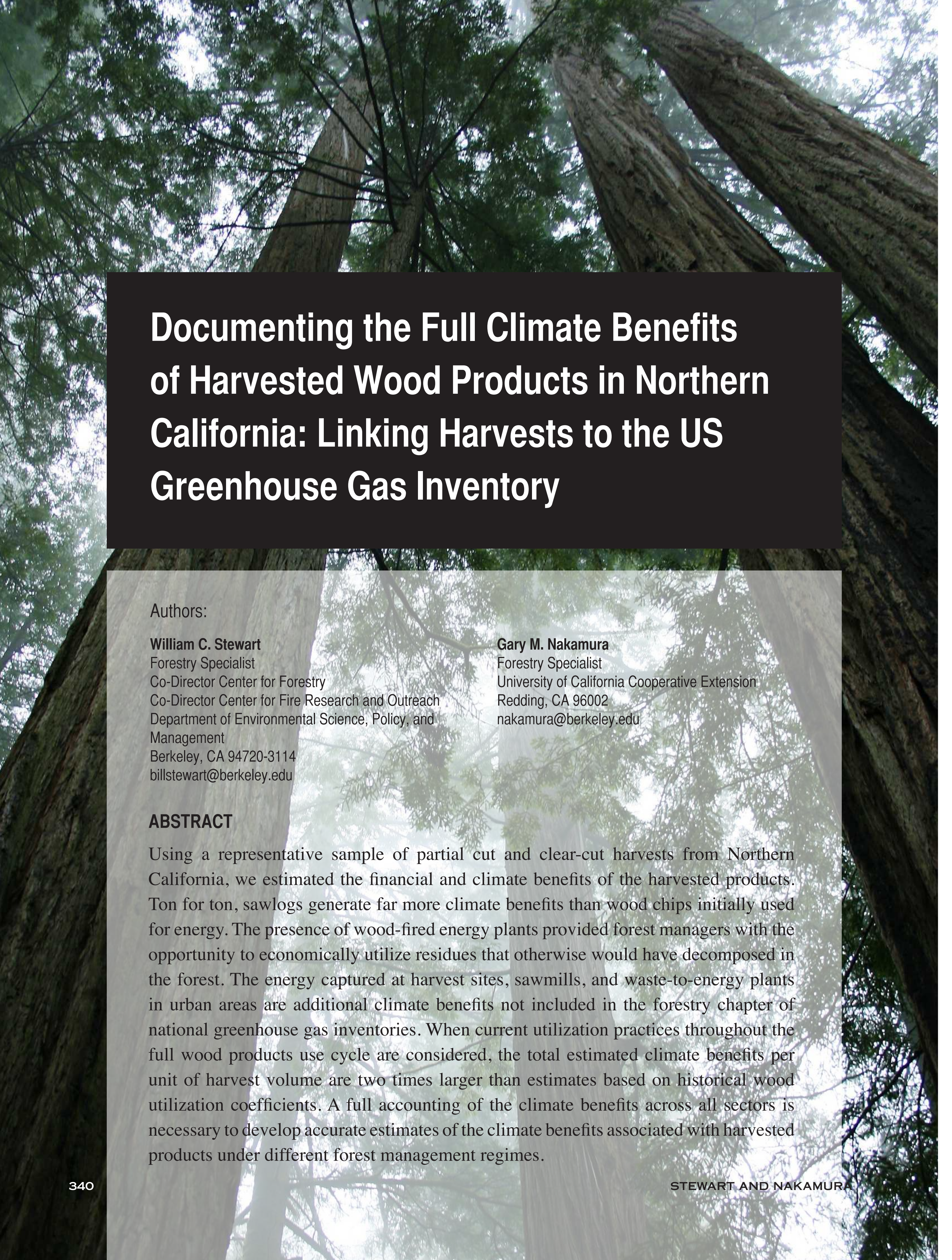

Documenting the Full Climate Benefits of Harvested Wood Products in Northern California: Linking Harvests to the US Greenhouse Gas Inventory

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ABSTRACT

Using a representative sample of partial cut and clear-cut harvests from Northern California, we estimated the financial and climate benefits of the harvested products. Ton for ton, sawlogs generate far more climate benefits than wood chips initially used for energy. The presence of wood-fired energy plants provided forest managers with the opportunity to economically utilize residues that otherwise would have decomposed in the forest. The energy captured at harvest sites, sawmills, and waste-to-energy plants in urban areas are additional climate benefits not included in the forestry chapter of national greenhouse gas inventories. When current utilization practices throughout the full wood products use cycle are considered, the total estimated climate benefits per unit of harvest volume are two times larger than estimates based on historical wood utilization coefficients. A full accounting of the climate benefits across all sectors is necessary to develop accurate estimates of the climate benefits associated with harvested products under different forest management regimes.

