GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2015) 7, 820–835, doi: 10.1111/gcbb.12193

Net change in carbon emissions with increased wood energy use in the United States

PRAKASH NEPAL[1], DAVID N. WEAR[3] and KENNETH E. SKOG[2]

[1]School of Renewable Natural Resources Building, LSU AgCenter, Baton Rouge, LA 70803, USA, [2]USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726-2398, USA, [3]USDA Forest Service, Center for Integrated Forest Science and Synthesis, Department of Forestry and Environmental Resources, 5223 Jordan Hall, Raleigh, NC 27695, USA

Abstract

Use of wood biomass for energy results in carbon (C) emissions at the time of burning and alters C stocks on the land because of harvest, regrowth, and changes in land use or management. This study evaluates the potential effects of expanded woody biomass energy use (for heat and power) on net C emissions over time. A scenario with increased wood energy use is compared with a dynamic business-as-usual scenario where wood energy use is driven by its historical relationship with gross domestic product. At the national level, we projected that up to 78% of increased cumulative C emissions from increased wood burning and up to 80% of increased cumulative radiative forcing would be offset over 50 years by change in forest area loss, biomass regrowth on land, C storage in harvested wood products, and C in logging slash left in forests. For example, forest area is projected to decline in both scenarios, but 3.5 million hectares more are retained in the high wood energy-use case. Projected C offsets over a 50 year period differed substantially by US region (16% in the North, 50% in the West, and 95% in the South) not only because of differences in forest regrowth and induced investment in retaining and planting forest, but also because of shifts in competitive advantage among regions in producing various wood products. If wood systems displace coal systems that have 75% of the C emissions of wood energy systems per unit energy, then the nationwide net C emissions offset would be reduced to 71–74%. If displacing natural gas systems that have 40% of the level of wood bioenergy emissions per unit energy, the nationwide net C emissions offset would be 46–52%.

Keywords: biogenic carbon accounting, carbon neutrality factor, cumulative radiative forcing, forest carbon, logging slash, harvested wood products, market-induced indirect land-use change, wood energy

Received 19 December 2013; revised version received 18 February 2014 and accepted 28 March 2014

Introduction

The primary objective of this study was to provide a detailed analysis of the net C emission effects of expanded wood energy use in the United States. This article identifies individual and net C fluxes by first estimating how increased demand for wood biomass to produce energy (for power, heat, and combined heat and power) can affect (1) consumption, production, and trade of other wood products, including resulting domestic wood harvests and C added to wood products, (2) the area of land added to or retained in forest, and (3) the intensity of forest management and resulting forest growth rates.

To evaluate the effect of increased wood use for energy, over time, we compare two scenarios that use the same integrated set of economic, population, and climate change projections. The first scenario is a business-as-usual (BAU) baseline reference case and the second is an alternative scenario with substantially increased wood energy use over 50 years. These scenarios, originally named RPA A1B and RPA HFW were developed for the USDA Forest Service 2010 Resources Planning Act (RPA) Assessment and are based on the A1B marker scenario from the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment report (USDA Forest Service, 2012a). Our study started with the RPA A1B and RPA HFW scenarios but final harvest levels were adjusted from the original scenarios as discussed in the methods section. Our adjusted scenarios are named A1B and A1BHFW to distinguish them from original RPA A1B and RPA HFW scenarios. Our A1B scenario represents a scenario with high wood energy consumption and our A1BHFW (HFW refers to 'historical fuelwood') represents a scenario with lower wood energy consumption where wood energy demand is projected based on the historical relationship between wood fuel feedstock demand and gross domestic products (GDP). In the original RPA A1B and RPA HFW scenarios, wood

Correspondence: Prakash Nepal, tel. +1 608 231 9362, fax +1 608 231 9592, e-mail: pnepal@fs.fed.us

fuel feedstock consumption was projected to be 15 times and two times the 2006 levels, respectively by 2060. In this study, because of adjustments in final harvest levels, wood fuel feedstock consumption in the A1B scenario is projected to be about five times the 2006 level by 2060, and the consumption of fuel feedstock in the A1B HFW scenario is projected to be about the same as 2006 level by 2060 (Table 1). As shown in Table 1, the two scenarios only differ in the projected level of wood energy consumption otherwise they share exactly the same assumptions about economic drivers.

Wood-based energy has been viewed as a means to reduce C emissions if biomass resources are sustainably managed and used with efficient bioenergy systems (Marland & Schlamadinger, 1997; Gan & Smith, 2007; Richter *et al.*, 2009). This view holds that the use of woody biomass energy may have a role in climate change mitigation as a substitute for fossil energy sources such as coal, oil, and natural gas. However, the degree to which wood bioenergy actually reduces emissions and the timeframe to obtain benefits is debated (Manomet Center for Conservation Sciences, 2010; Zanchi *et al.*, 2012; Agostini *et al.*, 2013). As wood demand for energy increases, markets for wood products adjust and altered prices lead to land-use changes, altered investment in forest management, and altered consumption and trade of forest products (Ince *et al.*, 2011b; Daigneault *et al.*, 2012). These market processes alter C stored in forests, nonforest, and in wood products in end uses and landfills (Ince *et al.*, 2011b; USDA Forest Service, 2012a). Several studies show that estimates of the net greenhouse gas (GHG) implications of biomass energy use depend on what factors are included in the analysis. These factors could include the types of biomass feedstock (e.g. logging slash, roundwood, wood mill residue, agricultural biomass, municipal waste); time needed for new biomass growth to replenish the amount of C removed from forests and emitted, or in the case of residues, the rate of avoided decay emissions; the type of fossil fuel being replaced (i.e. coal, oil, or natural gas); the efficiency of bioenergy and fossil fuel technologies; the direct and indirect land use and management changes induced by the increased use of biomass for energy; and the geographical scope and timeframe of the analysis (Schlamadinger *et al.*, 1995; Fargione *et al.*, 2008; Searchinger *et al.*, 2008; Melillo *et al.*, 2009; Manomet Center for Conservation Sciences, 2010; US Environmental Protection Agency, 2011; Zanchi *et al.*, 2012). Estimates of GHG impacts of wood energy use can also be influenced by the choice of a baseline reference case and by including other sectors such as agriculture in the impact evaluation.

Table 1 Global A1B and HFW scenarios considered by the 2010 RPA assessment

Characteristic	Scenario A1B	Scenario HFW
Global real GDP growth (2010–2060)	High (6.2×)	High (6.2×)
Global population growth (2010–2060)	Medium (1.3×)	Medium (1.3×)
Global expansion of primary biomass energy production	High	Fuelwood demand follows historical trends in all countries
US GDP growth (2006–2060)	Medium (3.3×)	Medium (3.3×)
US population growth (2006–2060)	Medium (1.5×)	Medium (1.5×)
US expansion of US wood fuel feedstock (2006–2060)	High (~15×)* (~5×)†	Historical relationship (~2×)* (~1×)†
Pine plantation increase in the US South (2006–2060), million ha	27 (1.7×)	21 (1.3×)

*Wood energy consumption in the original 2010 RPA scenario.
†Wood energy consumption after adjustments to match harvest levels of USFPM/GFPM and the FDM.

Our objective was to account for the factors described above (with some limitations) in estimating the net GHG impact of large-scale increases in wood energy use by comparing future scenarios that feature 'with' and 'without' cases for expanded wood energy use. These scenarios include various sources and types of biomass feedstock, biomass growth, and bioenergy technologies, as well as effects on land use and forest management, as influenced by market dynamics.

Few studies have comprehensively examined the GHG implications of wood-based energy for heat and power. Most studies that assess the GHG impacts of wood energy are limited in scope. For example, some studies consider only certain feedstocks (e.g. Zanchi *et al.*, 2012), whereas others do not include important market responses (e.g. Manomet Center for Conservation Sciences, 2010) to increasing wood use for bioenergy (e.g. shifts in production and trade of wood products and prices for various types of wood biomass, retaining more land in forest, increased tree planting, and intensified forest management). As the demand for wood energy grows, multiple wood feedstocks such as logging slash, mill residue, and roundwood might be used (Ince *et al.*, 2011a,b). A number of simulation studies show that roundwood may be used when the price of wood energy is high enough to compete with traditional uses such as pulpwood (Galik *et al.*, 2009; Abt *et al.*, 2010a; Ince *et al.*, 2011b; Daigneault *et al.*, 2012). Assessing timber market responses to expected expansion in the use of wood for bioenergy is important, as expansion in wood energy demand might reduce consumption of other wood products, increase timber prices, and induce land use and management changes. The loss of C stored in standing forests because of increased harvest for bioenergy may be offset by increased forest area, forest plantations, and intensified management induced by increased demand for bioenergy (Abt *et al.*, 2012; Daigneault *et al.*, 2012; Nepal *et al.*, 2012; Sedjo & Tian, 2012). A few studies incorporate market response in their analyses of C emissions associated with expanded wood energy use and show in varying ways that land-use change and resulting C change can affect net C emissions (Abt *et al.*, 2012; Daigneault *et al.*, 2012; Sedjo & Tian, 2012; White *et al.*, 2013).

