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Forest carbon benefits, costs and leakage effects of carbon reserve scenarios in the United States

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ABSTRACT

This study evaluated the potential effectiveness of future carbon reserve scenarios, where U.S. forest landowners would hypothetically be paid to sequester carbon on their timberland and forego timber harvests for 100 years. Scenarios featured direct payments to landowners of \$0 (baseline), \$5, \$10, or \$15 per metric ton of additional forest carbon sequestered on the set aside lands, with maximum annual expenditures of \$3 billion. Results indicated that from 1513 to 6837 Tg (Teragrams) of additional carbon (as carbon dioxide equivalent, CO_2e) would be sequestered on U.S. timberlands relative to the baseline case over the next 50 years (30–137 Tg CO_2e annually). These projected amounts of sequestered carbon on timberlands take into account projected increases in timber removal and forest carbon losses on other timberlands (carbon leakage effects). Net effectiveness of carbon reserve scenarios in terms of overall net gain in timberland carbon stocks from 2010 to 2060 ranged from 0.29 tCO_2e net carbon increase for a payment of \$5/tCO_2e to the landowner (71% leakage), to 0.15 tCO_2e net carbon increase for a payment of \$15/tCO_2e to the landowner (85% leakage). A policy or program to buy carbon credits from landowners would need to discount additions to the carbon reserve by the estimated amount of leakage. In the scenarios evaluated, the timber

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set-asides reduced timberland area available for harvest up to 35% and available timber inventory up to 55%, relative to the baseline scenario over the next 50 years, resulting in projected changes in timber prices, harvest levels, and forest product revenues for the forest products sector.

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Introduction

Forests draw carbon from the atmosphere in the process of photosynthesis, and the carbon may remain stored for long periods in trees and other forest vegetation (in above- and belowground biomass and in forest soils) and in forest products in use or in landfills. Because of such capacity to store carbon, interest in using forests for climate change mitigation has been growing, and several strategies to use forests for achieving mitigation goals have been suggested. For example, avoiding deforestation or protecting existing forests, planting new forest area, decreasing harvest intensity, increasing forest growth, forest thinning to reduce fire threat, 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 are important forest-related strategies that can contribute to climate change mitigation (Malmsheimer et al., 2011; McKinley et al., 2011; Ryan et al., 2010).

The U.S. forest sector is considered to have a substantial potential to contribute to climate change mitigation (U.S. EPA, 2011; Heath et al., 2010; Perlack et al., 2005), primarily through improved forest management and afforestation. The capacity of the U.S. forest sector to mitigate climate change by carbon sequestration that offset atmospheric greenhouse gas (GHG) emissions could be augmented by the implementation of appropriate government incentives and/or policy and programs, and such policies may affect the forest management choices of forest landowners. For example, a rational landowner may accept or reject carbon offset contracts involving timber set-asides depending on the perceived opportunity costs (Van Deusen, 2010; Sohngen and Brown, 2008) of timber harvest versus carbon offset payments. Once the landowner decides to enter into carbon contracts involving timber set-asides, the qualified tracts of lands entering into the contract are likely to be withdrawn from harvests,[1] which can also impact forest product markets in several ways.

For example, according to economic theory, restricting timber harvest on some lands via voluntary set aside contracts would decrease the nationwide shares of timberland area and timber inventory available for harvest; shift timber harvest to other lands without set aside contracts; increase timber prices and forest product prices; decrease forest product production, consumption, and net exports; and decrease forest sector employment and profitability (Latta et al., 2011; Wong and Alavalapati, 2002). This is because the expected market effects of reduced availability of timberland area and timber inventory for timber harvest are to generally reduce timber supply and increase timber prices, which can be conceptualized as a leftward shift of the available timber supply curve within a given region (Fig. 1). This study aims to assess the broad U.S. timber market impacts and forest product market impacts of timber set-asides by estimating changes in timber supply and prices, and resulting impacts on forest product revenues, due to hypothetical government programs that would pay forest landowners to voluntarily forego timber harvest and accumulate forest carbon. In addition, the study aims to assess the carbon leakage effects of such voluntary timber set-aside programs, by assessing the changes in timber harvest and timber removals that would occur on remaining timberlands without set-aside contracts.

