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Projection of U.S. forest sector carbon sequestration under U.S. and global timber market and wood energy consumption scenarios, 2010–2060

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ABSTRACT

This study provides a modeling framework to examine change over time in U.S. forest sector carbon inventory (in U.S. timberland tree biomass and harvested wood products) for alternative projections of U.S. and global timber markets, including wood energy consumption, based on established IPCC/RPA scenarios. Results indicated that the U.S. forest sector's projected capacities for carbon sequestration could be notably altered by use of forest resources for energy. A scenario with large expansion in U.S. wood energy consumption (16-fold increase by 2060) coupled with high global growth in gross domestic product would convert U.S. timberlands to a substantial carbon emission source by 2050, as timber growing stock inventories would be depleted because of increased biomass energy production. In contrast, the same high growth in the economy coupled with much smaller expansion of U.S. wood biomass energy consumption (less than two-fold increase by 2060) would result in a projected increase in average annual additions to U.S. forest sector carbon by up to four-fold by 2060. Results also indicated that higher cumulative carbon emissions from increased use of wood for energy could be partially offset—over time—by increased forest plantations and more intensive forest management that could be stimulated by the increased use of wood for energy. The modeling framework will enable future use of the USFPM/GFPM market modeling system to evaluate the impacts of forest carbon offset policies on forest carbon and forest products markets, by allowing carbon offset payments to compete in the model with forest products or wood energy for the control and use of available timber resources.

1. Introduction

The forest sector's role in sequestering atmospheric carbon dioxide (CO_2) has long been recognized by scientists and policy makers, and interest in using forests in climate change mitigation efforts has been growing. Examples of how the forest sector can be used to mitigate greenhouse gas (GHG) accumulation include avoiding deforestation or protecting existing forests, planting new forest area, decreasing harvest intensity, increasing forest growth, increasing carbon storage in harvested wood products (HWP), using wood biomass for energy to replace fossil fuels, and substituting wood for fossil-fuel-intensive products [1–3].

Studies have indicated that clearing of large forest areas for agriculture during early American history caused U.S. forests to be net emitters of carbon [1,2]. However, since the mid-20th

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century, with improved forest management and conservation practices and less land clearing for agriculture, the U.S. forest sector has achieved net positive carbon sequestration [4–8], with increasing net forest growth exceeding removals, and net accumulation of carbon stocks in HWP held in end uses, and HWP held in landfills [6,9]. For example, in 1990, forests and wood products sequestered 681 Tg y $^{-1}$ of carbon, which increased to 863 Tg y $^{-1}$ by 2009 [4]. (One teragram (Tg) is one million metric tons.) Consequently, the U.S. forest sector offset roughly 13% of U.S. anthropogenic CO_2 emission in 1990 (5100 Tg y^{-1}) and 16% in 2009 (5505 Tg y $^{-1}$) [4]. In addition, the U.S. EPA [4] reported that the forest sector, including forest vegetation, soils, and HWP, accounted for 85% of total 2009 net CO_2 sequestration in the United States. These figures suggest that the U.S. forest sector has had an important role in U.S. GHG emission mitigation, but to maintain this role it is important to understand how timber markets, timber harvests, and projected timber inventories will affect future forest sector carbon sequestration.

The role that the U.S. forest sector can potentially play in providing additional offsets of GHG emissions is substantial because of the large area under forest cover (forest lands) and large area of commercial timberlands (lands capable of producing timber in excess of 1.4 m^3 ha^{-1} y^{-1}), 304 and 208 million ha respectively [10]. Also, the United States is a leading producer and consumer of wood products, leading to significant potential for carbon sequestration in HWP. Historically, U.S. forest sector carbon sequestration increased as the United States recovered the forest carbon that was lost due to land clearing for agriculture, deforestation, and harvesting during preceding centuries, from the 18th century to early 20th century [2].

Maintaining the forest sector contribution to GHG mitigation requires that we not only understand current and past trends in carbon flux but also project how that capacity will be affected by future changes in the U.S. and global economy and U.S. forest products markets. Projecting a future forest sector carbon sequestration trend requires understanding of future trends in timber growth, harvest, and forest product output, with special attention to the effect of potential substantial change in use of wood biomass for energy. Economic processes such as timberland investment and management are driven by market trends and influence the quantity of carbon stored in forests and HWP. Market drivers of carbon change in forests and products include demand for wood products, supply of timber, and change in imports and exports of wood products. Consequently, analysis of policies promoting forest carbon sequestration and offset of fossil fuel emissions needs to consider the changing demand for forest products at a national and global level [2]. Although past studies have focused on estimating current and past trends in the forest sector carbon stock and net carbon flux in U.S. forests [4,5,7,11], less information is available about the likely future trajectory of U.S. forest sector carbon sequestration given alternative economic scenarios with various changes in the economy, population, demand for forest products, timber supply, and global forest products trade. A few studies that suggest future trends in U.S. forest sector carbon sequestration were based on assumptions about continuation of baseline (business-as-usual) scenarios [8,12]. Studies investigating long-term trends in forest carbon sequestration under a range of alternative market scenarios are lacking.

The goals of this study were to provide the models and make projections of long-term U.S. forest sector carbon accumulation under alternative global timber market scenarios, with significantly varying levels of change in forest products demand, production, consumption and trade flows in U.S. and global timber markets, including future consumption of wood for bioenergy. More specifically, this study compared four alternative global market scenarios with widely varying assumptions about future wood biomass energy consumption, based primarily on scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). This study was also motivated by a goal to provide a modeling framework that could analyze and project the impact of programs to purchase forest carbon credits on forest and HWP carbon storage and on timber markets and trade.

2. Methods

This study used a set of models to project trends in (a) U.S. and global forest product markets, production, consumption, and trade, (b) U.S. timber growth and inventory, and (c) U.S. timberland tree biomass and HWP carbon accumulation. The following sections describe these models, including our timber growth and inventory projection approach, forest carbon and biomass volume estimation techniques, and the alternative global economic scenarios used in the study.

2.1. *Projecting forest product market trends under alternative global economic scenarios*

The U.S. Forest Products Module (USFPM) [13] was used in conjunction with the Global Forest Products Model (GFPM) [14] to provide long-range economic projections of U.S. and global forest product markets, production, consumption, and trade for U.S. and global economic scenarios. The USFPM/GFPM model is based on the same dynamic partial market equilibrium framework as the original GFPM [14]. In the USFPM/GFPM modeling framework, the market equilibrium production, consumption, and trade of various forest products is estimated by maximizing total producer and consumer surplus in a given year [14]. The various U.S. wood products that were analyzed in this study included lumber, plywood/veneer, oriented strandboard (OSB), industrial particleboard, fiberboard, mechanical pulp, chemical/semichemical pulp, newsprint, printing and writing paper, other paper and paperboard, and wood fuel feedstock, which included mill residues, harvest residues, and short-rotation woody crops. Provided that the projected equilibrium prices for wood fuel feedstock reached levels that permit economical substitution, the USFMP/GFPM modeling framework allowed sawlogs/veneer logs to be used as pulpwood/composite timber, and in turn pulpwood/composite, logging residues, and fiber residues to be used as fuel feedstock [13]. More details of the USFPM/GFPM model are provided by Ince et al. [13] and Buongiorno et al. [14].