INTRODUCTION

The potential to increase climate benefits through changes in the management of existing forests is a topic of increasing interest but limited certainty (Nabuurs et al. 2007). A positive net climate benefit balance from managed temperate forests was proposed and initially demonstrated with modeled forest simulations by Schlamadinger and Marland (1996) and supported by other modeled forest examples (Perez-Garcia et al. 2005, Eriksson et al. 2007, Hennigar et al. 2008). Numerous policy analyses support the benefits of continued sustainable management of temperate forests (Nabuurs et al. 2007, Canadell and Raupach 2008, Malmsheimer et al. 2011) based on modeled forest stands, harvesting assumptions, and consumer use patterns. While most European studies based on project level data generally concur with these conclusions (Gustavsson and Sathre 2011, Gustavsson et al. 2011, Makela et al. 2011, Richardson 2011, Werhahn-Mees et al. 2011, Kilpeläinen et al. 2012), a number of US-based authors have suggested that greater climate benefits in temperate forests could be achieved by reducing harvest levels below sustainable harvest levels (Harmon et al. 1996, Gutrich and Howarth 2007, Nunery and Keeton 2010, Gunn et al. 2011, Hudiburg et al. 2011).

The goal of this study was to use project-level data from a region that exemplifies best practices in terms of efficient utilization of harvested products to test whether the divergence in outcomes is primarily related to assumptions regarding the allocation of harvested biomass into long-lived products, paper products, energy, and uncollected waste. Because many of the studies in the United States used similar forest growth models but still came to conflicting conclusions, this article focuses solely on the harvested products. We analyzed the utilization of wood biomass from 28 recent harvest operations conducted by five different forest owners over 6,870 hectares in Northern California. The operations included a mix of partial cut and clear-cut harvests in a region with both sawmills and wood-fired energy plants but no pulp mills or wood-based panel plants. We estimated the financial benefits using regional product prices and costs. We estimated climate benefits with utilization efficiencies at the harvest, mill, consumer, and postconsumer stages from both historically based estimates (Smith et al. 2006) as well as more recent estimates (Skog 2008, Smith et al. 2009, Keegan et al. 2010b, US Environmental Protection Agency 2012).

METHODS

To develop a representative sample of harvested products, we collected project data from private forest landowners in the northern interior region of California where there are five large sawmills and five wood-fired energy plants. High wholesale energy prices and long-standing state policies supporting wood-fired energy plants have been important in supporting wood-fired energy plants that purchase logging residues for fuel. More than half of the timberland in the region is publicly owned, but nearly all the harvest volume currently comes from private lands (California State Board of Equalization 2010). Private landowners use both partial cuts and clear-cuts to produce sawlogs for sawmills as well as chips for wood-fired energy plants. Based on Forest Inventory and Analysis (FIA) data for California harvests between 2001 and 2005, 49 percent of harvest area was partial cuts and 51 percent was clear-cuts (Christensen et al. 2008, Smith et al. 2009).

All of the harvests in our sample were conducted under the sustainable forest practice regulations of the California Forest Practice Rules (California Department of Forestry and Fire Protection 2009), and all the forest landowners were certified under the Sustainable Forestry Initiative or the Forest Stewardship Council systems. High-value sawlogs are the dominant consideration of California forest managers (Keegan et al. 2010a). Because the harvests were undertaken by profit-making entities, it was assumed that collecting forest chips for energy was done because it had a positive cash flow, was a silvicultural investment for future timber harvests, or was a less expensive option for disposing of harvest residues.