An important and variable element of previous studies has been the choice of baseline used to compare to the policy alternative of increased wood energy use. Some studies use an anticipated baseline (e.g. Daigneault *et al.*, 2012), which includes projected changes in C stocks that would occur because of economic forces without a change in energy policy. Some evaluations use a 'reference point' baseline case (e.g. Fargione *et al.*, 2008). Using a reference point baseline implicitly assumes an interest in degree to which C stocks change from a starting date for a single scenario. All causes of change in C stocks are considered, including but not limited to, change in economic drivers or policies that would increase bioenergy demands.

The analysis here compares a scenario with strong expansion in wood energy use to a scenario with increases that are close to historical levels. We use these two scenarios to estimate the effect of expanded wood energy use on timber prices and harvest, forest products consumption and trade, land retained in forest, and investments in an additional forest plantation area. These impacts, in turn, have implications for changes in C stored in forests, forest soils, logging slash left to decay onsite, harvested wood products (HWP), and on other lands affected by related changes in land use or management. Estimates of C emissions account for these forest sector dynamics but also address the differences in conversion efficiencies for wood and the energy system being displaced (in our analysis, either natural gas or coal). We also explore the implications of using an anticipated baseline or reference point baseline to estimate net C emissions from an increase in wood energy use.

Materials and methods

Scenarios

This analysis builds from the results of the 2010 RPA Forest Assessment (USDA Forest Service, 2012a), which examines the potential impacts of four global scenarios on future land uses, forest products markets, and forest conditions, including C stored in forests and HWP. The 2010 RPA scenarios use assumptions from IPCC global scenarios to provide different integrated views of change in economic activity, population, climate conditions, and bioenergy demands. The RPA scenarios included county level 'downscaled' projections of climate change, population, and income for the United States that are used to generate 50 year projections of forest inventory and land-use change. The global drivers of forest product markets including wood energy demand are used to make projections of production, consumption, and trade for all countries with additional detail for the United States. Results are summarized in the 2010 RPA Assessment (USDA Forest Service, 2012a) and details on the scenarios are contained in USDA Forest Service (USDA Forest Service, 2012b).

The 2010 RPA Assessment identifies four economic driver/wood energy scenarios, three of which are directly tied to IPCC scenarios and are labeled RPA A1B, RPA A2, and RPA B2 and a fourth, labeled RPA Historical Fuelwood or RPA HFW that provides a variant to RPA A1B and extends the range of bioenergy demands considered. Table 1 summarizes several drivers for the RPA A1B and RPA HFW scenarios. The RPA HFW scenario shows wood used in the United States for energy in 2060 would be roughly double the amount in 2010, while the RPA A1B scenario shows wood used for energy would expand by a factor of 15 over the same time. This article uses the same RPA A1B and RPA HFW scenarios but with adjusted final harvests as described below. The adjusted scenarios are termed A1B and A1BHFW. The article first evaluates the effect of wood energy increase between the A1B and the A1BHFW scenarios. These two scenarios use identical economic and population growth projections. However, in the A1BHFW scenario, wood energy demand in each country, rather than being based on the IPCC A1B scenario, is determined by the econometric relationship of fuelwood demand growth to GDP growth in all countries (Simangunsong & Buongiorno, 2001). In predicting the A1BHFW wood energy consumption for each country, we used the econometric models of Simangunsong & Buongiorno (2001), and the GDP projections used in the Forest Service 2010 RPA assessment (USDA Forest Service, 2012a) as the predictor variables. The drivers in Table 1 are taken from the RPA analysis and so are fixed in this exercise. It is assumed that whatever policies increase wood energy use for the A1B scenario do not significantly change the cost of energy (i.e. electric power or natural gas) from the A1BHFW scenario. In 2012, wood fuel provided about 2% of the feedstock energy consumed in the United States (US Environmental Protection Agency, 2014). About half of wood fuel was solidwood or chips, and half was pulping liquor. USFPM/GFPM projects the use of wood for pulping liquor as part of pulpwood consumption by pulp mills. After adjustments, our A1B scenario projects wood fuel consumption in the form of solidwood or chips would increase from about 1% to 5% of the 2012 US fuel consumption level. This could result in a limited net decrease in consumption and price of fossil fuels which would slightly increase returns for both forest and agricultural products and increase rents paid to both forest and agricultural land with the shift favoring the more energy intensive agricultural sector. This limited effect could result in slightly lower retention of forest land and additional plantations for A1B than we project.

Estimating the C emission effects of increased bioenergy consumption

To identify the effects that increasing wood use for energy and associated harvest levels could have on forest C stocks, nonforest land C stocks, and C stored in HWP, the analysis used four interlinked models of the US forest sector (Fig. 1): (a) the United States Forest Products Module combined with the Global Forest Products Model (USFPM/GFPM), (b) the Forest Dynamics Model (FDM), (c) the All Land Use Model (ALUM), and (d) a harvested wood products C accounting model – WOODCARB II. USFPM/GFPM (Buongiorno *et al*., 2003; Ince *et al*., 2011b) provides forecasts of forest products markets and timber harvesting associated with the economic, population, and technological forecasts. ALUM (Wear, 2011) provides forecasts of all land uses in response to projected changes in population, incomes, and land rents (including timber price where appropriate). The FDM (Wear *et al*., 2013) provides projections of the forest inventory and C stocks in response to changes in forest age and forest type, land use, timber harvesting, and climate futures anticipated under each scenario. The WOODCARB II model (Skog, 2008) provides estimates of C stored in HWP. In addition, a spreadsheet model of logging slash decay provides projection of changes in logging slash C. The linkages among the models are shown in Fig. 1.

USFPM/GFPM solves for production/prices in the forest products sector (i.e. prices are endogenous to the model) while FDM and ALUM take prices as exogenous inputs and provide aggregate supply estimates to the USFPM/GFPM. An iterative process is needed to find solutions where prices and supplies are aligned across the models. This is comparable to formal decomposition approaches that solve master (market) problems and sub- (micro-unit production) problems iteratively until convergence (Sagastizabal, 2012). We establish convergence criteria (described below) that allow us to map the market solution from USFPM/GFPM to a set of land-use/forest inventory changes to complete the detailed assessment of C implications.

Domestic C stocks for the forest sector include the C stored in the forest inventory of each region of the United States (from FDM, and a side spreadsheet model developed for this study to track logging slash C in forests) and C stored in the HWP as estimated by WOODCARB II using projections of wood and

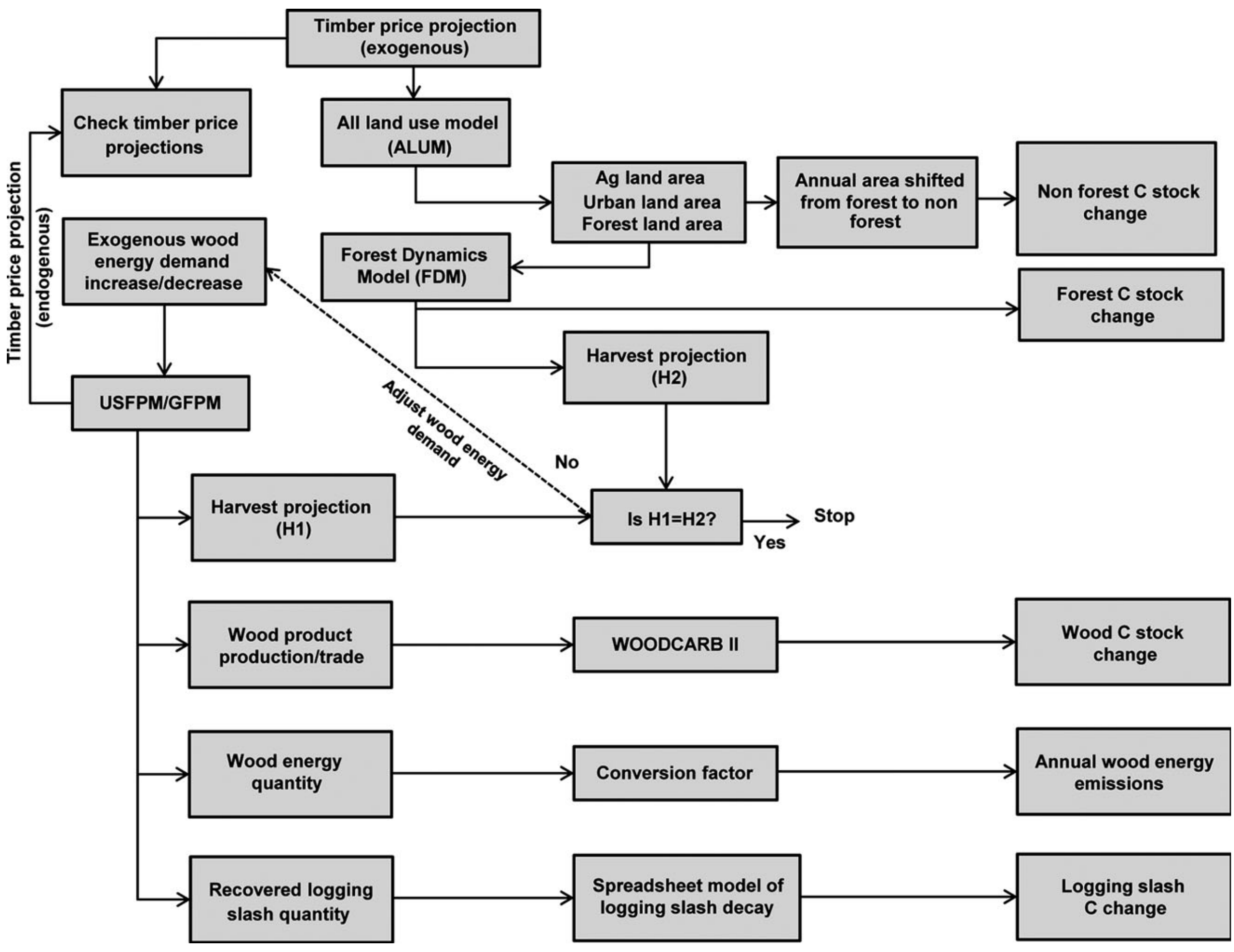

Fig. 1 Links among the models used in the study.