The four alternative global economic scenarios that we analyzed here were used previously in a recent nationwide forest assessment study and were based on various assumptions about global economic growth, wood energy consumption, and global changes in population [13]. Three of the scenarios were derived originally from the "Special Report on Emissions Scenarios (SRES)" prepared for IPCC [15] and were adapted for use in the USDA Forest Service 2010 Resource Planning Act (RPA) forest assessment [13] with minor adjustments of assumptions about U.S. population and economic growth. The original SRES scenarios included many dozens of global scenarios grouped into four sets of scenario families (A1, A2, B1, and B2) that are derived from their respective qualitative "storylines". The A1 storyline and scenario family represents future global scenarios with very rapid economic growth, moderate global population growth (peaking in mid-century and declining thereafter), and rapid introduction of new and more efficient technologies, with major underlying themes of global economic convergence, capacity building, and increased cultural and social interactions, with substantial reduction in regional differences in per capita income. In contrast, the A2 storyline and scenario family describes a heterogeneous world with underlying themes of self-reliance and preservation of local identities, higher global population growth, and slower economic growth and technological change. The B2 storyline and scenario family emphasizes localized solutions to economic, social and environmental sustainability, and represents a world with an emphasis on sustainable development and moderately increasing global population, intermediate levels of economic development and slow technical change. Further discussion of the IPCC scenarios can be found in the SRES report by Nakicenovic and Swart (2000). The RPA Assessment used the established IPCC marker scenarios for the A1, A2, and B2 storylines, the A1B AIM, A2 ASF, and B2 MESSAGE scenarios, plus a variant of the A1B called the "historical fuelwood" scenario [19]. Our study used the same four scenarios. Following the RPA approach, we analyzed this limited set of global scenarios in order to highlight important results that are determined by future assumptions about global economic growth and wood energy consumption. Our purpose was not to analyze the full spectrum of possible future scenarios, nor to suggest which scenarios are more or less likely to occur, but rather our purpose was to identify important impacts of alternative future assumptions as revealed by a discrete and limited set of future scenarios.

The three IPCC-based scenarios used in the U.S. Forest Service RPA assessment (A1B, A2, and B2) feature a wide range of projected expansion in U.S. and global wood energy consumption (Table 1). The IPCC SRES scenarios projected that production and consumption of alternative forms of energy (including biomass, natural gas, coal, etc.) would expand as global oil production was projected to generally peak in the decade 2020–2030 [15], although the scenarios varied widely in their projected expansion in biomass energy consumption. The additional fourth RPA scenario was also included (the HFW scenario) that assumed a more modest increase in wood energy demand as determined by estimated historical econometric relationships between wood energy demand and GDP growth in each country [16]. The three IPCC-based scenarios were named A1B, A2, and B2 (using IPCC nomenclature), and the fourth scenario was called the HFW ("historical fuelwood") scenario. The need for including an additional HFW scenario was that no IPCC scenarios adequately captured the A1B economic conditions at modest rather than high biomass energy production, while the current ongoing expansion of natural gas production suggested that such a scenario was needed. The four alternative global economic scenarios analyzed in this study were expected to have different impacts on future U.S. timber markets, forest resource conditions and trends [13], and consequently we expected the scenarios to result in starkly different projected quantities of carbon sequestered in forests and HWP. Again, our purpose was not to show all possible future outcomes, or to suggest which future scenarios were more or less likely, but only to show how the important future trends in forest carbon sequestration would respond to a discrete set of alternative future scenarios.

In terms of U.S. population growth, the A1B scenario represented midrange growth, whereas A2 and B2 scenarios represented the highest and lowest growth, respectively. In terms of U.S. economic growth, the A1B scenario assumed highest GDP growth, followed by A2 and B2 scenarios. The A1B scenario also assumed the largest growth in U.S. wood energy consumption (a 16-fold increase by 2060, after global oil production is projected to peak within the next decade or two, according to IPCC), whereas both A2 and B2 scenarios assumed significant but more modest growth (nine-fold and four-fold increase by 2060, respectively). The HFW scenario had exactly the same economic and population growth assumptions as the A1B scenario but much lower future wood energy consumption (less than a two-fold increase by 2060), as determined by the historical relationships of fuelwood

Table 1 – Summary of the three alternative IPCC-based 2010 RPA scenarios[a].

Variables	A1B	A2	B2	HFW
Global real GDP growth (2010–2060)	High (6.2 ×)	Medium (3.2 ×)	Medium (3.5 ×)	Same as A1B
Global population growth (2010–2060)	Medium (1.3 ×)	High (1.7 ×)	Medium (1.4 ×)	Same as A1B
U.S. GDP growth (2006–2060)	Medium (3.3 ×)	Low (2.6 ×)	Low (2.2 ×)	Same as A1B
U.S. population growth (2006–2060)	Medium (1.5 ×)	High (1.7 ×)	Medium (1.3 ×)	Same as A1B
Global expansion of primary biomass energy production (2000–2060)	High (5.9 ×)	Medium (3.1 ×)	Medium (3.2 ×)	Low (0.3 ×)
U.S. expansion of wood fuel feedstock consumption (2000–2060)	High (16 ×)	Medium (9 ×)	Medium (4 ×)	Low (2 ×)
Southern Pine Plantations (2006–2060), million ha	27	21	19	Same as A2

× Represent magnitude of increase relative to the beginning year (2006 or 2010).
a Source: Ince et al. [13].

demand to GDP growth in all countries. Again, the HFW scenario can be regarded as identical in economic assumptions to the A1B high growth scenario, but with much less future expansion of wood energy because of expansion in other forms of energy (such as natural gas for example).

In addition, the A1B scenario assumed the largest increase in pine plantation growth in the U.S. South because of the large expansion in wood energy consumption (with pine plantation area expanding from about 16 million ha in 2006 to 27 million ha by 2060), whereas the B2 scenario assumed a much more modest increase in pine plantation area to just 19 million ha in 2060, and the A2 scenario assumed an increase in southern pine plantation area to 21 million ha in 2060. The HFW scenario incorporated the A2 southern pine plantation assumptions. The range of assumptions regarding future southern pine plantation area for the RPA scenarios were identical to plantation area assumptions that were developed previously in the Southern Forest Futures report by Wear et al. [17].

Finally, the U.S. demand for wood fuel feedstock was driven in the HFW scenario using an elasticity of 0.22 with respect to GDP [16] and with a price elasticity of −0.50 [13], whereas consumption of wood fuel feedstock in the other scenarios was determined by shifting demand curves to achieve predetermined growth levels for fuelwood consumption. Note that none of these scenarios are intended to represent a most likely baseline or "business as usual" scenario, although the B2 or HFW scenarios might be considered to more closely represent recent historical economic trends (e.g. taking into account the recent global economic recession). Table 1 provides a summary of the basic assumptions for the alternative IPCC-based (RPA) scenarios and the A1B HFW scenario.

2.2. *Projecting timber growth and inventory*

A spreadsheet model was developed to project growth in timber growing stock inventory by three U.S. regions (North, South, and West, Fig. 1) and two species groups (softwood and hardwood). Timber growing stock inventory for a particular year was estimated by adding growth of growing stock to the previous year's inventory and subtracting USFPM-projected market equilibrium timber growing stock harvest quantity. The annual growth of growing stock (net of mortality) was predicted as a nonlinear function of regional growing stock density. Functional parameters were estimated in our earlier study [18] using cross-sectional county-level data on net annual growth as percentage of inventory and growing stock densities. The change in timberland area by U.S. regions and scenarios over time, one of the key variables in projecting growing stock density over time, was exogenous to the model and was obtained based on forest land area projections for the most recent RPA forest assessment [19].

Because projections of U.S. timber inventory, timber supply, and timber harvest are interrelated, an iterative solution procedure was used to determine convergent and consistent solutions of timber inventory and harvest, where the spreadsheet timber growth model used USFPM projections of timber harvest by region, and in turn provided USFPM with regional projections of growing stock inventory to shift regional timber supply curves (using an inventory elasticity of 1.0 for the USFPM timber supply equations). The models were run iteratively in this manner until a reasonably stable equilibrium solution was obtained (usually requiring less than a dozen iterations).