The lack of pulp mills and major wood-based product facilities in California means that the only economically viable use of low-value forest biomass wood chips collected at the harvest site is to generate thermal energy for use inside the plant or electricity that is sold into the regional grid. A network of wood-fired power plants was constructed in the 1980s in response to the Public Utilities Regulatory Policies Act (PURPA 1978; Hirsh 1999). California currently has 23 biomass-fueled energy plants, with about half of them located in forested regions (Mayhead and Tittmann 2012). While reducing wildfire risks through fuel treatments and biomass utilization has been proposed for many fire-prone forests in California and other dry forests (Becker et al. 2009) and has been demonstrated to be cost-effective in this region (Fried et al. 2003, Daugherty and Fried 2007, Barbour et al. 2008), the area actually treated to reduce fire risk has been small compared with the area of silvicultural treatments undertaken for other objectives on private forest lands.

Sampling of study sites

We interviewed the five major private forest landowners in the region who provided us project-level operational data on recent projects. To develop a representative view of the regional climate benefits, we applied the average per hectare values for partial cut and clear-cut harvests to the ratio of those treatments in the region as measured in the most recent FIA survey. The study involved 28 timber harvest projects that applied a mix of partial cuts and clear-cuts on 6,870 hectares of private land in Northern California between 2000 and 2008. The sites were located between 40°15′36″N and 41°53′24″N latitude and 120°39′0″W and 122°39′0″W longitude. Elevations ranged from 581 to 2,216 m in a region with a Mediterranean climate, a long summer dry season, and significant fire risk. The forest types are mainly dry mixed conifer forests dominated by ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), white fir (*Abies concolor* (Gord. & Glend) Lindl.), incense-cedar (*Calocedrus decurrens* (Torr.) Florin), and California black oak (*Quercus kelloggii* Newb.). The region also has high risks of large-scale, damaging crown fires (California Department of Forestry and Fire Protection 2008, Christensen et al. 2008).

Analysis of biomass utilization

Information was provided by the operators on the silvicultural methods, the harvest method (machine whole tree harvest or manual felling and bucking), the weights of harvested and uncollected material, the moisture contents of the products, and the distance to the sawmill and biomass facilities. The mass of logging residue left on site was extrapolated from operator estimates of the number and size of slash piles, the amount of scattered biomass left on the sites, and volume-to-weight conversions from Hardy (1996). The five different operators provided similar estimates of logging residues per unit of area, but the lack of recorded measurements increased the chance that we underestimated the volume of logging residues left on site for eventual pile burning.

Based on 2006 California sawmill inventory results in Smith et al. (2009) and Keegan et al. (2010b), 75 percent of the delivered sawlogs ended up as wood products, 24 percent was used for energy, and 0.9 percent was uncollected waste. These more recent studies document a much more efficient process than the assumed 20 percent uncollected waste in Harmon et al. (1996) or the assumed 16 percent uncollected waste in Smith et al. (2006).

Financial analysis

To account for variable market prices of sawlogs and woody biomass delivered to power plants, we applied the decadal average market prices and industry-wide estimates of harvesting cost to all the operations. Over 95 percent of area of partial cuts and clear-cuts in our sample were harvested with mechanical whole tree harvesting methods in which the tops and branches came to the landing as part of the tree, were separated from the sawlogs, and then chipped and loaded into chip vans. The net revenue for sawlogs and chips accounted for the costs to bring the trees to the landing as well as the transport cost by log trucks to the sawmills and chip vans to the power plants. We could not include the significant costs associated with planning, permits, and the regulatory approval process because we were not able to reconstruct these costs.

Analysis of the carbon balances and climate impacts

The postharvest forests should continue to accumulate carbon at or above current rates because private forest owners are required to meet postharvest stocking requirements and are inclined to implement improved technologies to achieve higher value growth of their forest stands. Clear-cut harvest areas are replanted to meet state forest practice laws and will not be harvested for decades. Partial cut harvest areas will typically be harvested periodically every 10 to 20 years. The harvested woody biomass goes into products, energy, or uncollected waste. Sawlogs will be delivered to sawmills where dimensional lumber is the main product and chips are a secondary product. The products are sold and used for a variety of products with varying carbon retention half-lives. Based on the average initial allocation of products over the past 30 years in which half of all timber products go into single family houses and half goes into multifamily buildings and other uses (McKeever and Howard 2011) and the estimated half-life of different types of wood products (Skog 2008), we calculated a 52-year half-life for wood products manufactured in California. This is considerably longer than the retention estimate in Smith et al. (2006) that is mathematically equivalent to a 25-year half-life for wood products manufactured in California. The Smith et al. (2006) tables are embedded in the now suspended Department of Energy's 1605b guidelines (US Department of Energy 2012) that are still used in many voluntary greenhouse gas accounting systems, all of the recent US Forest Service carbon calculators (US Department of Agriculture Forest Service–Northern Research Station 2012), as well as in the current forest offset protocols accepted by the California Air Resources Board (2011) for evaluating forest offset projects.