paper product production and trade from USFPM/GFPM. The spreadsheet model tracks logging slash C based on first order exponential decay and assumed half-life of logging slash (16.5 years) according to Eqn (1) (IPCC, 2000).

$$k = \frac{\ln(2)}{HL} \quad (1)$$

where k is decay rate, ln is natural logarithm, and HL is half-life of logging slash left on forest sites. Using a half-life of 16.5 years in Eqn (1) results in k value of 0.04.

When forest is converted to other land uses, not all of the C from the forest (primarily soil C) is transferred to the atmosphere. The soil C remains in the new land use (e.g. in pasture or in cropland). Accordingly, we account for C change over time on all land that was in forest in 2010, the beginning of our projection period. Table 2 shows the processes that are included in our analysis and lists the C stock changes and C emissions to the atmosphere that are used to estimate the net additions of C to the atmosphere as a result of changes in wood energy use in the United States.

Table 2 System boundaries: stocks and fluxes included when estimating changes in terrestrial and wood product carbon stocks and GHG emissions to the atmosphere

	US Economic Sectors					
	Forestry	Agriculture	Urban	Energy	Other sector	Other countries
C Stock						
Forest C above and below ground	Included	N/A	N/A	N/A	N/A	Not included
Logging slash C	Included	N/A	N/A	N/A	N/A	Not included
Wood products C from domestic harvest	Included	N/A	N/A	N/A	N/A	Not included
Wood products C from exports	Included	N/A	N/A	N/A	N/A	Not included
Wood products C from imports	Not included	N/A	N/A	N/A	N/A	Not included
Agriculture soil C change due to conversion of land between agriculture and forest	Included	Included	N/A	N/A	N/A	Not included
Agriculture soil C Change due to conversion of land between urban and forest	Included	N/A	Included	N/A	N/A	Not included
Agriculture above ground C	N/A	Not included	N/A	N/A	N/A	Not included
C Emissions						
From wood energy	Included	N/A	N/A	N/A	N/A	Not included
From forest management and harvesting operations (e.g. fossil fuel emissions)	Not included	N/A	N/A	N/A	N/A	Not included
From forest products manufacturing (e.g. plant fossil fuel emissions)	Not included	N/A	N/A	N/A	N/A	Not included
From fossil energy use	Included when considering wood energy substitution for natural gas or coal	N/A	N/A	Included when considering wood energy substitutionfor natural gas or coal	N/A	Not included
From agriculture sector management and harvest operation fuel use	N/A	Not included	N/A	N/A	N/A	Not included
Emissions from other economic sectors	N/A	N/A	N/A	N/A	Not included	Not included

N/A = Not applicable.

The first part of the analysis develops projections of wood energy use and forest C (including logging slash left on harvest sites), and HWP C for the two scenarios – A1B and A1BHFW. Land-use change projections were driven by RPA projected population, personal income, and, where relevant, timber prices. The scenarios were based on the original RPA projections but final harvest levels were adjusted from the original scenarios as discussed below. The second part of the analysis uses information on projected C stocks and projected harvests to (a) estimate the difference in wood energy emissions and difference in C stocks between the two projections over time, and (b) estimate C neutrality factor (CN_t) and cumulative radiative forcing (CRF) neutrality factor ($CRFN_t$) to define the degree to which increased wood energy emissions (between the two scenarios) would be offset by differences in C stocks between the two scenarios.

Step 1: For each scenario, 50 year forest sector harvest projections were first made using USFPM/GFPM and economic drivers from the RPA scenarios and then for the HFW case, wood energy demand based on the historical relationship between fuelwood demand and GDP. USFPM/GFPM projects harvest (for products and energy) for four timber categories: hardwood sawtimber, softwood sawtimber, hardwood nonsawtimber, and softwood nonsawtimber. USFPM/GFPM also determines the wood harvested for energy from each of these categories for three US regions (North, South, and West). Harvests derive from several categories of removals of timber from forests including removals from growing stock inventory on timberland, from 'additional removals,' which can include land clearing and from nongrowing stock sources that include parts of trees and forests that are not part of growing stock inventory. FDM provides removals consistent with the FIA measures of total removals. We use the historical relationship between sawtimber and nonsawtimber removals and product harvest by product class to convert removals into estimates of the total harvest quantity in each period, for use in the next step.

Step 2: A 50 year projection of land-use change, timber inventory, growing stock (GS) removals, and forest C inventory, and C on land converted from forest to nonforest for the two scenarios was made using ALUM and FDM runs. Historical relationships between product outputs and growing stock removals link harvest estimates from USFPM/GFPM to inventory removals in FDM. For each scenario, FDM provides several stochastically generated projections of the portion of harvest that is removal of growing stock. For each scenario, one of the stochastically generated projections was selected to provide the best match with the harvest levels for the USFPM/GFPM run for the same scenario. We selected a FDM realization that provided closest match to the harvest projections from the USFPM/GFPM. Inventory/carbon projections are consistent with the harvest quantities and projections of standing biomass and C totals are much less variable than projections of harvest/removal quantities (as is the case in the measured inventory values), so matching the harvest quantities was not likely to generate 'highly skewed' estimates of inventory volumes and C.

Step 3: A 50 year projection of the estimated change in agricultural and urban land was provided by the ALUM model for each of the two scenarios based on socioeconomic futures defined by the A1B storyline. For the two scenarios, the projection of urban land area was the same because, in each case, the urban area is determined by the same projections of population and personal income. Agricultural and forest land use is responsive to changes in rural land rents only in the South (Wear, 2011). Accordingly, the land use projections for the North and the West regions are identical for A1B and HFW. For the two scenarios, the area of agricultural and forest land in the US South can differ between cases because the extent of agricultural land can be influenced by timber prices and crop returns (we did not find a significant relationship between land use outcomes and these variables in other regions of the country). Real crop returns are held constant by assumption for this analysis. C storage varies depending on land-use distribution. To estimate the difference in agricultural land C between cases, we apply 40 metric tons of soil C per hectare of cropland and pasture land as reported by the U.S. Environmental Protection Agency (US Environmental Protection Agency, 2012).

Step 4: Because the FDM growing stock removal levels, after conversion into harvest levels, are not an exact match of the initial harvest projections from USFPM/GFPM for a given scenario, USFPM/GFPM was rerun to more precisely match the growing stock removal projections between the two models. Wood energy demand was adjusted in USFPM/GFPM until the decadal projections of cumulative harvest matched the corresponding FDM projection of growing stock removals within about $\pm1\%$ for the entire United States and within about $\pm10\%$ for the US regions. Note that this adjustment of wood energy demand to match harvest levels between the USFPM/GFPM and the FDPM alters the periodic fuel feedstock consumption levels. The expansion in US wood fuel feedstock consumption by 2060 in the original RPA A1B and RPA HFW scenarios were 15 times and two times that of 2006 levels, respectively. However, after the adjustments of wood energy demand, the fuel feedstock consumption in 2060 in the A1B and A1BHFW scenarios were projected to about five times and one times the 2006 levels, respectively (Table 1), resulting in cumulative US wood fuel feedstock consumption in the A1B scenario that are about five times higher than that of A1BHFW scenario by 2060 (Table 3).

Step 5: A separate spreadsheet was used to project C stored in logging slash left on the land after harvest for products and energy for each of the two scenarios using average logging slash decay rates defined by Eqn (1). The volume of logging slash left on the land after harvest for products and energy was obtained from USFPM/GFPM. Logging slash volumes are modeled in USFPM/GFPM as byproducts of timber harvest activities, and its recovery is constrained to not more than 60% of available residue volumes for reasons that are both economical (higher costs of recovering additional volumes) and practical in terms of forest management (leaving some residues in the forest for nutrient cycling, wildlife habitat protection, etc.) (Ince *et al.*, 2011b). Projected total forest C for the two scenarios includes the forest C projections provided from FDM runs (includes live tree C above and below ground, understory C above and below ground, C in standing and down dead wood, C in litter, and C in soil) and projections of logging slash C left on the land.