2.3. *Estimating and projecting tree biomass carbon*

This study estimated the carbon stock and stock changes (carbon flux) for total tree biomass on timberland defined as a function of growing stock timber inventory volume on timberland. Total tree biomass is here defined as all standing live and dead aboveground and belowground tree biomass on timberland. Timberland is roughly two-thirds of forest land in the United States and is specifically forest land that is open to commercial timber harvesting and is capable of producing in excess of 1.4 m^3 ha^{-1} y^{-1} of industrial wood in natural stands [10]. As such, timberland is the category of forest land that is

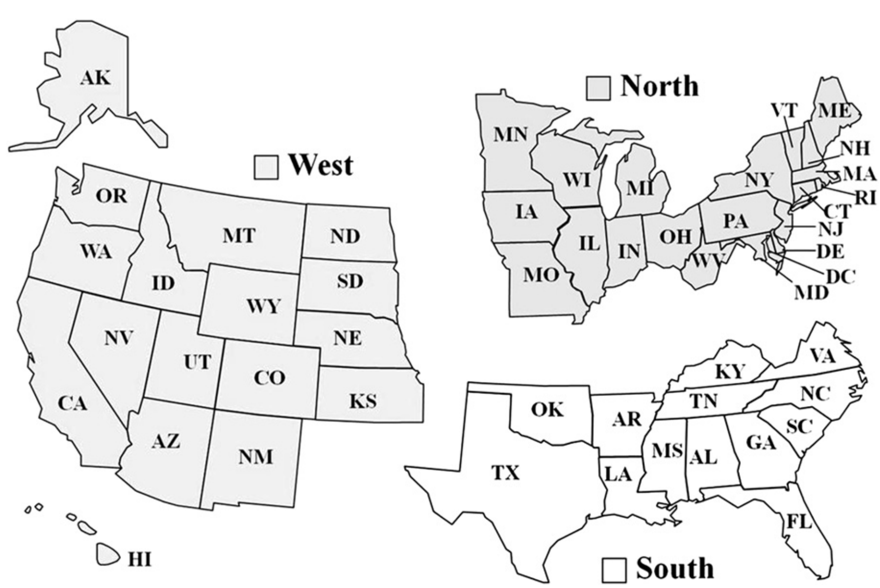

Fig. 1 – The three U.S. subregions of the USFPM, North, South, and West.

most directly impacted by timber harvesting and timber management. Other forest land (non-timberland), such as land in parks, wilderness areas or unproductive lands, are not likely to be impacted much by expansion in wood energy consumption, so we regarded the conditions of forest carbon on those lands as exogenous to our analysis. We acknowledge that such lands do contribute to forest carbon flux (via carbon emissions or sequestration), but we assumed that variation in future timber harvest on timberland would have little or no impact on the forest carbon flux of non-timberland. Thus, we projected future carbon stocks and carbon flux for timberland only.

As measured by nationwide timber inventory data (and as represented in the USFPM/GFPM model), timber growing stock inventory volume in the United States consists of the volume of wood on timberland in merchantable trees larger than 12.7 cm in diameter. Total tree biomass volume on timberland is a broader measure that includes smaller trees, non-merchantable trees, dead trees, and belowground biomass. It does not, however, include trees on lands that are not open to timber harvest, such as national parks. Regional tree biomass carbon stock on timberland was estimated using ratios of total tree biomass weight to growing stock volume presented in Table 2, which were derived using latest FIA data. Note that these ratios would be slightly different if old inventory data were used. Carbon stocks in non-timberland forests, forest floor litter, understory vegetation, and soil carbon were not estimated in this study for two reasons. First, estimating carbon in pools other than tree biomass would require that we develop accurate empirical relationships to predict carbon in soil or forest floor carbon pools as a function of timber inventory volume or some other variables utilized by the USFPM/GFPM. Unfortunately, there was little empirical evidence to correlate carbon stocks in those pools with data on timber inventory volume. Second, for the purpose of analyzing current and potential future forest carbon offset credit markets, the tree biomass carbon pool on timberland is most relevant to consider because the timberland tree biomass carbon pool accounts for the largest share of total carbon in forests, about 60% [2,3], and timber growth, timber harvests, and related changes in timberland tree biomass carbon have the greatest effect on total forest carbon change [5].

Estimating carbon in timberland tree biomass involved two main steps: converting merchantable timber growing stock volume (cubic meters) to total timberland tree biomass weight (metric tons), and then biomass weight to biomass carbon weight. The merchantable timber growing stock volume was converted to total tree biomass weight using regional average ratios of total biomass weight to merchantable volume (Table 2). We used data from the FIA database [20] on total tree biomass and growing stock volume in U.S. timberlands to estimate the biomass to growing stock ratios for the North, South, and West. Biomass weight was multiplied by 0.5 to estimate carbon weight [4]. The above- and belowground tree biomass estimates include bole, tops and limbs, saplings, stump, bark, and coarse root biomass of all live and standing dead trees above 2.5 cm in diameter but do not include foliage biomass [20].

Table 2 – Average ratio of total tree biomass[a] to merchantable timber growing stock volume in timberland, for three U.S. regions based on latest FIA data.

	Ratio of total biomass (dry t) to growing stock volume (m^3)	
Region	Softwood	Hardwood
North	0.868	1.307
South	0.923	1.370
West	0.803	1.096

a Total tree biomass includes bole, tops and limbs, saplings, stump, bark, and coarse root biomass of all trees above 2.5 cm in diameter but does not include foliage biomass.

2.4. *Estimating carbon in HWP*

The Woodcarb II model was used to estimate changes in HWP carbon held in products (in-use), discards from use, and transfers into and emissions out of solid waste disposal sites. It is used because it is the model that produces the official estimates of annual additions of carbon stored in HWP for the annual US EPA report on GHG emissions and sinks as required under the United Nations Framework Convention on Climate Change [4]. The carbon stock and annual stock change estimates were made using the "production accounting approach" [21], which tracks the carbon in wood and paper products that are produced from timber harvested within the United States. Carbon in exports is included, and carbon in imports is excluded. Exports were treated as though they remained in the United States. Inputs to the Woodcarb II model included U.S. wood products production, and export/import projections derived from USFPM/GFPM. The estimates of current and projected net annual additions of carbon to products in use and products in landfills were constructed using estimated annual additions and losses to products in use and products in dumps and landfills since 1900 [9]. Annual losses from end uses were estimated using estimated half-lives and first-order decay curves. A portion of losses go to landfills. Annual losses from wood and paper decay in landfills were estimated using half-lives and first-order decay curves applied to the degradable portion of wood and paper. More specifically, the projections of net annual additions of carbon to HWP in end uses and landfills were made using projected production and trade amounts and half-lives for products in use and in landfills that were assumed to remain the same as those used for the period 2000 to 2010 [9]. Further details on the Woodcarb II model are provided by Skog [9].

2.5. *Estimating uncertainty in projections*

The approach to estimating uncertainty in our forest sector carbon inventory projections focused on those variables and parameters that we estimated, including the uncertainty in our projected timber growing stock inventory, uncertainty in factors used to convert timber growing stock volume to biomass carbon, and uncertainty in HWP projection parameters. The uncertainty in each parameter is specified by an estimated probability distributions, and we used Monte Carlo simulations to evaluate the effect of these uncertainties on projections of forest carbon and HWP carbon. Two separate

Monte Carlo simulations [22,23] were made to estimate the uncertainty in projection of carbon in tree biomass and in HWP using @Risk software [24]. The simulations provided mean values and confidence intervals over the projection period. The simulation process consisted of two steps: specification of the error in (1) parameters estimating timber inventory (e.g., error in parameters estimating timber growth) and (2) parameters converting timber inventory to total carbon stock (e.g., ratio of growing stock volume to total tree biomass). Similarly, estimating uncertainty associated with projecting the carbon pool of HWP involved specification of the error in the base year estimate of HWP carbon stock and also specification of error in estimates of annual additions of HWP to the carbon pool [9]. A ±15% error was applied to parameters estimating timber growth/inventory across all regions and species groups. This bound represented a 95% confidence interval for the majority of parameters that were estimated for three regions and two species groups reported in Nepal et al. [18]. Similarly, a ±15% error was applied to the ratios converting growing stock volume to total tree biomass volume across all region and species groups, assuming that these error bounds covered 95% of the distribution. Such a definition of error in converting timber volume to carbon volume is consistent with other studies (e.g., Heath and Smith [25]). In simulating uncertainty in HWP carbon projections, a one-time error was applied in estimating carbon stock in the base year (−17% and +18%) and then subsequent errors associated with estimating net annual additions to HWP carbon stocks (−22% and +19%) as reported by Skog [9]. These error bounds associated with estimating carbon in HWP represented 90% of the distribution [9]. The parameters associated with HWP carbon estimates were specified to have a positive correlation (0.9). Correlations among parameters associated with estimating timber growth were not specified, because it is unknown how growth parameters in one region will be correlated with another region. Finally, separate Monte Carlo simulations were run for individual regions and the whole U.S., with each simulation including 500 iterations.