Woody biomass is currently the second largest source of renewable energy in the United States, with the majority of the energy being used within sawmills and pulp mills and a minor share to generate electricity for sale to the grid (US Environmental Protection Agency 2011). Using more wood residues for energy is often promoted as part of larger renewable energy programs (European Union 2009, United Nations Economic Commission for Europe/Food and Agriculture Organization 2009). We followed the Intergovernmental Panel on Climate Change assumption (Sims et al. 2007, US Environmental Protection Agency 2012) that the use of terrestrial carbon, as opposed to geologic carbon, for energy is carbon neutral. This assumption is mathematically similar to assuming that the wood-based energy replaces coal-based energy (Rannik et al. 2002; Wahlund et al. 2002, 2004; Wolf et al. 2006; Ranta et al. 2007; Sims et al. 2007; Cherubini et al. 2009; Ferreira et al. 2009; Soliño et al. 2009; Walker et al. 2009; US Environmental Protection Agency 2012).

While it does not explicitly show up in national greenhouse gas inventories, there is considerable evidence that using wood rather than steel or cement in buildings reduces the total amount of energy used to produce building products as well as to heat and cool the buildings. Policy analyses of national forest sector models from around the world have produced a wide range of estimates of the energy benefits of using wood in buildings (Lippke et al. 2004, Perez-Garcia et al. 2005, Gustavsson and Sathre 2006, Gerilla et al. 2007, Sathre and Gustavsson 2007, Woodbury et al. 2007, Upton et al. 2008, Sathre and O'Connor 2010). A meta-analysis by Sathre and O'Connor (2010) of 21 international studies concluded that each ton of carbon in wood building products avoided an additional 1.1 tons of carbon emissions that would have occurred through producing more fossil fuel–intensive materials such as steel and cement.

Little is known about the current efficiency of postconsumer collection of wood residues or what the efficiency will be when future consumers throw products away. California's increasingly strict regulations to improve the recycling and utilization of waste products (California Air Resources Board 2008) would suggest that the Smith et al. (2006) estimate that only 65 percent of postconsumer wood waste will be sent to engineered landfills or waste-to-energy plants is low. For our analysis, we assume that improved regulations and technology will result in 90 percent of future post-consumer wood going to engineered landfills or wood-fired energy plants.

RESULTS AND DISCUSSION

Biomass utilization: harvest and removals

The 28 harvest operations over 6,870 hectares produced 221,555 metric tons of carbon (MgC) in sawlogs and forest biomass chips. Table 1 depicts the individual projects that ranged in size from 31 to 788 hectares and often included different types of silviculture within a single harvest plan. According to the California's Forest Practice Rules (California Department of Forestry and Fire Protection 2009), partial cut or commercial thinning operations do not require replanting if they are maintained in fully stocked condition. Clear-cut harvests involve the removal of all trees except residual live and dead trees retained for habitat and aesthetics and require replanting and maintenance of 740 trees per ha.

Nearly half of the harvested output came from projects that included both commercial thin subunits and clear-cut harvest subunits. In addition, the sample harvests were not necessarily representative of the harvest pattern across the re-

Table 1. Harvest area and volumes from 28 harvests.