Table 3 Projected cumulative wood energy emissions (million metric tons of C), by US regions, for scenarios with high wood energy (A1B) and low energy (A1BHFW) consumption, 2010–2060, by US regions*

	A1B				A1BHFW				Difference, A1B and A1BHFW†			
Year	North	South	West	US	North	South	West	US	North	South	West	US
2010	8	18	9	35	7	14	7	28	−1	−4	−2	−7
2020	148	394	116	658	103	200	85	388	−45	−194	−31	−269
2030	536	1166	279	1981	274	433	160	867	−262	−734	−119	−1114
2040	1062	2193	510	3765	453	668	237	1358	−610	−1525	−273	−2407
2050	1562	3368	763	5694	617	881	317	1815	−946	−2486	−446	−3878
2060	2160	4534	1070	7764	745	1071	399	2214	−1415	−3463	−671	−5549

*See Table S1 in the supporting information document for the factors to convert volume of woods to carbon mass.
†Note that the expansion in US wood fuel feedstock consumption by 2060 in the original RPA A1B and RPA HFW scenarios were 15 times and two times that of 2006 levels, respectively. However, this study applied adjustments in fuel feedstock demand to match harvest levels of USFPM/GFPM and the FDM. After this adjustment, cumulative US wood fuel feedstock consumption in the A1B scenario was 4.5 times higher than that of A1BHFW by 2060.

Step 6: C stored in HWP made from wood harvested in the United States, was estimated using the projected amounts of forest products production and trade from USFPM/GFPM using the WOODCARB II model.

For each decade from 2010 to 2060, we compute the difference in cumulative wood energy emissions and the difference in C stocks in forests, logging slash, HWP, and cropland/pasture land using Eqns (2) and (3).

$$\Delta\text{Cumulative } E_t = (\text{Cumulative } E_t{}^{\text{ALT}} - \text{Cumulative } E_t{}^{\text{HFW}}) \quad (2)$$

$$\Delta\text{CStocks}_t = (\text{FC}_t^{\text{HFW}} - \text{FC}_t^{\text{ALT}}) + (\text{LS}_t^{\text{HFW}} - \text{LS}_t^{\text{ALT}}) + (\text{CP}_t^{\text{HFW}} - \text{CP}_t^{\text{ALT}}) + (\text{HWP}_t^{\text{HFW}} - \text{HWP}_t^{\text{ALT}}) \quad (3)$$

HFW indicates values for the A1BHFW scenario. ALT indicates values for the A1B scenario. Cumulative E_t is cumulative wood energy C emissions up through time t; FC is forest carbon (including forest soil C); LS is logging slash carbon; CP is soil carbon on crop and pasture land; and HWP is carbon in HWP.

Using the two scenarios, we estimate CN_t over time, which indicates the degree to which the change in C stocks offsets cumulative emissions up to a given point in time (Eqn 4). Our equation for CN_t is adapted from the equation provided by (Schlamadinger *et al.*, 1995) to estimate net C emissions for a wood energy plant compared to a fossil energy reference case.

$$\text{CN}_t = 1 + \frac{\Delta\text{CStocks}_t}{\Delta\text{Cumulative } E_t} \quad (4)$$

For our analysis, changes in cumulative emissions are positive because of the increased use of woody biomass between scenarios. Changes in C stocks are expected to be nonpositive – i.e. some net decline in C stocks with increased consumption of woody biomass. The question then is the degree to which change in C stocks mirrors emissions. If the difference in C stocks were equivalent to the difference in cumulative emissions (that is no compensatory growth occurred) then the CN_t would equal zero. If, however, the difference in C stocks was less than the difference in cumulative emissions ($0 < \text{CN}_t < 1$) then growth and other changes to stocks offset a portion of the emissions generated by the woody biomass.

Other values of CN are possible. For example, $\text{CN}_t > 1$ would indicate that expanding C stocks would more than compensate for the increase in emissions. Conversely, $\text{CN}_t < 0$ would indicate that C stocks would contract by more than the increase in emissions.

We also compute CRFN_t, which is similar to C neutrality factor but estimates the degree to which the change in CRF associated with C stock change offsets change in CRF associated with wood energy emissions up to a given point in time.

$$\text{CRFN}_t = 1 + \frac{\text{CRF}\,(\overline{\Delta\text{CStocks}_t})}{\text{CRF}\,(\overline{\Delta E_t})} \quad (5)$$

$\overline{\Delta CStocks_t}$ and $\overline{\Delta E_t}$ are vectors of annual differences in stocks and emissions, between the two scenarios for years 1 through *t*. CRF for a vector of stock or emission differences is computed in two steps. First, the radiative forcing is computed for each year's difference in stocks or emissions. The radiative forcing for 1 year's difference is computed for each year thereafter out to the time horizon *t*. Second, all the radiative forcing totals for each year's difference in stocks or emissions are added to obtain a grand total of CRF associated with all the differences in stocks or emissions from year 1 to year *t*. Unlike CN_t, CRFN_t is influenced by the specific timing of differences in emissions and stocks. Earlier differences in emissions or C stocks make a larger contribution to CRF by the end of the time period (e.g. 50 years) relative to later differences in emissions or C stocks. The difference in radiative forcing caused over time by a given year's difference in stocks or emissions was estimated by using a CO_2 response function from the IPCC 4th Assessment Working Group I Report (IPCC, 2007) (see page 213, footnote 'a'). Helin *et al.* (2013) in their review of approaches to inclusion of the forest C cycle in life cycle assessment recommend the use of a climate impact estimator, such as radiative forcing, that accounts for the timing of emissions and sinks and cite several instances of its use.

Sensitivity analysis

The CN_t factors estimated from Eqns (4) and (5) assumes that a wood energy system substitutes for a fossil fuel system that emits the same amount of CO_2 per unit of energy as the wood energy system so that the change in cumulative emissions from wood burning equals changes in cumulative emissions from fossil fuel burning. However, if wood emits more CO_2 per unit of energy than the fossil fuel being replaced, then the actual CN_t factors will be lower because of differences in emissions per unit energy produced. We estimated CN_t factors for cases where we assume a wood system substitutes for a fossil system that emit either 40% or 75% of CO_2 per unit of energy relative to CO_2 emissions per unit for a wood energy system. In other words, we evaluate two cases, where a wood energy system is assumed to be either 60% or 25% less efficient, respectively, than a fossil energy system. The 40% efficiency case approximates use of modern wood power system in place of a modern natural gas system. The 75% efficiency case approximates substitution of wood feedstock for 20% of the coal feedstock in an existing coal power plant. We have taken these substitution cases from a study by the Manomet Center for Conservation Sciences (2010) (see page 21, Exhibit 2-1).

To conduct sensitivity of different logging residue decay rates on the estimated CN_t and $CRFN_t$, we used a range of decay rates (k = 0.14 and 0.02) corresponding to 5- and 32 year half-lives to cover much of the range for dead decay wood reported in literature (National Council for Air & Stream Improvement, 2004). Because decay rates can sometimes be longer, we also use two extreme assumptions of no decay (k = 0) and near instantaneous decay (k = 0.99).

Results

The models indicate differences in cumulative wood energy emissions (Table 3) and differences in C inventory in different C pools (Table 4) between the two scenarios. Nationwide, A1B wood energy use cumulatively emits 5549 Tg more C than A1BHFW by 2060, more than 62% of this difference is in the US South, followed by the North (26%), and the West (12%). The nationwide C accumulation in forests, by 2060, was ~1300 Tg less in A1B than in A1BHFW, which is less than the difference in nationwide cumulative emissions, thus providing a nationwide emissions offset as indicated by a CN_t factor of 0.78 by 2060 (Table 5). The corresponding value for the nationwide offset of $CRFN_t$ is 0.80. By region, the differences in cumulative wood energy C emissions between the A1B and A1BHFW scenarios, by 2060, is largest in the South (3463 Tg), followed by the North (1415 Tg), and the West (671 Tg). In contrast, the difference in forest C between the A1B and A1BHFW scenario, by 2060, is largest in the North (1201 Tg less in A1B), followed by the West (179 Tg less in A1B) with South accumulating higher forest C even in higher wood energy case (68 Tg more in A1B). Accordingly, US South offsets almost all wood energy CO_2 emissions (CN_t = 0.95) and CRF of emissions ($CRFN_t$ = 1.0), by 2060. The West offset 50% and 60% of wood energy and CRF emissions by 2060, as indicated by CN_t of 0.50 and $CRFN_t$ of 0.60, respectively. C emissions recovery is small (CN_t = 0.17 and $CRFN_t$ = 0.16 by 2060) for the North. Factors influencing differences among regions are discussed below.