2.6. *Linkage between scenarios and individual model components*

Fig. 2 shows how above described scenarios and models were linked in the process of projecting timber growth, growing stock inventory, equilibrium harvest quantities, and carbon stocks in timberland tree biomass and HWP. The starting point for our analyses was the specification of the alternative scenarios (four IPCC-based scenarios). Given the specific assumptions about population, GDP, and wood energy growth in these scenarios, the USFPM/GFPM demand and supply parameters were adjusted to reflect the predetermined growth in these variables by 2060. The initial USFPM/GFPM run with such adjustments provided initial estimates of the market equilibrium harvest quantities over the projection period to 2060. However, because growth in timber inventory is affected by the quantity of harvests, this harvest quantity was applied in the spreadsheet-based timber inventory model to obtain new timber inventory projections by region. In addition, timber supply quantity (harvest) is a function of price and available inventory, so the changes in timber inventory shifts the timber supply curves, and changes the market equilibrium harvest quantity. Therefore, the new timber inventory level was used in the USFPM/GFPM to obtain new market equilibrium harvest levels. This iterative process continued until a convergent solution was obtained. This process generally required about a dozen of iterative runs of USFPM/GFPM and the timber inventory model for each scenario. Finally, the projected convergent timber inventory level in each scenario was used to estimate tree biomass carbon for corresponding scenarios using the statistical ratio of U.S. timberland timber inventory volume to dry weight biomass (Table 1). Finally, the projected quantities of market equilibrium timber harvest; and forest products production, and trade were used as inputs to the Woodcarb II model to estimate carbon in HWP.

3. Results

3.1. *Tree biomass carbon projections*

In 2010, all alternative scenarios started with virtually the same level of tree biomass carbon stock on U.S. timberland—about 52,200 Tg of carbon dioxide equivalent (CO_2e) (1 t carbon = (44/12) t CO_2e). Over the 50-year projection period (2010–2060), three of the IPCC-based global economic scenarios (A2, B2, and HFW) showed consistently increasing U.S. tree biomass carbon stocks, whereas the biomass carbon stock was declining beyond 2045 for the A1B scenario with highest wood energy consumption (Fig. 3a). By 2060, the HFW scenario (with lowest wood energy consumption) showed the highest total tree biomass carbon stock (89,938 Tg CO_2e), followed by scenarios B2 (88,597 Tg CO_2e), A2 (79,470 Tg CO_2e), and A1B (61,126 Tg CO_2e). The A1B scenario, with its assumed 16-fold expansion in U.S. wood energy consumption and also largest expansion in global fuelwood consumption, resulted in generally the lowest U.S. tree biomass carbon stock on timberland throughout the projection period, although the A1B carbon stock actually increased until 2045 and declined thereafter, and there was still an overall net gain in tree carbon stock by 2060.

These results suggested that, depending on future global economic scenarios, U.S. tree biomass carbon stock on timberland could increase by a wide range (17%–72%) over the next five decades. The A1B scenario, representing the largest growth in the global economy coupled with medium-range population increases and the largest expansion in U.S. wood energy production (16-fold increase by 2060), resulted in the lowest carbon stock by 2060 (just a 17% increase relative to 2010, or 8758 Tg CO_2e). The HFW scenario featured the same economic and population growth as the A1B scenario but much less expansion in wood energy consumption (less than two-fold increase for the United States). The HFW scenario showed the largest increase in carbon stock by 2060 (a 72% increase relative to 2010, or 36,674 Tg CO_2e, four times more accumulation of carbon on timberland than for the A1B scenario). In comparison, the A2 and B2 scenarios with more modest global growth in the economy and intermediate levels of wood energy consumption resulted in 51% (27,011 Tg CO_2e) and 70% (36,408 Tg CO_2e) increase in U.S. carbon stock by 2060, respectively.

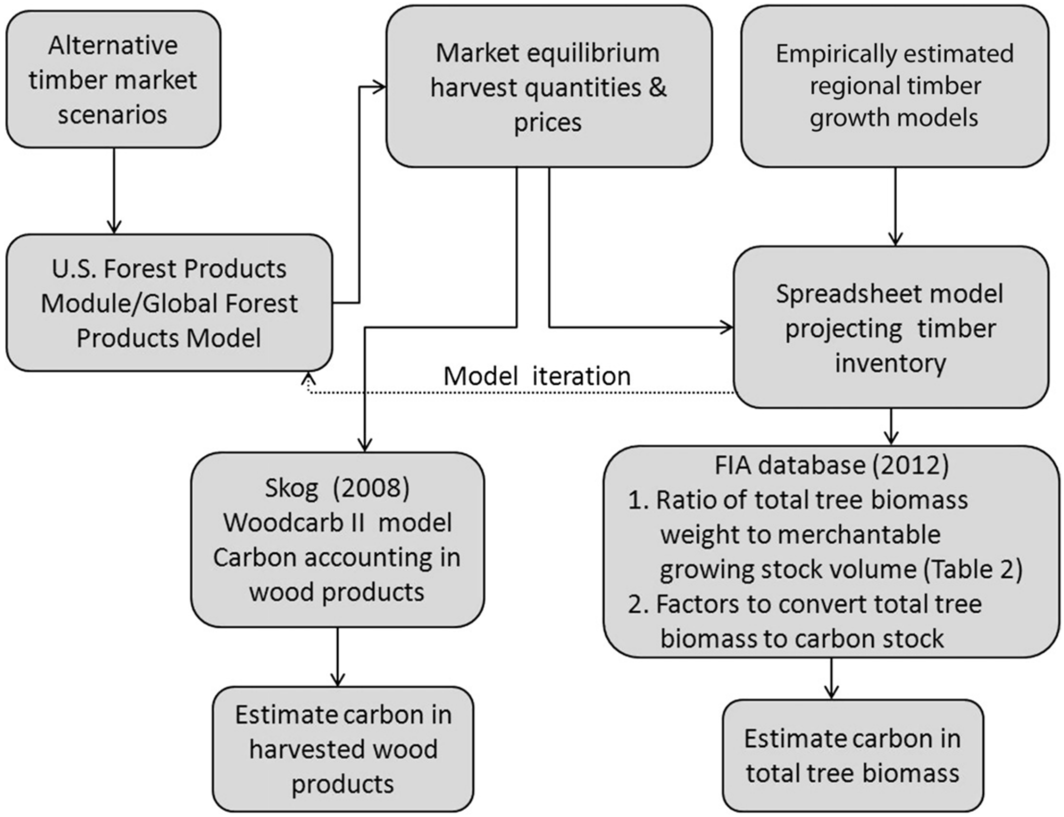

Fig. 2 – Flowchart summarizing steps in estimating carbon accumulation in U.S. timberland tree biomass and harvested wood products.

The impact of future global economic scenarios on annual changes or flux in forest carbon stock was more pronounced (Fig. 3b). Annual additions to carbon stock on timberland declined in the A2 and A1B scenarios. The annual additions to carbon stock in the B2 scenario increased until 2055, then declined. The HFW scenario, in contrast, showed a continuous increase in tree biomass carbon annual additions throughout the projection period. High timber removals in the A1B scenario resulted in net annual emissions of tree biomass carbon starting in 2050, and the net annual emissions were 230 Tg CO_2e in 2050, 523 Tg CO_2e in 2055, and 946 Tg CO_2e in 2060. The HFW scenario had the largest average annual rate of tree biomass carbon sequestration over the entire projection period at 748 Tg CO_2e/y, followed by the B2 at 722 Tg CO_2e/y, A2 at 539 Tg CO_2e/y, and A1B at 181 Tg CO_2e/y.