No.	Year	Total area (ha)	Partial cut (ha)	Clear-cut (ha)	Total harvest (MgC/ha)	Logs (MgC/ha)	Chips (MgC/ha)	Uncollected logging residue (MgC/ha)	Distance to energy plant (km)
1	1997	648	648	0	12.4	0.0	10.2	2.2	121
2	1997	132	132	0	16.3	0.0	14.1	2.2	121
3	2001	31	31	0	38.8	29.1	8.7	1.0	40
4	2001	623	623	0	11.0	3.4	7.5	0.1	48
5	2002	788	788	0	26.5	5.4	21.0	0.1	40
6	2004	247	247	0	31.4	22.8	8.4	0.1	48
7	2004	438	438	0	27.9	8.9	18.8	0.1	48
8	1996	501	501	0	19.9	7.6	12.2	0.1	97
9	1998	95	95	0	39.8	19.7	19.2	0.9	24
10	1999	116	93	23	40.7	30.9	8.2	1.5	37
11	2000	221	146	75	31.4	21.0	4.0	6.4	113
12	2000	123	95	29	20.8	12.1	5.5	3.2	129
13	2003	221	221	0	26.5	22.9	2.2	1.4	161
14	2004	558	447	112	26.7	14.4	10.0	2.2	113
15	2004	323	270	53	23.3	9.6	11.5	2.2	113
16	2000	255	83	173	49.2	33.4	14.9	0.9	97
17	2003	349	21	328	45.9	33.7	11.1	1.0	145
18	2006	39	0	39	81.2	56.0	22.9	2.2	97
19	1999	382	195	187	38.2	29.0	7.0	2.2	145
20	2002	197	0	197	76.1	64.3	9.6	2.2	97
21	2004	160	0	160	113.5	98.2	13.1	2.2	97
22	2004	61	43	18	33.8	26.4	0.0	7.4	73
23	2004	61	0	61	43.7	37.9	0.0	5.8	73
24	2004	66	0	66	89.8	87.6	0.0	2.2	89
25	2004	36	0	36	41.8	39.5	0.0	2.2	89
26	2003	36	0	36	84.6	82.3	0.0	2.2	145
27	2003	92	0	92	58.2	56.0	0.0	2.2	145
28	2005	72	0	72	77.2	74.9	0.0	2.2	81

Table 2. Harvest site allocation of harvested biomass per hectare for Northern California (n = 28).

Silviculture	Mean MgC/ha (SE)			
	Sawlogs	Forest chips for energy	Uncollected logging residue	Total harvested
Partial cut	5.3 (1.6)	13.3 (1.2)	0.9 (1.9)	19.5 (1.9)
Clear-cut harvest	52.2 (4.7)	7.9 (3.3)	2.5 (0.7)	62.6 (5.5)

Table 3. Post sawmill and energy plant allocation of harvested biomass for Northern California (n = 28).

	Wood products	Sawmill energy	Sawmill waste	Forest chips for energy	Uncollect–ed logging residue	Total harvested
Partial cut (PC) (MgC/ha)	3.9	1.3	0.1	13.3	0.9	19.5
Clear-cut harvest (CC) (MgC/ha)	39.3	12.5	0.5	7.9	2.5	62.6
Avg. California harvest (½ PC, ½ CC) based on Forest Inventory and Analysis surveys (MgC/ha)	21.6	6.9	0.3	10.6	1.7	41.1
% of total	52	17	1	26	4	100

gion. To develop unique per hectare estimates for the partial harvests (mainly commercial thins) and clear-cut harvests, we used an ordinary least squares model (Cottrell and Lucchetti 2009) to develop area-based harvested biomass coefficients for partial and clear-cut harvests. The harvest volumes in Table 2 show the mass of wood removed as sawlogs, forest chips that are transported in chip vans to wood-fired energy plants, and uncollected logging residues.

At the sawmill, the sawlog biomass was partitioned into timber, clean chips to be used for higher value products or energy, hog fuel chips usable only for energy, and uncollected waste. At the wood-fired energy plants, all the biomass delivered in chip vans was used to generate energy. Without wood-fired energy plants willing to buy forest chips, all of the biomass would have been left as logging residues and unmerchantable ladder fuel trees. The after harvest and processing allocation of biomass from partial cuts, clear-cuts, and the regional average are shown in Table 3.

The field and sawmill processing results concur with other studies on the West Coast (Harmon et al. 1996, Hudiburg et al. 2011) that estimated only half the harvested biomass ends up in solid lumber products. Sawmill operators typically keep detailed accounts of the chips, shavings, and sawdust that can be used to generate energy or sold to other users. The absence of pulp mills and wood-based panel plants resulted in most of the collected biomass that did not go into lumber products being used for energy rather than being left in the forest or at the sawmill as uncollected waste. In other regions of the North America, much of the non-sawlog volume often goes to pulp mills and wood-based panel plants.