The results show that a substantial proportion of the nationwide increased wood energy emissions would be offset by differences in forest vs. agricultural land area, and differences in biomass regrowth, logging slash left to decay onsite, and C stored in HWP. Table 5 shows how the CN_t and $CRFN_t$ factors vary over time for (a) forest C pool only, (b) forest and logging slash C pools, (c) forest, logging slash, and land-use transfer C pools, and (d) all C pools (forest, logging slash, land-use transfer, and HWP). When only forest C pools were considered (excluding logging slash C stock), the nationwide CN_t factors for 2020, 2030, 2040, 2050, and 2060 were 0.90, 0.92, 0.81, 0.78, and 0.76 ($CRFN_t$ values of 0.88, 0.91, 0.87, 0.83, and 0.80), respectively (Table 5). These results suggest that nationwide increases in forest C alone could offset more than 92% to 76% of nationwide increased C emissions from burning wood to produce energy or 91% to 80% of nationwide increased radiative forcing by 2020 to 2060, respectively. The Southern forests provide a largest projected C offset over the 50 year period, followed by the West. The Northern forests provide the smallest C recovery of the increased wood energy emissions during the study period.

Inclusion of C change in logging slash C stock left to decay on site increased both the nationwide and regional CN_t and $CRFN_t$ factors through 2020 but decreased them through 2060. Adding logging slash decay will increase the CN_t factors as long as emissions from slash decay is lower for the A1B case than the A1BHFW case. It is possible for slash emissions to be larger in the A1B case with higher roundwood harvest than for the A1BHFW case as wood energy shifts greater use of pulpwood (with higher fuel feedstock price) and promotes complementary production of sawtimber (lowers logging costs) and reduces imports. Land use projections for the North and the West are identical between A1B and A1BHFW scenarios, but they are responsive to changes in rural land rents in the South. Accordingly, C stock change due to land-use transfers affected only the Southern and the nationwide CN_t and $CRFN_t$ factors. Land-use transfers decreased the Southern and the nationwide CN_t and $CRFN_t$ factors for all time periods. Finally, including HWP C, increased the nationwide CN_t and $CRFN_t$ factors for all time periods. Similar effects can be expected for the regional CN_t and $CRFN_t$ factors. However, because our study modeled HWP C

Table 4 Projected carbon inventory (million metric ton) in forests, logging slash left on site, land-use transfer, and harvested wood products for scenarios with high wood energy (A1B) and low energy (A1BHFW) consumption, by US regions, 2010–2060

		Carbon pool																			
		Forest				Logging slash*				Land-use transfer†				Harvested wood products‡				All pools			
Scenario	Year	North	South	West	US	North	South	West	US	North	South	West	US	North	South	West	US	North	South	West	US
A1B	2010	14 333	12 394	14 599	41 325	49	92	33	174	0	0	0	0	–	–	–	2491	14 382	12 486	14 632	43 990
	2020	14 333	12 440	14 613	41 386	121	228	86	435	0	0	0	0	–	–	–	2841	14 455	12 668	14 699	44 663
	2030	14 175	12 324	14 425	40 924	182	275	109	566	0	0	0	0	–	–	–	3225	14 357	12 599	14 534	44 714
	2040	13 812	12 085	14 273	40 170	243	318	107	668	0	0	0	0	–	–	–	3647	14 055	12 403	14 380	44 485
	2050	13 266	11 747	14 206	39 219	291	351	111	752	0	0	0	0	–	–	–	4163	13 557	12 098	14 316	44 134
	2060	12 760	11 389	14 015	38 164	363	380	123	866	0	0	0	0	–	–	–	4744	13 123	11 769	14 138	43 775
A1BHFW	2010	14 333	12 394	14 599	41 325	47	90	32	170	0	14	0	14	–	–	–	2492	14 380	12 498	14 631	44 001
	2020	14 418	12 379	14 615	41 412	110	217	83	410	0	43	0	43	–	–	–	2830	14 528	12 640	14 698	44 696
	2030	14 379	12 217	14 417	41 013	140	271	122	534	0	72	0	72	–	–	–	3197	14 519	12 561	14 539	44 816
	2040	14 305	11 963	14 349	40 616	191	328	151	670	0	101	0	101	–	–	–	3570	14 496	12 391	14 499	44 956
	2050	14 156	11 616	14 313	40 085	257	387	191	836	0	129	0	129	–	–	–	3945	14 413	12 132	14 504	44 995
	2060	13 961	11 321	14 194	39 477	342	450	281	1073	0	158	0	158	–	–	–	4267	14 304	11 929	14 475	44 975

*See equation S1 and Table S2 in the supporting information document for the details on logging slash C estimates.
†Agriculture and forest land use differ by scenarios only in the South.
‡HWP C is modeled at the national level only.

Table 5 Carbon neutrality factor (CN_t) and cumulative radiative forcing neutrality factor ($CRFN_t$) for the scenarios with high wood energy (A1B) and low energy (A1BHFW) consumption considering carbon accumulated in forests, logging slash, land-use transfer, and harvested wood products, 2010–2060, by US regions

	CN_t factor considering different C pools*															
	Forest C				Forest + logging slash C				Forest + logging slash + land-use transfer C§				Forest + logging slash + land-use transfer + HWP C¶			
Year	North	South	West	US	North	South	West	US	North	South	West	US	North	South	West	US
2010‡																
2020	−0.90	1.32	0.92	0.90	−0.64	1.37	1.02	1.00	−0.64	1.15	1.02	0.84	−0.64	1.15	1.02	0.88
2030	0.22	1.15	1.06	0.92	0.38	1.15	0.95	0.95	0.38	1.05	0.95	0.88	0.38	1.05	0.95	0.91
2040	0.19	1.08	0.72	0.81	0.28	1.07	0.56	0.81	0.28	1.01	0.56	0.77	0.28	1.01	0.56	0.80
2050	0.06	1.05	0.76	0.78	0.09	1.04	0.58	0.76	0.09	0.99	0.58	0.72	0.09	0.99	0.58	0.78
2060	0.15	1.02	0.73	0.76	0.17	1.00	0.50	0.73	0.17	0.95	0.50	0.70	0.17	0.95	0.50	0.78
$CRFN_t$ factor considering different C pools†																
2010‡																
2020	−1.41	1.38	0.92	0.88	−1.08	1.45	1.02	0.99	−1.08	1.18	1.02	0.80	−1.08	1.18	1.02	0.85
2030	−0.19	1.21	1.02	0.91	0.02	1.23	0.97	0.96	0.02	1.09	0.97	0.86	0.02	1.09	0.97	0.89
2040	0.08	1.14	0.88	0.87	0.22	1.15	0.77	0.89	0.22	1.05	0.77	0.82	0.22	1.05	0.77	0.85
2050	0.09	1.10	0.81	0.83	0.19	1.10	0.67	0.83	0.19	1.02	0.67	0.78	0.19	1.02	0.67	0.82
2060	0.10	1.07	0.78	0.80	0.16	1.06	0.60	0.79	0.16	1.00	0.60	0.75	0.16	1.00	0.60	0.80

*See Data S3 in the supporting information document for the details on CN_t factor estimates.
†See Data S4 in the supporting information document for the details on $CRFN_t$ factor estimates.
‡The projection of forest C stocks for both scenarios is same for 2010, the year when the projection of forest C stock was started. The resulting CN_t and $CRFN_t$ factors for 2010, therefore, are not reported as they do not offer meaningful interpretations.
§Agriculture and forest land use differ by scenarios only in the South.
¶HWP C is modeled at the national level only.

only at the national level, we could not estimate the effect of HWP C on regional CN_t and $CRFN_t$. Overall, the addition of forest slash decay, land-use transfers, and HWP C to forest C change had a relatively small net effect on CN_t and $CRFN_t$ for the periods through 2060.

Changes in forest C stocks over time for a scenario reflect several simultaneous factors. For the two scenarios, a common set of downscaled economic and demographic factors define urbanization within the land-use model. The degree to which newly developed lands are derived from forests or other agricultural land uses is partially determined by the projection of timber prices (we assume that agricultural crop returns were constant over the projection period). This price responsiveness proved significant and was included in simulations only in the South region, where rural land uses have been highly flexible since World War II (Wear, 2011). In the South, the difference in forest area between A1B and A1BHFW amounts to 3.5 million ha by 2060. Another change to forests induced by market changes is the extent of planted pine forests in the South. A1B, with strong increases in prices results in an additional 5.6 million ha of planted pine by 2060 when compared with A1BHFW. New planted pine comes not only from afforestation of some agricultural land but also (and largely) from replanting harvested forests with other forest types. C stocks change irrespective of management as forests age, disturbances occur, and climate changes. Taken together, these changes alter the distribution and the growth rates of forests across all forest types.