A similar pattern of impacts for the alternative scenarios was observed in annual net additions to tree biomass carbon for the three U.S. subregions, except for the U.S. West, which had relatively small declines in carbon sequestration on timberland for scenario A1B (Table 3). In the West, the average annual carbon sequestration values during 2010–2060 for A1B, A2, B2, and HFW scenarios were 150, 179, 197, and 178 Tg CO_2e/y, respectively. In contrast, the alternative scenarios had wider ranges of impacts on carbon sequestration in the North and South regions, and especially for the A1B scenario. For example, during 2010–2060, the average net annual additions to tree biomass carbon in the North were 8, 222, 312, and 313 Tg CO_2e/y in A1B, A2, B2, and HFW scenarios, respectively. Likewise, for the same period, the average annual tree biomass carbon sequestrations in the South were 23, 138, 213, and 257 Tg CO_2e/y for A1B, A2, B2, and HFW scenarios, respectively. The results also indicated that the U.S. North would have the largest average net annual additions under the A2, B2, and HFW scenarios, whereas U.S. West would have the largest average net annual additions for the A1B scenario, as compared to other regions. The different trends in carbon sequestration across regions were because of different rates of timberland area change and different harvest levels resulting in differing growth responses as determined by corresponding changes in growing stock density. For instance, the West experienced less of a decline in timberland area and harvests in A1B scenario, resulting in more or less constant growing stock density and timber growth rate relative to other regions.

3.2. HWP carbon projections

Projections of U.S. production, and net trade in forest products across alternative scenarios had differing impacts on projected quantity of accumulated carbon in U.S. HWP. The differences were largely driven by projected U.S. lumber production and export. This was because a high proportion of lumber products are used in long-lived end uses. In all scenarios, the projected carbon stocks in HWP increased steadily over the projection period. The total U.S. HWP carbon stock was projected to be the largest in the A1B scenario, followed by the HFW, A2, and B2 scenarios (Fig. 4a). The A2

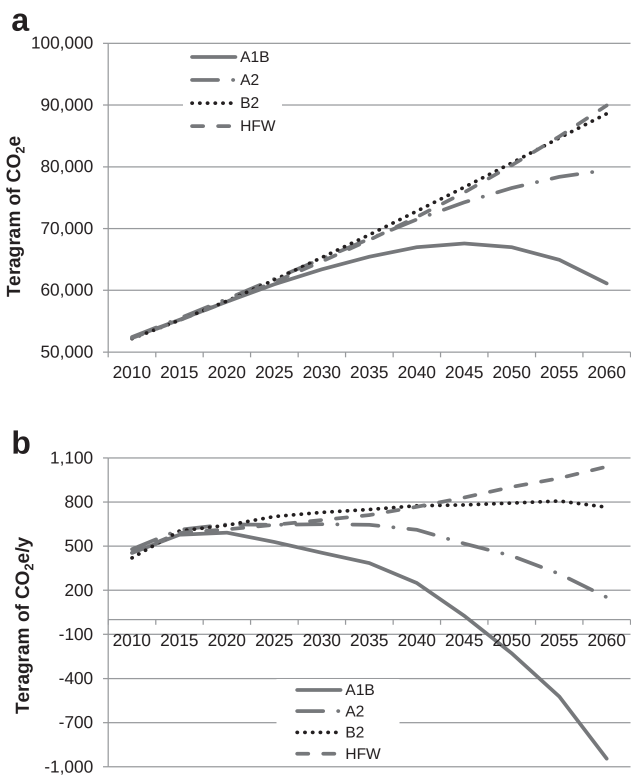

Fig. 3 – Projected total U.S. tree biomass carbon (a) stock (Tg CO_2e) and (b) flux (Tg CO_2e/y) for A1B, A2, B2, and HFW scenarios during 2010–2060.

scenario resulted in the smallest quantity of projected carbon stocks due to lowest U.S. lumber production in this scenario (the A2 scenario had lowest U.S. net exports of lumber). Average annual net additions to HWP carbon stocks over the projection period were 159, 142, 138, and 111 Tg CO_2e/y for the A1B, HFW, B2, and A2 scenarios, respectively. Whereas the A1B, HFW, and B2 scenarios had continuous increases in net annual additions to HWP carbon, the A2 scenario fluctuated over the projection period (Fig. 4b).

3.3. *Estimates of uncertainty in projections*

The estimated 90% confidence interval of projected tree biomass and HWP carbon stocks for the projection years 2010, 2020, 2030, 2040, 2050, and 2060 are presented in Table 4. The estimated uncertainty in projecting tree biomass carbon for the entire United States was ±6% of its estimated mean in the year 2010, rising to −26% and +29% in the projection year 2060. While associated projection errors were smaller for the entire United States, they were somewhat larger for the regional projections. For example, errors in projecting tree biomass carbon for the U.S. North, South, and West ranged from −10% to +12% in 2010 to as large as −50% to +72% in 2060. The estimates of uncertainty in projecting HWP carbon were −17% to +18% of the estimated mean in 2010, which remained more or less constant throughout the entire projection period, rising only by 1% by 2060. Note that the estimates of confidence bounds of our projections did not take into account uncertainty in climate projections such as temperature, precipitation, and greenhouse gas emission, which were beyond the scope of this study. Therefore, the confidence bounds of our projections might have been underestimated because taking into account uncertainty in climate projections would likely render such confidence bounds wider.

4. Discussion

Our analysis suggests that variation in wood energy demands among a discrete set of global economic scenarios can be a substantial factor influencing projected U.S. timber harvests and timber inventory levels, and consequently can be a substantial factor influencing projected U.S. forest sector carbon stocks. For example, the A1B scenario, with a 16-fold

Table 3 – Projected timberland tree biomass carbon stock changes in U.S. North, South, West, and all regions for A1B, A2, B2, and HFW scenarios, 2010–2060.

Sce-nario	Region	Carbon stock changes (Tg CO_2e/y)										
		2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
A1B	North	224	259	250	209	164	124	39	−101	−252	−405	−607
	South	95	161	178	150	119	91	50	−21	−111	−231	−419
	West	134	158	164	169	171	169	161	149	133	114	81
	All	453	578	591	528	455	384	249	26	−230	−523	−946
A2	North	234	275	286	280	272	267	247	199	155	106	38
	South	110	174	191	188	191	188	167	126	92	28	−55
	West	136	162	170	178	186	191	196	192	186	178	170
	All	479	611	647	645	649	646	611	517	434	312	153
B2	North	213	270	285	306	321	325	332	333	335	336	320
	South	74	169	185	211	215	221	232	233	238	246	222
	West	133	163	172	184	195	203	210	214	220	225	223
	All	420	602	642	701	730	749	774	780	793	806	765
HFW	North	225	265	275	286	297	307	324	339	358	364	371
	South	96	166	177	195	214	233	264	302	345	388	449
	West	135	159	162	164	167	171	179	189	199	210	220
	All	455	590	614	645	677	711	767	830	902	961	1040

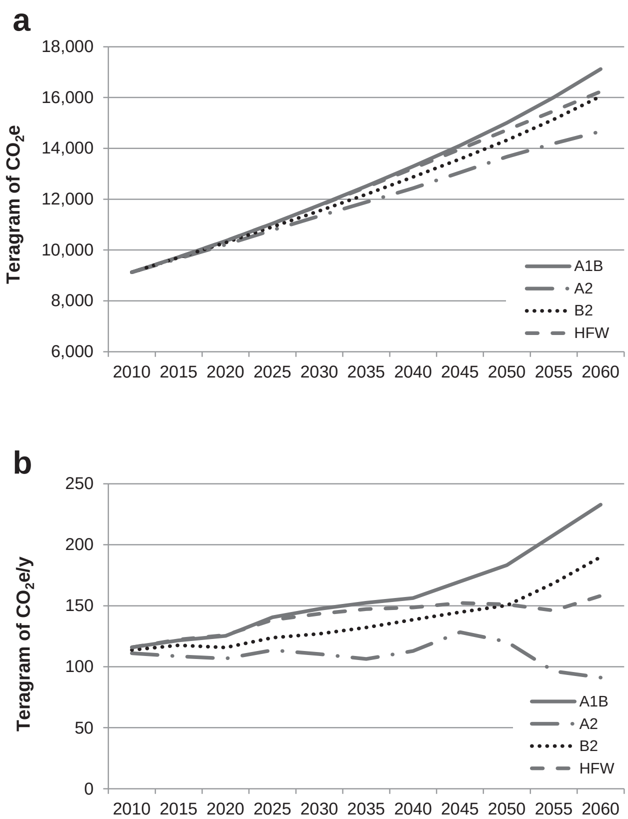

Fig. 4 – Projected total harvested wood products carbon (a) stock (Tg CO_2e) and (b) flux (Tg CO_2e/y) during 2010–2060 for A1B, A2, B2, and HFW scenarios based on production accounting approach.