More specifically, this study seeks to answer two questions: what are long-term net impacts on (a) carbon sequestration and (b) forest product markets of a hypothetical program that would pay some U.S. forest landowners for carbon accumulation on their lands by voluntarily setting aside timberland

[1] It may be possible that future carbon policy would allow some forms of harvests in the contracted timberland (e.g., to maintain productivity). However, here we focus on the possibility of long-term harvest withdrawal (avoiding harvest for at least 100 years).

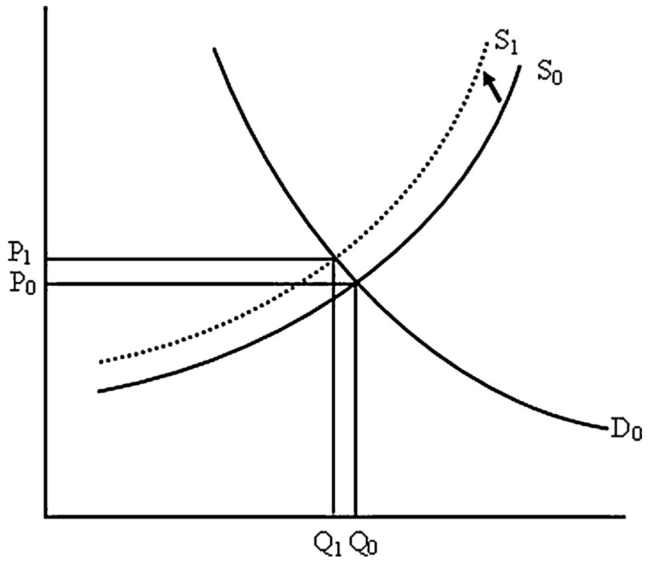

Fig. 1. A theoretical shift of regional timber supply curve (S_0 to S_1) due to timber set asides, and new market equilibrium price and quantity (P_1 and Q_1).

as carbon reserves for at least 100 years[2] avoiding timber harvest on set aside land? To answer these questions, we developed hypothetical scenarios that we could analyze using the U.S. Forest Products Module (USFPM) (Ince et al., 2011a,b)) and Global Forest Products Model (GFPM) (Buongiorno et al., 2003) modeling system. The scenarios simulate the market impacts of a voluntary program for forest landowners who set aside their timberland with direct payments for future increases in forest carbon sequestration relative to baseline regional forest carbon stocks. In general, reducing timber harvest in order to increase regional forest carbon stock is one of the recognized strategies to use forests for CO_2 sequestration or climate change mitigation. Climate change mitigation benefits of timber set-asides can arise if additional atmospheric carbon is sequestered and regional average forest carbon stocks increase when trees are not harvested.

However, timber set asides can also result in more pressure to harvest timber on the remaining available timberland that is not under carbon contract, reducing the net gain in total forest carbon sequestration. This “leakage effect”, is important in determining the cost effectiveness of climate change mitigation policies and carbon offset strategies. Generally, a carbon offset credit can be given only for additional carbon sequestered, net of any leakage effects. Thus, to understand the true mitigation benefit of alternative scenarios, we compute the total forest carbon accumulation, in both the available and unavailable (timber set-asides) portions of timber inventory, and we compare that to the total cost of timber set-aside payments.