Financial analysis of harvest product revenues

The net value of the delivered harvested products is the best estimate of financial benefits to the forest owner. Forest landowners will not deliver large volumes of wood for generating carbon neutral energy if the benefits are not greater than the costs. We used the reported stumpage values for the three major timber species as well as average logging costs (California State Board of Equalization

Figure 1. Distance versus chip value at the landing. Value ($MgC) of chips at the landing = 4.93 - 0.30 - distance (kilometers). n = 15, r^2 = 0.69, ANOVA Prob > F = <0.0001.

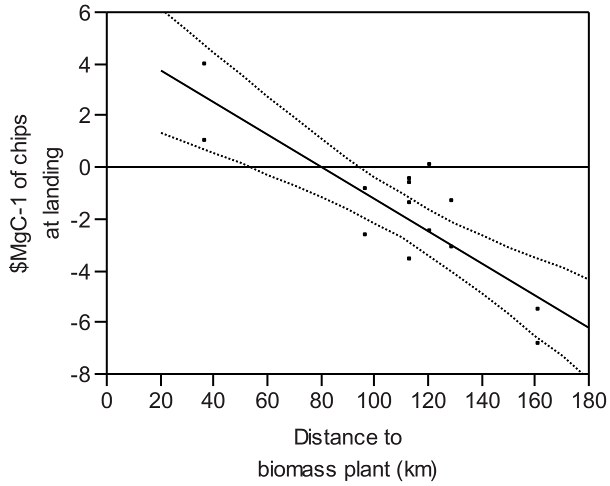
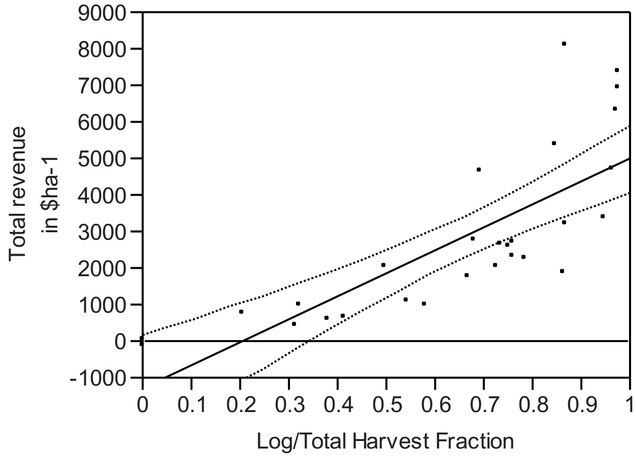


Figure 2. Log/harvest fraction versus net revenue per hectare. Dollars of net revenue per hectare harvested = 1,277 + 6,267 (sawlog/total harvest). n = 28, r^2 = 0.60, ANOVA Prob > F = <0.0010.



1998–2008) to estimate the gross value of sawlogs at the landing. After subtracting an average sawlog harvest and transport costs to sawmills (Hartsough 2003), we estimated the net value of delivered sawlogs to be US$76/MgC. With whole tree harvests, the branches, tops, and noncommercial trees are already brought to the landing, so no logging costs were apportioned to the forest chips. We estimated the net value of the forest chips collected at the harvest by subtracting the transport costs from the delivered prices for bone dry tons of chips as reported by the operators.

The haul distance from the landing to biomass plants had a significant effect on the net value of biomass chips at the landing. When collection and transportation costs are subtracted from the reported delivered prices of US$24/MgC ± US$3/MgC for wood chips over the period 2000 to 2008, the net revenue per ton was negligible. We used the reported prices and transport costs from the 15 projects with the same forester to develop a standardized price and cost per kilometer schedule. The net value of the chips at landings of varying distances from energy plants was then applied to all the projects. Figure 1 shows the value of the chips at the landing based on 15 deliveries with comparable data on revenues and costs.