increase in U.S. wood energy consumption and largest expansion in global fuelwood consumption, resulted in the lowest average net annual additions to forest sector carbon (carbon in tree biomass on timberland and carbon in HWP) (224 Tg CO_2e/y during 2010–2060) due to highest timber removals [13] and the lowest timber inventory projections [18]. The timber removals were so substantial that they caused U.S. timberland to become a projected carbon emission source by 2050 in the A1B scenario. In contrast, the HFW scenario, with less than two-fold increase in U.S. wood energy consumption by 2060, was projected to retain the highest timber inventory levels and showed the largest annual forest sector carbon sequestration rate (792 Tg CO_2e/y). The A2 and B2 scenarios, with modest mid-level expansions in wood energy consumption, accumulated forest sector carbon at modest annual sequestration rates (569 and 760 Tg CO_2e/y, respectively). The results indicated that use of forest resources for energy above 16-fold from current levels would most likely result in net losses to U.S. timberland carbon stocks by the middle of this century. However, this evaluation of the differences among scenarios is only a partial analysis in that an increase in use of wood for lumber and wood panels can also substitute for steel and concrete, which emit more carbon in manufacturing, and increased use of wood for energy can reduce carbon emissions from use of fossil fuels.

Increases in wood energy demand did not necessarily result in lower carbon storage in HWP. Instead, the carbon in HWP was determined by the projected quantity of wood that was harvested for conventional forest products production in the respective scenarios. The projected global demand for industrial wood products and U.S. wood product trade had a greater impact on the U.S. HWP carbon than the projected demand for wood energy. For example, the A1B and HFW scenarios were at opposite extremes in projected wood use for energy, but they both featured the highest global consumption of roundwood for industrial wood products (mainly because they had highest global GDP growth) and thus they resulted in the largest quantity of carbon sequestered in U.S. wood products in use and in landfills. The analysis also indicated that a strong demand for mill residues and harvest residues for very high global wood energy consumption would boost lumber output due to higher prices paid for wood residues and higher revenues for timber harvest activities [13]. This economic boost of lumber output because of high wood residue prices would in turn contribute to higher accumulation of carbon in HWP, as was observed in the A1B scenario.

Variation in global roundwood prices for alternative scenarios resulted in varying levels of U.S. lumber trade, which influenced U.S. harvest and resulting levels of carbon stored in forests and HWP. Although the United States was projected to

Table 4 – Estimated 90% confidence interval of projected values of carbon in timberland tree biomass and in harvested wood products by U.S. regions[a].

Carbon pool: region	90% confidence interval of projected values (%)					
	2010	2020	2030	2040	2050	2060
Tree biomass: North	−12 + 12	−15 + 16	−18 + 22	−23 + 30	−26 + 35	−30 + 41
Tree biomass: South	−10 + 10	−12 + 13	−18 + 19	−28 + 32	−40 + 51	−50 + 72
Tree biomass: West	−11 + 12	−12 + 13	−15 + 18	−19 + 23	−22 + 30	−26 + 37
Tree biomass: U.S.	−6+6	−8 +8	−11 + 11	−14 + 16	−19 + 22	−26 + 29
Harvested wood products: U.S. total	−17 + 18	−17 + 18	−18 + 19	−18 + 19	−19 + 19	−19 + 19

a Error specification for projecting tree biomass carbon included a ±15% error in growth parameters in estimating timber inventory and a ±15% error in converting merchantable volume to total tree volume. For HWP carbon, −17% and 18% error in base year estimate and −22% and 19% error in estimates of annual wood products additions were specified. The error bounds for the tree biomass carbon estimate parameters covered 95% of the distribution, and those for the harvested wood products covered 90% of the distribution. Note that 90% confidence interval is reported for the projected values.

remain a net importer of lumber in all scenarios, the A1B and B2 scenarios led to increasing lumber exports over time for U.S. lumber producers, as higher global demand for wood energy led to larger increases in foreign average industrial roundwood prices than in average U.S. industrial roundwood prices [13]. However, in the A2 and HFW scenarios, the U.S. was a larger importer of lumber because the foreign average industrial roundwood prices did not increase as much as U.S. roundwood prices. This result has an important implication for carbon sequestration policy that would seek to increase carbon in forests and HWP. Increased exports of U.S. lumber could mean less carbon sequestered in forests (because of higher timber harvest) but more carbon stored in HWP under the production accounting approach. The design of carbon policies for the forest sector needs to consider the effects on both forest carbon and HWP carbon of forest product trade and resulting domestic market development as well as effects of wood energy consumption. Note that the projections of roundwood prices for U.S. and other countries depend on assumed elasticities of roundwood supply with respect to price. Although there is lack of clear consensus in the literature about what values these elasticities should take, studies generally indicate that roundwood timber supply is fairly inelastic (with price elasticity less than 1) partly because timber supply is limited to timber stands that have matured and are made available for harvest by forest landowners. To some extent forest landowners will respond to higher or lower price signals, but they are also limited in their response by availability of mature timber. This study assumed the same short-run elasticity of delivered roundwood supply with respect to price in all countries (0.5). The projection of roundwood price changes would vary if different price elasticities were assumed for U.S. and global timber supply.

Finally, we note that forest inventory projections for the alternative scenarios included the expansion of plantation area for the U.S. South that was estimated for the RPA scenarios in the recent RPA Assessment [13], which were also identical to those estimated for the recent Southern Forest Futures report [17]. Pine plantations expanded the most in the A1B scenario by 2060 (by 11 million ha) and the least in the B2 scenario (by 3 million ha), reflecting the fact that those scenarios had the highest and lowest projected timber demands (driven mainly by the wood energy demand assumptions). The USFPM/GFPM model also projected economic expansion of agricultural short-rotation woody crop supply in the A1B scenario (by 8 million ha) because of sufficiently high wood prices in that scenario, but not in the other scenarios. The RPA projections generally supported the view that landowners would respond to higher wood energy demands with intensified management and expansion of tree plantations. This projected intensification of timber management tended to offset what would otherwise be more substantial depletion of timber inventory and forest carbon in a high wood energy demand scenario such as A1B. Previous studies have likewise indicated that increases in U.S. net forest sector carbon sequestration over the past decades was largely due to improved forest management practices, regeneration of previously cleared forest areas, and harvesting less timber than was grown [5,6].

Our model projections also showed the approximate magnitude of accelerated carbon additions to forests that could occur with increased wood energy use and more intensive forest management, by comparing results from the A1B and HFW scenarios. These two scenarios had exactly the same U.S. and global economic growth and population assumptions, but U.S. and global wood energy demand was much higher for the A1B scenario. Cumulatively over the entire 50-year projection period, the A1B scenario demanded about 31×10^9 cubic meters more wood for energy in the United States than did the HFW scenario. This equaled emissions of about 30×10^9 t of CO_2e, based on a rough conversion factor of 530 kg dry weight biomass per cubic meter (30 lb./ft^3)[1]. Of course the much higher use of wood for energy caused the projected U.S. timber growing stock volume to be lower in the A1B scenario, but the decrease in growing stock biomass carbon from the HFW to the A1B scenario was much less than the level of wood energy carbon emission, 14×10^9 t of CO_2e, or about 50% less. This suggested, roughly, the potential degree to which expansion of forest plantation area, slowing loss of forest land, and stimulation of growth with lower density forest stock could offset an increase in wood energy emissions, indicating roughly 50% carbon emission offset because of higher forest growth. This estimate is approximate because the forest carbon estimates have not accounted for changing carbon in logging residue on harvest sites. A more detailed accounting may indicate a somewhat lower level of forest carbon recovery after increased wood energy use. Nevertheless, the results do show that the increase of wood fuel carbon emissions in a scenario with much higher wood energy use is likely to be offset to some extent (as much as 50%) because of the likely forest management and growth response to higher timber removals.