The change in forest C stock between scenarios for the United States as a whole and for each region is influenced by complex changes in national and regional forest product markets as wood energy demand increases. The increase in wood energy use for scenario A1B relative to A1BHFW influences trade and how much timber is harvested in the United States in two ways. First, higher levels of fuel wood use in foreign countries (A1B vs. A1BHFW) tend to shift competitive advantage to the United States to produce products, particularly lumber. This competitive advantage allows the United States to increase imports of roundwood to partially meet the US lumber demand. The expansion of plantation timber production also increases competitive advantage and domestic lumber production. The effect of increased harvest in foreign countries to provide more roundwood for the United States is more than offset by a greater than equivalent decrease in US lumber imports. These shifts in trade result in a net decrease in harvest in other countries (A1B vs. A1BHFW) and avoid leakage in the form of extra forest C stock decrease in other countries due to increased US wood energy use. However, this result is dependent on our assumption that an increase in wood energy use in the United States for scenario A1B will be accompanied by higher levels of wood energy use in other countries relative to scenario of A1BHFW. The increase in wood energy demand in the South that consumes more logging residue and the shift to greater production of timber have market-induced effects on production of oriented strandboard production (OSB) in the North and softwood plywood in the West with associated effects on change in timber harvest and forest C (between A1B and A1BHFW). The net effect of these changes in the South, particularly increased pulpwood prices in the South include a shift of OSB production from the South entirely to the North thus increasing harvest in the North and decreasing forest C and resulting in a low CN_t factors for the North. The net effect of the changes in the South, particularly increased timber production from plantations results in a shift in competitive advantage for production of softwood plywood from the West entirely to the South, thus decreasing harvest in the West and increasing forest C and resulting in a high CN_t factors for the West. A key finding is that complex market interactions among the United States and foreign countries and among US regions in response to increasing wood energy demand can have a significant impact on CN_t factors in particular US regions.

Values of the neutrality factors are determined primarily by the change in C within forests (including afforestation). Accounting for land-use transfers to forests for all periods reduced neutrality factor estimates, and including HWP C, increased neutrality factor estimates. Including land-use change decreases the CN_t and $CRFN_t$ factors because the A1B scenario retains 3.5 million ha land (by 2060) in forests that would have been in agricultural uses in the A1BHFW scenario. Therefore, the A1BHFW scenario includes C on these agricultural lands that does not appear in the A1B scenario and appears as a 'loss' of agricultural C when estimating C change between the A1BHFW scenario and the A1B scenario.

Thus, the analysis indicates 76% of the US biomass energy emissions (80% of radiative forcing) could be offset by forest C change alone, over the 50 year period. One important implication of this study is that increased demands for and emissions from biomass for energy could be largely offset by forest regrowth and market-induced investments in the form of retained forest area, afforestation, and the area of planted pine forests in the southeastern United States. The inclusion of additional C pools can either decrease or increase the CN_t and $CRFN_t$ factors but only to a limited degree.

Comparing C emissions from wood energy with those from fossil fuel alternatives requires a comparison of the efficiency of energy conversion in terms of CO_2 emissions per unit of energy produced for the two approaches. The estimates for CN_t and $CRFN_t$ can be adjusted to account for the lower CO_2 emissions per unit of energy, relative to wood, of alternate fossil energy systems. Here, we assume that displaced fossil fuel systems have CO_2 emissions per unit of energy that are 40% or 75% less than emissions per unit energy for wood energy systems. For the 40% case, nationwide CN_t and $CRFN_t$ values for 2060 using forest C change alone are 0.41 and 0.51, respectively (Table 6). When all C stock changes are included, the values are 0.46 and 0.52, respectively. That is, for the Manomet study example power plant cases, substituting a modern wood energy power plant for a modern natural gas plant would result in 41–52% less net C emissions through 2060 depending on the measure and accounting for forest, land use, and product C stock changes. For the 75% case, CN_t and $CRFN_t$ values for 2060 using forest C change alone are 0.68 and 0.74, respectively (Table 6). When all C stock changes are included, the values are 0.71 and 0.74, respectively. That is, for the Manomet study example power plant cases, substituting wood feedstock for 20% of coal feedstock in a coal power plant would generate 68–74% less net C emissions than burning coal depending on the measure and accounting for forest, land use, and product C stock changes.

We also examined how estimates would differ by using a 2010 reference point baseline (RPB) rather than an anticipated baseline. The C neutrality factor number for an anticipated baseline case is the portion of the difference in cumulative C emissions between two cases that are recovered in C stocks by time *t*. For a RPB case, the neutrality number is the portion of difference in cumulative emissions to time *t* that do not appear as a change from the baseline initial year C stocks to time *t*. So if the C stocks is the same at time *t* than in the initial year then 100% of the emissions do not appear as a change in the initial C stocks ($CN_t = 1$). If the C stocks at time *t* are above the initial level by an amount equal to 20% of the cumulative emissions then CN_t is 1.2. If C stocks decrease by 30% of the amount of the cumulative emissions by time *t* then CN_t is 0.7. Based on emission and stock estimates in Tables 3 and 4, we computed RPB neutrality factors for both A1B and A1BHFW scenarios. The RPB 'C neutrality factor,' for A1B using forest C change alone, is 0.36 by 2060. So by 2060, 36% of the cumulative emissions do not appear as a forest C

Table 6 Carbon neutrality factor (CN_t) and cumulative radiative forcing neutrality factor ($CRFN_t$) for the United States (assuming wood energy systems are replacing fossil energy systems that emit 40% and 75% as much CO_2 per unit of energy as wood energy systems) for scenarios with high wood energy (A1B) and low energy (A1BHFW) consumption considering carbon accumulated in forests, logging slash, land-use transfer, and harvested wood products, 2010–2060

Year	Forest C only	Forest + logging slash C only	Forest + logging slash + land-use transfer C	Forest + logging slash + land-use transfer + HWP C
Case 1, wood replaces fossil fuel alternative that emit 40% as much CO_2 per unit energy as wood*				
CN_t factor considering different C pools§				
2010‡				
2020	0.76	0.99	0.59	0.69
2030	0.80	0.87	0.71	0.77
2040	0.54	0.53	0.43	0.51
2050	0.44	0.39	0.30	0.44
2060	0.41	0.32	0.24	0.46
$CRFN_t$ factor considering different C pools¶				
2010‡				
2020	0.71	1.07	0.60	0.71
2030	0.77	0.95	0.70	0.78
2040	0.66	0.76	0.59	0.67
2050	0.57	0.61	0.48	0.58
2060	0.51	0.49	0.39	0.52
Case 2, wood replaces fossil fuel alternative that emit 75% as much CO_2 per unit energy as wood†				
CN_t factor considering different C pools§				
2010‡				
2020	0.87	1.00	0.78	0.84
2030	0.89	0.93	0.85	0.88
2040	0.75	0.75	0.70	0.74
2050	0.70	0.67	0.63	0.70
2060	0.68	0.64	0.60	0.71
$CRFN_t$ factor considering different C pools¶				
2010‡				
2020	0.84	1.04	0.78	0.85
2030	0.88	0.98	0.84	0.88
2040	0.82	0.87	0.78	0.82
2050	0.77	0.79	0.72	0.77
2060	0.74	0.73	0.67	0.74

*The estimates of CN_t and $CRFN_t$ factors are based on assumption that wood energy system replaces natural gas generated electricity system that emits 40% of CO_2 relative to CO_2 emissions per unit of wood energy system. See Tables S3 and S4 in the supporting information document for the details.

†The estimates of CN_t and $CRFN_t$ factors are based on assumption that wood energy system replaces coal generated electricity system that emits 75% of CO_2 relative to CO_2 emissions per unit of wood energy systems. See Tables S3 and S4 in the supporting information document for the details.

‡The projection of forest C stocks for both scenarios is same for 2010, the year when the projection of forest C stock was started. The resulting CN_t and $CRFN_t$ factors for 2010, therefore, are not reported as they do not offer meaningful interpretations.

§The CN_t factors were estimated using equation S3 presented in the supporting information document.

¶The $CRFN_t$ factors were estimated using equation S4 presented in the supporting information document.

loss relative to the reference point. If C held in logging slash and HWP is included then the RPB neutrality factor would be 0.95 by 2060. So by 2060, 95% of the emissions do not appear as C stock loss. Or alternately, only 5% of the cumulative emissions do appear as a C stock loss. For the anticipated baseline case, the neutrality number in 2060 was 0.76 for forest C alone or 0.78 for all C stocks. The C neutrality factor calculated using the RPB indicates that extra wood energy emissions above the starting emissions level that do not appear as a loss of forest or total C stocks which are 36% and 95% of the extra emissions, respectively. However, the forest C loss (or gain) is due to all causes, not just the increased use of wood for energy. In our particular A1B scenario, the neutrality number is positive for both the RPB case and the anticipated baseline case. For RPB cases, it is possible that the C neutrality factor number could be 1 or greater than 1 when C is accumulating even as wood energy use is increasing because of factors not related to wood energy use or it could be less than zero if C stocks are falling faster than the amount of harvest for wood energy. Use of RPB cases to evaluate 'C neutrality' over time does not indicate the impact cumulative emissions have on forest C in the case where there are other factors beyond removals of wood for wood energy that influence C stock change.

We also estimated the sensitivity of CN_t factors to logging slash decay rates using lower and higher values for half-lives of logging slash on forest sites (5 and 32 years, giving k values of 0.14 and 0.02 in Eqn (1), respectively) and two extreme assumptions of no decay (k = 0) and near instantaneous decay (k = 0.99). The results are shown in Table 7. The variation in decay rate has very little impact on the estimated CN_t factor. The insensitivity of CN_t factor to logging slash decay rate can be explained by two factors. First, the difference in logging slash C stock between cases was a small fraction of the difference in total cumulative emissions (1–5%). Second, the variation in decay rate did not increase this share to a notable degree (Table 7).