The net value of wood chips at the landing across the projects varied considerably because of market prices and site-specific conditions. Although the estimated value of chips at the landing was less than zero where the distance to the biomass plant was greater than 80 km, chips were shipped more than 80 km at 13 of the 21 sites where both sawlogs and chips were removed. While some biomass utilization models assume that chips will not be hauled if the value is negative, biomass harvesting was apparently a less expensive logging residue treatment than the operational and permitting costs associated with burning logging residues at the harvest site. Logging residue disposal to reduce fire risk is a legal requirement of state forest practice rules and costs are significant. When deciding to undertake costly collection and removal of chips from harvest operations, operators mentioned the advantages of reduced risk from escaped control burns or future wildfires. Biomass harvests can also be considered silvicultural investments to reduce fire and insect risks and improve the quality and growth of the remaining trees. The low and often negative value of chips at the landing required operators to include some sawlogs in nearly every harvest to avoid a negative cash flow for individual operations. Figure 2 illustrates the relationship of the sawlog fraction of total harvests to the estimated net revenue per acre for the 28 projects.

Based on the harvested amounts of sawlogs and biomass chips, these commercial operations in Northern California included at least 20 percent sawlogs in the total removals and appeared to strive to at least break even on each harvest op-

Table 4. Historic and current best practices woody biomass utilization coefficients.

Utilization step	Pre-2008 USFS wood utilization coefficients[a]			Post-2008 USFS wood utilization coefficients[b]		
	Product	Energy	Waste	Product	Energy	Waste
1. At the harvest site	0.60	0.00	0.40	0.70	0.26	0.04
2. At the sawmill and energy plant	0.67	0.17	0.16	0.75	0.24	0.01
3. After the product's initial lifetime[c]	0.43	0.22	0.35	0.65	0.25	0.10

[a] Source: Smith et al. 2006. USFS = USDA Forest Service.
[b] Sources: California Air Resources Board (2008), Skog (2008), Smith et al. (2009), Keegan et al. (2010b), US Environmental Protection Agency (2012).
[c] Engineered landfill deposition is considered to the be the "product."

Table 5. Estimated climate benefits in tons of CO_2 equivalent (tCO_2 eq) of harvested products from a 100-tCO_2 eq representative harvest in Northern California.[a]

Forest product–related climate benefits	Pre-2008 USFS wood utilization coefficients	Post-2008 USFS wood utilization coefficients
Long-term carbon storage in products	15	27
Long-term carbon storage in landfills	11	7
Energy from logging residues	0	26
Energy from sawmill residues	17	23
Energy from postconsumer residues	7	11
Energy benefits from product substitution	16	30
Total	66	123

[a] 1 MgC = 3.667 tCO_2 eq. USFS = USDA Forest Service.

eration. Because of the long haul distances in this region, biomass harvesting revenues alone would not cover operational costs at current prices for the majority of the forested lands.

Climate benefits

The interest in developing more accurate estimates of how long wood products remain in use in developed countries has led to significant improvements in the empirical basis for the estimates. While some policy models use historical data with low conversion efficiencies to estimate current and future utilization (Harmon et al. 1996, Smith et al. 2006), more recent work has documented high and continually improving conversion efficiencies from harvest to postconsumer collection (Barlaz 2006, Skog 2008, Smith et al. 2009, Keegan et al. 2010b). In addition to log–to–wood product utilization improvements of 20 percent over the past 30 years for West Coast sawmills (Keegan et al. 2010b), large gains in utilization of all bark, chips, shavings, and sawdust have also been documented (Smith et al. 2009). Table 4 compares the estimated allocation of woody biomass at three steps for older and more recent forest product utilization coefficients. The products from each step are moved onto the next step where there is another allocation of the product into new products, energy, and waste.

Table 5 compares climate benefits under two sets of published utilization coefficients. Emissions and climate benefits for forest projects are commonly measured in tons of CO_2 equivalent (tCO_2 eq) over a 100-year period. The first column of values summarizes the climate benefits based on the product allocations in Smith et al. (2006) that are also used in most current voluntary forest carbon standards. The last column summarizes the climate benefits based on representative deliveries to Northern California sawmills and energy plants, current estimates of plant efficiencies (Skog 2008, Smith et al. 2009, Keegan et al. 2010b, McKeever and Howard 2011), an estimate of improved post-consumer disposition of woody biomass in California when it is eventually transferred from the consumer to the waste management sector (US Environmental Protection Agency 2012), and the estimated energy benefits of using more wood and less steel and cement in building (Sathre and O'Connor 2010).