Although recent U.S. forest growth rates are thought to be higher than those before European settlement because of recovery from past land use and disturbance, the current growth rate is not expected to continue indefinitely [3]. This statement is consistent with our findings that indicated a declining trend in tree biomass carbon flux especially toward the later part of projection period for all scenarios except the HFW scenario, as increasing average growing stock density led to lower per acer growth of U.S. forests in all scenarios during the 50-year projection period. A direct comparison of our tree biomass carbon projections with projections made in previous studies was difficult due to differences in modeled scenarios, reported carbon pools, scope of timberland ownership, and the number of U.S. regions and states covered in the projections. Also, previous projections included only 48 states (excluding Alaska and Hawaii), whereas our projection included all 50 states. For example, Birdsey and Heath [12] projected forest carbon for scenarios based on ATLAS/TAMM projected estimates of area, volume, growth, and removals for forest classes defined by region, ownership, forest types, site class, stocking class, and age class from 2000 to 2040 for the conterminous United States. Their scenarios were not directly comparable to ours,

[1] In estimating this value, the wood volume was first converted to dry weight biomass (roughly, 1 m^3 = 530 kg dry biomass). The dry weight wood biomass was then converted to carbon weight (1 kg biomass = 0.5 kg carbon), which was further converted to CO_2e (1 kg carbon = 44/12 kg CO_2e).

because they were based on different forest product demand assumptions (higher output of forest products but lower demands for wood energy), and thus their projections showed higher harvest levels early in the projection period, smaller forest carbon stock levels, and only a modest increasing trend in the U.S. tree biomass carbon stock (Fig. 5a). However, with higher forest product output, their projections showed a larger and sharply increasing trend in HWP carbon stock (Fig. 6a). Our estimated projection of annual changes in tree biomass carbon stock differed from that of Birdsey and Heath [12], but our projection captured the ranges of estimates provided in theirs, especially beyond the year 2020 (Fig. 5b). Our HWP carbon projections were lower than those of Birdsey and Heath [12] (Fig. 6a).

We also compared our projections of forest and HWP carbon during 2006–2010 with historical estimates reported by U.S. EPA [4] for the same period. Our projected value of tree biomass and wood products carbon for the entire 50 U.S. state timberlands was, as expected, lower than EPA estimates for the 48 states forest lands but the projected trend was quite similar (Figs. 7 and 8). Timberlands are about two-thirds of total U.S. forest land area. The EPA estimates of total tree

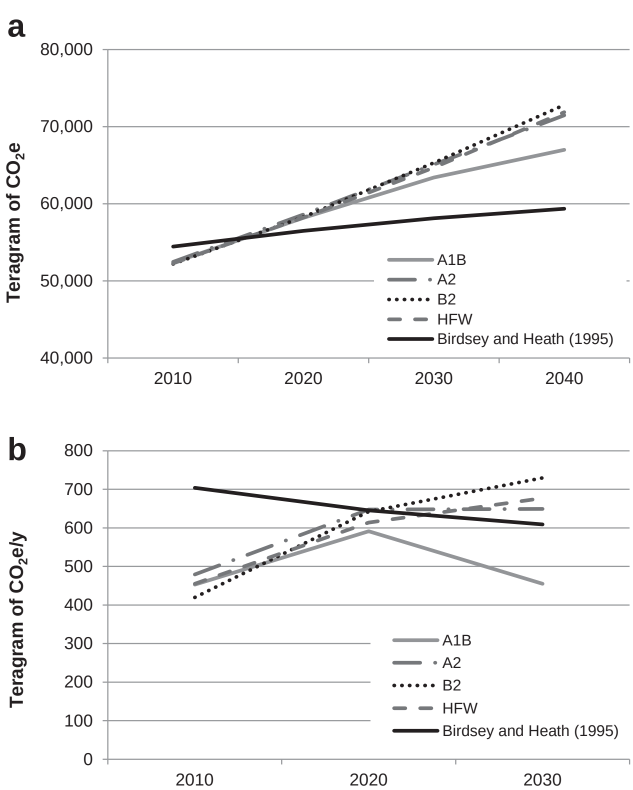

Fig. 5 – Comparison of projected U.S. timberland tree biomass carbon (a) stock (Tg CO_2e) and (b) flux (Tg CO_2e/y) for A1B, A2, B2, and HFW scenarios in this study and a base scenario in Birdsey and Heath [12] during 2010–2040. The flux estimates in Birdsey and Heath [12] include average annual changes in forest floor, soil, understory, and tree biomass in U.S. timberland, whereas this study includes only annual changes in tree biomass carbon in U.S. timberland. Also, the estimates of Birdsey and Heath [12] exclude Alaska and Hawaii, but this study includes these states.

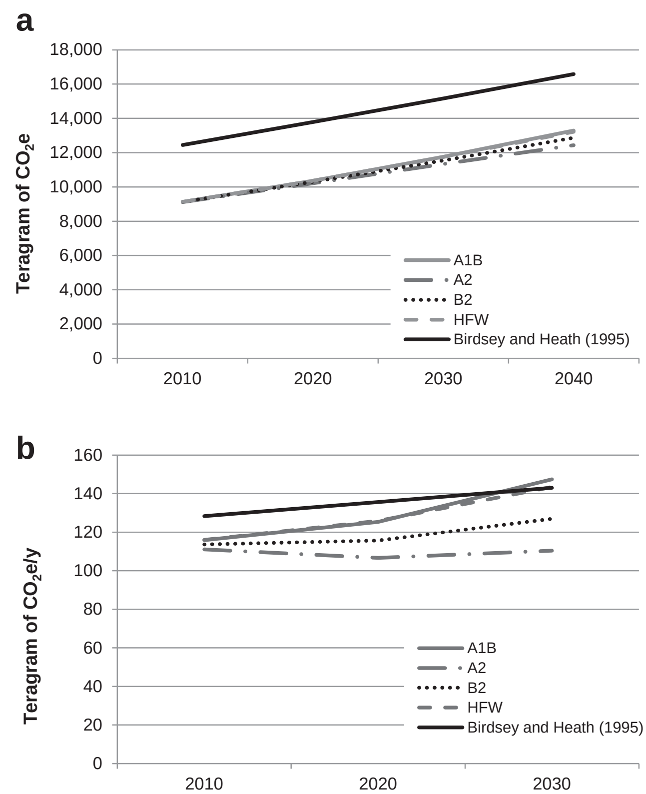

Fig. 6 – Comparison of projected total U.S. harvested wood products carbon (a) stock (Tg CO_2e) and (b) flux (Tg CO_2e/y) for A1B, A2, B2, and HFW scenarios in this study and a base scenario in Birdsey and Heath [12] during 2010–2040. Estimates of Birdsey and Heath [12] exclude Alaska and Hawaii, but this study includes these states.

biomass carbon for the 279 million ha of U.S. forest lands (304 million ha, including Alaska and Hawaii) are approximately 40% higher than our estimates for the 208 million ha of U.S. timberlands. Also, the EPA estimates include foliage and down deadwood biomass carbon, which our study did not include. Thus, in this case, the differences in the results can be attributable to the differences in land areas and types of carbon pools (foliage and down deadwood biomass) that are considered, and also the effects of the recent economic recession. RPA projections were based on selected IPCC-based scenarios that were developed prior to the most recent global economic recession and therefore did not take into account the recent decrease in wood use. The recent historical estimates of forest sector carbon by EPA reflected the effects of economic recession in timber removal and consequently on timber inventory levels, resulting in more carbon accumulation in tree biomass but less in HWP (Figs. 7 and 8).