Table 7 Sensitivity analysis for estimated factor (CN_t) and estimated differences in logging slash carbon stocks using scenarios with high wood energy (A1B) and low energy (A1BHFW) consumption for a range of decay rates (k), 2010–2060

Year	k = 0.99	k = 0.14	k = 0.04	k = 0.02	k = 0.00
Estimated CN_t factors					
2010*					
2020	0.78	0.84	0.88	0.89	0.90
2030	0.88	0.89	0.91	0.92	0.92
2040	0.80	0.80	0.80	0.81	0.81
2050	0.79	0.78	0.78	0.78	0.78
2060	0.82	0.80	0.78	0.78	0.78
Estimated $CRFN_t$ factors					
2010*					
2020	0.74	0.80	0.85	0.87	0.88
2030	0.84	0.87	0.89	0.90	0.91
2040	0.83	0.84	0.85	0.86	0.87
2050	0.81	0.81	0.82	0.82	0.83
2060	0.80	0.80	0.80	0.80	0.81
Estimated differences in logging slash C stocks					
2010*					
2020	−1	14	25	29	33
2030	3	15	32	39	50
2040	−8	−15	−1	9	25
2050	−27	−68	−84	−81	−70
2060	−26	−120	−207	−231	−251

*The projection of forest C stocks for both scenarios is same for 2010, the year when the projection of forest C stock was started. The resulting CN_t and $CRFN_t$ factors for 2010, therefore, are not reported as they do not offer meaningful interpretations.

Discussion

Our analysis used different market equilibrium scenario projections that had identical economic growth assumptions but differed in the level of energy consumption. The results show how increased emissions from producing bioenergy could be substantially offset by shifts in wood product output, changes in land held in forest, forest growth, timber harvest, and the resultant C stocks in forests, nonforest land, and HWP.

Although it is difficult to directly compare our results with other studies due to differences in modeling approaches, and temporal and geographical scales considered, they provide a basis for comparing our overall results and general conclusions. We find that our overall results agree with previous studies, which indicate that a substantial portion of wood energy emissions could be recovered by biological growth and price-induced investments in forest management and plantations (Abt *et al*., 2010b; Daigneault *et al*., 2012; Sedjo & Tian, 2012; White *et al*., 2013). For example, comparing scenarios of constant, 2%, and 4% annual increase in demand for bioenergy for the next 40 years, Sedjo & Tian (2012) find a substantial increase in forest C for the increased bioenergy demand scenarios compared to the constant demand scenario. For instance, with land supply unconstrained (i.e. that land is unlimitedly available for plantation), they show that a 2% increase in bioenergy demand for the next 40 years (which remains fixed at that level after 40 years) will lead to additional increase in forest C of about 30 Tg per year by next 90 years, with projected forestland almost doubling at about 11 million ha from current 6 million ha resulting from a very high increase in timber price. Similarly, taking into account harvest and planting decisions affected by demand for biomass energy and comparing emission reductions from reduced coal usage against changes in forest C stock caused by increased biomass harvest, Abt *et al*. (2010b) reported a reduction in emissions of up to 39 Tg of carbon dioxide equivalent (CO_2e) per year when about 50% of logging slash available from 10 southeastern US states replaced coal in power generation.

In another study, White *et al*. (2013) used an economic model of forest and agriculture sector to evaluate potential net change in emissions due to increased demands for US bioelectricity, taking into account total C stock change on both agriculture and forestland, and comparing two cases of increased wood-based electric power production to a BAU baseline scenario over the period 2010–2030. For the highest targets for bioelectricity production, their analysis projected increased land conversions from agriculture to forestry allowing for a larger proportion of biomass coming from agriculture. Therefore, they projected a highly negative to zero CN_t factors when forest C change alone was considered. However, when the net effects of both sectors were considered together, CN_t factor estimates were much higher at about 0.90 by 2055 for the increased bioelectricity scenario. Our CN_t factor estimate of 0.78 by 2060 closely agrees with their estimate but the difference is largely attributable to conversion of forest to agricultural land to produce short rotation herbaceous biomass for energy, which our study did not consider. However, our models allowed variation in purchase of agricultural land to plant forests, conversion of natural forest to plantation and conversion of forest to agricultural land for food crops or pasture. Similarly, in another study Daigneault *et al.*(2012) used global economic model of forest and land use to show the effects of US biomass energy policy on US and global C stock. They showed that increased demand for bioenergy leads to increased investments in forestry that could substantially offset increased emissions due to bioenergy use. For example, when the land supply was unconstrained, their analysis projects a forest land area expansion of 13 million ha, leading to an increase in forest C of about 40 Tg CO_2 per year by 2060 largely due to investments in forestry induced by higher timber prices resulting from increased bioenergy demand (additional 80 million m^3 per year in 2015 to about additional 172 million m^3 per year in 2060). Converting their projected numbers to differences in cumulative emissions and C stocks provides a CN_t factor estimate of about 2.0 by 2060, which is higher than our estimated CN_t factor of 0.78. The differences in estimates are due to projected differences in cumulative emissions and C stocks between the two scenarios considered. Daigneault *et al.* (2012) considered a base case with no wood energy use compared to a case with substantial biomass energy consumption which resulted in a 13 million ha expansion of forestland area. In contrast, our study has a more modest increase in wood energy use between scenarios and a resulting smaller expansion of forest area and smaller CN_t factor after a 50 year projection.

Our research also highlights the importance of developing carefully constructed 'with' and 'without' scenarios – i.e. an anticipated baseline – when evaluating the C impact of expanded wood energy use. Using a reference point baseline to evaluate the A1B scenario would have provided C neutrality factor indicating C loss was less than increased emissions, just as for the anticipated baseline cases, but would have indicated lower C 'recovery' when only forest C is included (0.36 vs 0.76) or higher recovery if all C stocks were included (0.95 vs 0.78). The C neutrality factors for the RPB and anticipated baseline cases measure two different relative C stock changes. For the RPB, these factors measure how much forest or total C decreases or increases from all causes (since the reference point) as a percentage of wood energy emissions. For the anticipated baseline case, they measure the forest or total C difference due to wood energy change as a percentage of wood energy emissions.

The most important finding is that a substantial portion of biomass C emissions from increased wood energy use would be offset over 50 years largely because of natural biological regrowth and price-induced changes in land use and management strategies (e.g. higher timber prices especially for pine pulpwood because of increased bioenergy demand lead to expanded areas of pine plantations). The CN_t and $CRFN_t$ factors in 2060 indicate C stock adjustments would offset wood energy C emissions by 78% and 80% respectively. By extending this analysis, we compared use of wood energy systems in place of natural gas energy systems with C emissions per unit output that are 40% of the level for the wood energy system. Use of the wood energy systems would result in 46% (CN_t) to 52% ($CRFN_t$) less C emissions/radiative forcing within 50 years. The C offset results are estimated to be better if wood is used in cofiring coal energy systems. These estimated C offset results over a 50 year period support the consideration of using wood energy as a part of broader climate policies.

The CN_t and $CRFN_t$ factors at the national level obscure some important differences among regions that reflect different land use, forest management, and forest product production responses. In the South, where forest area increases somewhat in response to higher timber prices and tree planting is a common practice, and conditions are conducive to rapid reforestation, increased harvests and emissions are completely offset by forest growth in young forests (CN_t and $CRFN_t > 1.0$ in 2060). The North experiences an increase in wood energy use (A1B vs A1BHFW) that is mostly not offset by recovery of forest C. Forest area does not change in response to changes in timber prices and although forests regrow after harvest, this regrowth is offset to a large degree by market shifts in regional product production. Harvest in the North increases to produce more oriented strandboard (OSB) as competitive advantage shifts from the South to the North and all OSB production in the South in A1BHFW is shifted to the North in A1B (CN_t and $CRFN_t > 0.16$ in 2060). The West experiences an increase in wood energy use that is offset by change in forest C more than for the North.

Although forest area does not change in response to increased prices for timber, forest regrowth after harvest is supplemented by reduced harvest as softwood plywood production shifts from the West to the South (A1BHFW to A1B) (CN_t and $CRFN_t$ > 0.50 in 2060).

Some caution should be taken when applying the results of our analysis to broad policy questions. Although our models account for wood products trade using global economic conditions linked to RPA A1B scenario, we cannot account for certain types of market leakage, especially regarding fossil fuel consumption outside the United States. Leakage would result in an overstatement of the C benefits of any energy/policy (Richardson & Macauley, 2012) and warrants further investigation. For example, limited decrease in fossil fuel demand may increase fossil fuel consumption to a limited degree in the United States and overseas partially but not wholly offsetting the C offsets from increasing US wood energy use. Our analysis focuses on a very strong expansion in the use of wood for energy production. On the basis of partial analysis, we speculate that C neutrality factor estimates for lower levels of wood energy use could be higher, but this deserves careful investigation. Our estimates of neutrality factors differ substantially by region. The factors differ not only because of differences in forest regrowth and induced investment in retaining and planting forest, but also because of how increased wood energy use by individual regions causes shifts in competitive advantage among regions in producing various wood products. This suggests that the C neutrality factors for individual regions cannot be estimated in isolation but would need to be estimated contingent on the level of change in wood energy use in other regions. Our estimates are uncertain to the extent that real world market responses may differ from our modeling. Landowners may change forest land area and management intensity with sufficient change in timber prices. Producers may be more or less responsive in changing regional product production in response to changes in wood supply prices.