The use of current and empirically documented coefficients on sawmill and consumer sector wood utilization efficiencies nearly doubled the full cycle estimate of climate benefits (123 vs. 66 tCO_2 eq from a harvest of 100 tCO_2 eq of forest biomass) compared with the widely used Smith et al. (2006) coefficients. The majority of the additional climate benefits are related to direct and indirect energy substitution benefits that are tracked in the energy chapter rather than the forestry chapter in national and international greenhouse gas emission inventories (US Environmental Protection Agency 2012). Carbon accounting methodologies such as Compliance Offset Protocol: US Forest Projects (California Air Resources Board 2011) that ignore all the foregone energy benefits of offset projects will significantly underestimate the climate benefits of the "no project" baseline harvest and therefore overestimate the number of offset credits that could be claimed by forest management projects based on a reduction in sustainable harvests.

The scientific consensus that increasing concentrations of greenhouse gases in the atmosphere are harmful has focused attention on estimating the current and potential climate benefits related to temperate forests. Various modeling based policy assessments have come to conflicting conclusions regarding forest harvesting and the net level of climate benefits related to managed forests of North America (Harmon et al. 1996, Lippke et al. 2004, Eriksson et al. 2007, Hennigar et al. 2008, Upton et al. 2008, Hudiburg et al. 2011). Our analysis of a representative set of harvests in Northern California in a region with competitive markets for both sawlogs and forest chips suggests that most of these differences arise directly from the assumptions regarding product utilization efficiencies and treatment of the energy produced from woody residues at the harvest, processing, and postconsumer stages. In particular, the projection of poorly documented historical estimates of wood utilization into the future rather than using current best practices as an estimate of standard practices in upcoming decades (Ince et al. 2011) implies a much more wasteful system of wood product utilization than what recent surveys have documented.

Estimating the total climate benefits of harvested wood products requires using four different chapters of the US greenhouse gases inventory (US Environmental Protection Agency 2012). The long-term carbon storage in wood products and landfills tracked in the Land Use, Land-Use Change, and Forestry chapter in the inventory constituted only 27 percent of the total climate benefits attributable to forest products in our study. The energy benefits of wood collected at the harvest, the sawmill, and after products were discarded by consumers are tracked in the Energy chapter and represented 48 percent of climate benefits related to the harvests. The substitution benefits of using wood rather than energy- and emission-intensive building materials represent another 24 percent of the climate benefits based on considering the avoided emissions of reduced production of steel, cement, and other energy-intensive products in the Industrial Processes chapter, as well as in reduced building energy use tracked in the Energy chapter. The emissions from paper production and waste paper utilization are tracked in the Waste chapter but were not covered in our study.

In California, sawlogs dominated the revenue to forest landowners because the current financial value of wood residues used for energy is low. Sawlogs also dominated total climate benefits due to the efficient use of sawmill residues and wood's long residency times and energy-saving properties when used in buildings. Forest owners in our study collected little if any revenue from forest chips sold to energy plants. Higher prices for carbon neutral energy would promote the collection of more logging residues and fuel reduction project residues.

CONCLUSIONS

Ton for ton, sawlogs generate far more climate benefits than wood chips initially used for energy. The presence of wood-fired energy plants provided forest managers with the opportunity to economically utilize residues that otherwise would have decomposed in the forest. The existence of a competitive forest biomass market of sawmills and wood-fired energy plants in Northern California significantly increased the climate benefits associated with the harvested wood products from these forests but had limited impact on the financial benefits to forest landowners. The collected logging residues were a major reason for our calculated total climate benefits being nearly double those based on commonly used accounting systems such as Smith et al. (2006) and nearly four times as great as forest project protocols (California Air Resources Board 2011) that ignore all energy benefits from the utilization of woody residues. The combination of high collection costs and relatively low prices for woody residues collected at the landing, sawmill, and postconsumer locations created a situation in which the private sector only collected and delivered woody residues to wood-fired energy plants if they were a by-product of other positive revenue operations. Greater financial recognition of the climate benefits not accounted for in the Land Use, Land-Use Change, and Forestry chapter of national greenhouse gas inventories could substantially increase the recognized climate benefits of an ecologically and economically sustainable forest sector.

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