5. Limitations

Our study has a number of limitations. One limitation is that the IPCC-based scenarios were developed prior to the most recent global economic recession and therefore did not take into account the recent decreases in wood use, or other recent

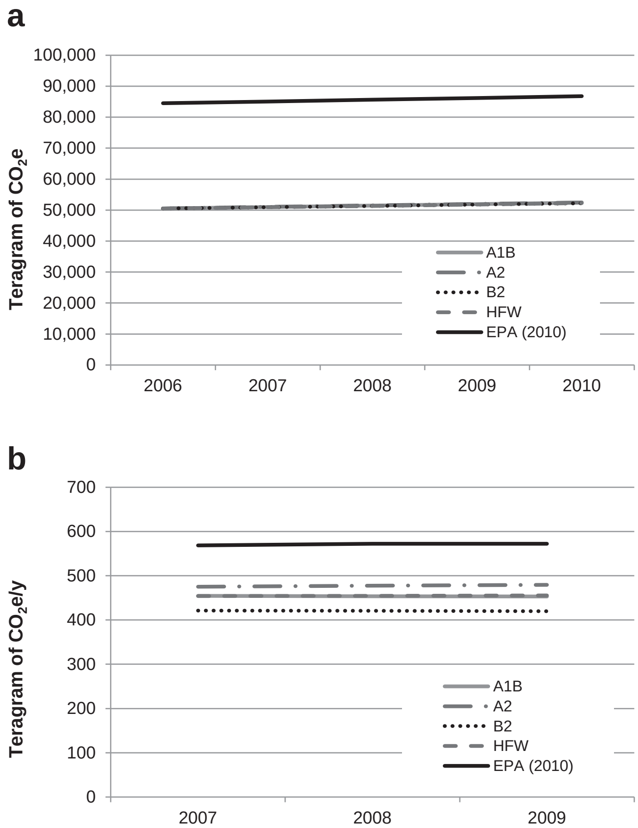

Fig. 7 – Comparison of projected historical total U.S. timberland tree biomass carbon s(a) stock (Tg CO_2e) and (b) flux (Tg CO_2e/y) for A1B, A2, B2, and HFW scenarios and historical estimates by U.S. EPA [4] during 2006–2010. Estimates of carbon stock and flux in this study are for timberland area only (208 million ha), whereas estimates by U.S. EPA [4] are for forest land area that includes both timberland and non-timberland area (304 million ha). The estimates of U.S. EPA [4] exclude Alaska and Hawaii, whereas our estimates include these states.

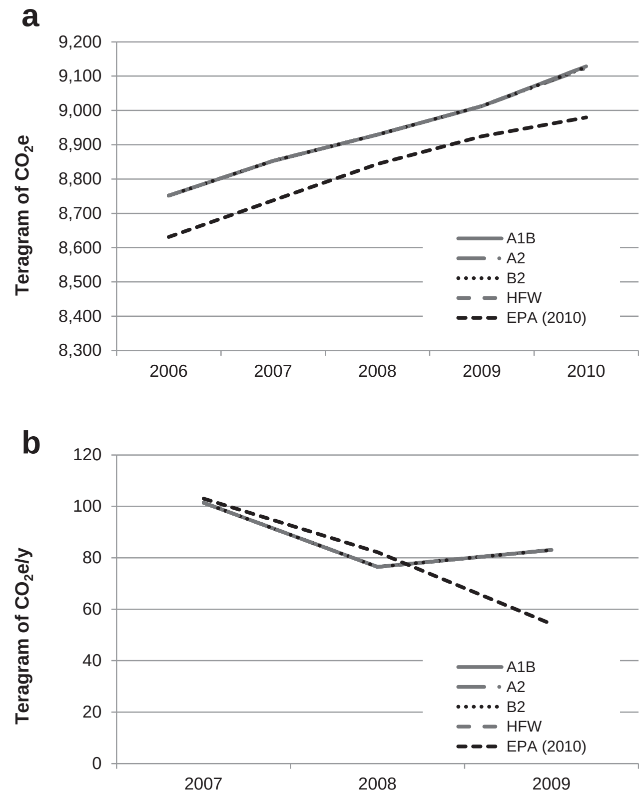

Fig. 8 – Comparison of projected historical U.S. harvested wood products carbon (a) stock (Tg CO_2e) and (b) flux (Tg CO_2e/y) for A1B, A2, B2, and HFW scenarios and actual historical estimates by U.S. EPA [4] during 2006–2010. The U.S. EPA [4] estimates exclude Alaska and Hawaii, whereas our estimates include these states. Note that all four alternative scenarios show similar HWP carbon stock and changes during 2006–2010.

structural changes in the U.S. economy such as expansion of natural gas supplies. For example, it is possible that plentiful supply of natural gas (if it is cheaper than wood energy) will reduce growth in consumption of wood energy. Similarly, we acknowledge that our projections did not take into account likely future climate changes, such as changes in temperature and precipitation, which will affect timber growth and inventory. Future climate change is generally expected to reduce net forest growth due to drought, increased intensity and frequency of fire, insect outbreaks and other disturbances [19]. However, authors believe that despite such limitations, the general conclusions drawn from this study are still valid and are useful in understanding the U.S. forest sector carbon impacts of future changes in wood energy consumptions.

The study used four established RPA scenarios (several of which were based directly on IPCC global scenarios). As described in the IPCC reports (Nakicenovic and Swart 2000), "*none of these scenarios are assigned any probabilistic occurrence. They are all equally valid and were based on an extensive assessment of emission driving forces such as demographic development, socio-economic development, and technological change; emissions in the scenario literature; alternative modeling approaches; and an "open process" soliciting wide participation and feedback*". In that same spirit, we emphasize that we did not intend that any of our scenarios a priori should be regarded as preferred or more "realistic", but rather the intent was to show the important forest sector carbon implications of the alternative future scenarios.

Finally, we reiterate that the results of this study related to tree biomass carbon pertain to U.S. timberland area only. Consistent with current literature, our modeling framework assumes no commercial harvests from non-timberland area [26]. Therefore, our model captures future U.S. forest sector carbon dynamics due to anthropogenic shifts in timber growing stock and timberland carbon stocks only, which may not necessarily correlate with forest sector carbon dynamics in non-timberland area. Further investigation is needed to ascertain possible association between changes in carbon sequestration in timberland and non-timberland area.

6. Conclusions

This paper described a modeling framework that can be used to project U.S. forest sector carbon inventory levels for various alternative global timber market scenarios. Timberland tree biomass carbon stock change estimates were made using timber growing stock inventory projections in a spreadsheet-based timber inventory model using USFPM/GFPM projections of timber harvest to adjust regional timber inventory over time. HWP carbon stock change estimates were made by the Woodcarb II model by using USFPM/GFPM projections of U.S. forest product production, and net imports. The range of alternative levels of global wood energy and timber consumption, influenced by projected trends in global economic and population growth across four scenarios, resulted in varying levels of U.S. timber harvest, timber inventory, and market trends consequently determining projected U.S. timberland and HWP carbon sequestration trends. The scenario with the highest level of projected wood energy and timber consumption resulted in the highest level of projected timber harvest and timber prices, which resulted in U.S. timberlands becoming a substantial carbon emission source toward the end of the projection period, although carbon in wood products in that scenario increased substantially, and projected expansion of tree plantations partly offset declines in timberland carbon stocks. Results indicated that higher cumulative emissions of forest carbon over the projection period due to increased combustion of biomass for wood energy were likely to be only partially offset by the end of the projection period (roughly 50% offset) by increased timber growth resulting from expanded plantations and more intensive forest management, due to the anticipated timber market response to increased demand for bioenergy.

The modeling approach described in this paper provides a tool for evaluating potential timber market implications of future carbon offset policies (a topic that we are planning to investigate in subsequent studies). We believe that such a modeling framework would be crucial in designing appropriate climate change policies and programs related to the forest sector. We acknowledge that the modeling framework is at present limited in the sense that it does not account for other important forest sector carbon pools such as forest floor, understory, and soil carbon pools. However, because the timberland tree biomass carbon pool constitutes the largest share of the total forest sector carbon pool, and is the carbon pool influenced most directly by dynamic changes in timber markets and timber harvest, the modeling approach can contribute a useful analysis of U.S. forest sector carbon offset strategies by providing a modeling framework to investigate dynamic change in U.S. forest sector carbon inventory on timberland and in forest products in relation to timber markets, wood energy, forest growth, and forest carbon offset credits.

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