Finally, agricultural land owner response to a new bioenergy market (with increased returns to agriculture) was only partially considered in this analysis. Increasing crop returns would lead to dampening of the investment/forest growth response to energy prices and reduce CN_t factors somewhat. Our models allowed variation in purchase of agricultural land to plant forests, conversion of natural forest to plantation and conversion of forest to agricultural land for food crops or pasture, but did not include the potential effect of increased biomass demand on conversion of forest to agricultural land to produce short rotation herbaceous biomass for energy. White *et al.* (2013) conducted an analysis of increased biomass demand for energy that included such conversion and found that if herbaceous crops have low enough cost, some forest would be converted to herbaceous crops – resulting in loss of forest C, but their carbon neutrality factor was estimated to be above 0.80 across both the forest and agriculture sector due to combined increased biomass growth from increased investments in the sectors.

Acknowledgments

We acknowledge funding support from the USDA Forest Service Renewable Resources Planning Act (RPA) assessment. Authors are thankful to Dr Peter J. Ince for his advice and planning of this research.

References

Abt R, Abt K, Cubbage F, Henderson J (2010a) Effect of policy-based bioenergy demand on southern timber markets: a case study of North Carolina. *Biomass and Bioenergy*, **34**, 1679–1686.

Abt R, Galik C, Henderson J (2010b) The nearterm market and greenhouse gas implications of forest biomass utilization in the Southeastern United States. *Climate Change Policy Partnership*, Duke University, Durham, NC. Available at: http://www.nicholas.duke.edu/ccpp/ccpp_pdfs/biomass.08.2010.pdf; last accessed 21 February 2013.

Abt K, Abt R, Galik C (2012) Effect of bioenergy demands and supply response on markets, carbon, and land use. *Forest Science*, **58**, 523–539.

Agostini A, Giuntoli J, Boulamanti A (2013) Carbon accounting of forest bioenergy: conclusions and recommendations from a critical literature review. In: *Report EUR 25354 EN* (ed. Marelli L), Joint Research Center of the European Commissions, Luxembourg, European Union.

Buongiorno J, Zhu S, Zhang D, Turner J, Tomberlin D (2003) *The global forest products model*. Academic Press, London, UK.

Daigneault A, Sohngen B, Sedjo R (2012) Economic Approach to Assess the Forest Carbon Implications of Biomass Energy. *Environmental Science & Technology*, **46**, 5664–5671.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science*, **319**, 1235–1238.

Galik C, Abt R, Wu Y (2009) Forest biomass supply in the southeastern United States-Implications for industrial roundwood and bioenergy production. *Journal of Forestry*, **107**, 69–77.

Gan J, Smith C (2007) Co-benefits of utilizing logging residues for bioenergy production: the case for East Texas, USA. *Biomass and Bioenergy*, **31**, 623–630.

Helin T, Sokka L, Soimakallio S, Pingoud K, Pajula T (2013) Approaches for inclusion of forest carbon cycle in life cycle assessment - a review. *Global Change Biology Bioenergy*, **5**, 475–486.

Ince P, Kramp A, Skog K, Spelter H, Wear D (2011a) U.S. forest products module: a technical document supporting the Forest Service 2010 RPA assessment. USDA For. Serv. Res. Pap. FPL-RP-662.

Ince P, Kramp A, Skog K, Yoo D, Sample V (2011b) Modeling future U.S. forest sector market and trade impacts of expansion in wood energy consumption. *Journal of Forest Economics*, **17**, 142–156.

IPCC (2000) *Good practice guidance and uncertainty management in national greenhouse gas inventories*. Vol. 5, page 5.7, IPCC/OECD/IEA/IGES, Hayma, Japan. Available at www.ipcc-nggip.iges.or.jp/public/gp/english/; last accessed Apr 2013.

IPCC (2007) *Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Manomet Center for Conservation Sciences (2010) Massachusetts biomass sustainability and carbon policy study: Report to the Commonwealth of Massachusetts Department of Energy Resources. ((ed./eds Walker T). Contributors: Cardellichio P, Colnes A, Gunn J, Kittler B, Perschel R, Recchia C, Saah D, and Walker T. *Natural Capital Initiative Report NCI-2010-03*. Brunswick, Maine.

Marland G, Schlamadinger B (1997) Forests for carbon sequestration or fossil fuel substitution? A sensitivity analysis. *Biomass and Bioenergy*, **13**, 389–397.

Melillo J, Reilly J, Kicklighter D *et al.* (2009) Indirect emissions from biofuels: How important? *Science*, **326**, 1397–1399.

National Council for Air and Stream Improvement (2004) Dynamics of coarse woody debris in North American forests: A literature review. Technical Bulletin No. 877. National Council for Air and Stream Improvement, Inc., Research Triangle Park, N.C.

Nepal P, Ince P, Skog K, Chang S (2012) Projection of US forest sector carbon sequestration under US and global timber market and wood energy consumption scenarios, 2010-2060. *Biomass and Bioenergy*, **45**, 251–264.

Richardson N, Macauley M (2012) Forest carbon economics: what we know, what we do not and whether it matters. *Climate Change Economics*, **3**, 1250022 (18 pages).

Richter D, Jenkins D, Karakash J, Knight J, Mccreery L, Nemestothy K (2009) Wood energy in America. *Science*, **323**, 1432–1433.

Sagastizabal C (2012) Divide to conquer: decomposition methods for energy optimization. *Mathematical Programming*, **134**, 187–222.

Schlamadinger B, Spitzer J, Kohlmaier G, Ludeke M (1995) Carbon balance of bioenergy from logging residues. *Biomass and Bioenergy*, **8**, 221–234.

Searchinger T, Heimlich R, Houghton R *et al.* (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, **319**, 1238–1240.

Sedjo R, Tian X (2012) Does wood bioenergy increase carbon stocks in forests? *Journal of Forestry*, **110**, 304–311.

Simangunsong B, Buongiorno J (2001) International demand equations for forest products: A comparison of methods. *Scandinavian Journal of Forest Research*, **16**, 155–172.

Skog K (2008) Sequestration of carbon in harvested wood products for the United States. *Forest Products Journal*, **58**, 56–72.

US Environmental Protection Agency (2011) Accounting framework for biogenic CO_2 emissions from stationary sources. US Environmental Protection Agency Office of Atmospheric Programs Climate Change Division. Available at: http://www.epa.gov/climatechange/Downloads/ghgemissions/Biogenic-CO2-Accounting-Framework-Report-Sept-2011.pdf/ (accessed 27 Jan 2013).

US Environmental Protection Agency (2012) Land use, land use change, and forestry. Chapter 7 in Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010. Available at: http://epa.gov/climatechange/emissions/usinventoryreport.html/ (accessed 7 April 2012).

US Environmental Protection Agency (2014) Monthly energy review. January 2014. Available at http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf/ (accessed 6 Feb 2013).

USDA Forest Service (2012a) Future of America's forests and rangelands: Forest Service 2010 Resources Planning Act Assessment. USDA For. Serv. Gen. Tech. Rep. WO-87.

USDA Forest Service (2012b) Future scenarios: a technical document supporting the Forest Service 2010 RPA Assessment. USDA For. Serv. Gen. Tech. Rep. RMRS-GTR-272.

Wear D (2011) Forecasts of county-level land uses under three future scenarios: A technical document supporting the Forest Service 2010 RPA Assessment. USDA For. Serv. Gen. Tech. Rep. SRS-141.

Wear D, Huggett R, Li R, Perryman B, Liu S (2013) Forecasts of forest conditions in regions of the United States under future scenarios: a technical document supporting the Forest Service 2012 RPA Assessment. USDA For. Serv. Gen. Tech. Rep. SRS-170.

White E, Latta G, Alig R, Skog K, Adams D (2013) Biomass production from the U.S. forest and agriculture sectors in support of a renewable electricity standard. *Energy Economics*, **58**, 64–74.

Zanchi G, Pena N, Bird N (2012) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Global Change Biology Bioenergy*, **4**, 761–772.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1. Estimating C emissions from wood energy use.
Data S2. Estimating C emissions from logging slash left to decay on forest sites.
Data S3. Estimating carbon neutrality (CN_t) factors.
Data S4. Estimating cumulative radiative forcing neutrality ($CRFN_t$) factors.
Data S5. Estimates of CN_t and $CRFN_t$ factors for the alternative assumptions about the relative efficiency of wood energy systems over fossil fuel systems in terms of CO_2 emissions per unit of energy.
Table S1. Conversion factors to convert volume of wood (m^3) to dry weight (kg) and to C mass (kg).
Table S2. Decay rates used in the study in estimating logging residue C accumulated after decay.
Table S3. CO_2 emissions (kg/MWH) for wood and fossil fuel system when generating electricity.
Table S4. Relative efficiency of wood energy system in terms of CO_2 emissions when wood energy system substitutes either coal or natural gas systems.