In this study, we produced 50-year projections (2010–2060) of the U.S. timber market impacts of hypothetical large-scale voluntary timber set aside payments, in the context of a forest product market baseline (business-as-usual) scenario. The baseline scenario assumes no timber set aside payments, whereas the alternative scenarios allow some timberland area to be set aside voluntarily as carbon reserves, with no harvest on the set-aside lands for 100 years, in return for carbon payments. The amount of timberland that landowners would set aside voluntarily was estimated based on a rational expectations model, with analysis of the net present value to landowners of expected timber harvests versus carbon offset payments over a 100-year period. The value of timber harvests were determined

[2] A 100-year commitment period is consistent with the required commitment period under the current forest carbon offset protocol of Climate Action Reserve (CAR) (CAR, 2010).

by endogenously projected timber price and timber harvest quantities, whereas the total value of carbon offset payments over time were determined by projected forest growth and carbon accumulation on set aside lands, using the assumed carbon offset payments per ton of CO_2e and the annual budget available for carbon purchase.

We describe results of the alternative scenarios in terms of their net projected CO_2 mitigation benefit (increased carbon storage relative to our baseline scenario on all timberland, both with and without set-aside payments), total expenses required to achieve mitigation benefits, remaining timberland area and timber inventory available for timber harvests, projected changes in market equilibrium timber stumpage prices, harvest volumes, and total forest products revenues. The overall objective of this study was thus to provide meaningful information related to long-term economic impacts of climate change mitigation efforts involving timber set-asides, including specifically the timber market implications of timber set-asides under alternative scenarios, to policy makers and other stakeholders who may be interested in the concept of using forests to mitigate climate change.

Methods

This study integrated a set of forest sector models to evaluate long-term carbon sequestration benefits, effective costs, and timber market implications of three alternative timber set aside scenarios over a 50-year projection period relative to a baseline scenario (without timber set asides). The baseline scenario featured economic projections from 2006 to 2060 for U.S. forest product markets and timber demands. The baseline scenario and all alternative scenarios included deep impacts on timber markets of the recent recession and downturn in housing construction since 2006. The scenarios all incorporated the most recent (2011) USDA Economic Research Service macroeconomic projections of future trends in real gross domestic product (GDP) and population growth (to 2030) for all countries worldwide (USDA ERS, 2012). We extrapolated those macroeconomic trends to extend our model projections from 2030 to 2060. The scenarios also included our latest updated outlook for U.S. housing construction, with a projected gradual rebound of single-family housing starts from recent depressed levels to a long-term trendline at around 1.1 million annual starts by 2015 and beyond.

For the purpose of analysis the three scenarios featured hypothetical government programs, each with a maximum annual expenditure level (in constant 2006 dollars) of $3 billion ($1 billion for each U.S. region) available after 2010 for purchase of timber set aside contracts, with the scenarios featuring one of three carbon payment levels for the additional carbon sequestration on set aside lands, at $5, $10, or $15 per metric ton of carbon dioxide equivalent (CO_2e). The three alternative carbon payment scenarios were named “Carbon-5”, “Carbon-10”, and “Carbon-15”, respectively. In order to assess the carbon leakage effects, the direct carbon payments to landowners are only for additional carbon sequestration on contract lands, and we compute separately the carbon flux (loss) on non-contract timberlands. The integrated modeling approach involved projecting for each scenario (a) the U.S. timber growth and inventory on both the set-aside timberland and the remaining timberland that is still available for harvest, (b) annual market equilibrium timber harvest quantities and prices, (c) area of timberland set-aside as carbon reserves, (d) quantity of carbon accumulation in tree biomass on all timberland, both set-aside and not set-aside, and (e) cost effectiveness of climate change mitigation efforts for each alternative scenario taking into account leakage effects. Fig. 2 shows the overall modeling approach and model flow, and the following section describes individual models and their roles in our analysis.

Projecting timber growth and inventory

A spreadsheet model was developed to project U.S. regional timber growth and timber inventory for both set aside and non-set aside timberland for hardwood and softwood timber growing stock. The timber inventory available for harvest in a given year was projected by adding projected timber growth to the previous year’s timber inventory, and subtracting USFPM/GFPM projected market equilibrium

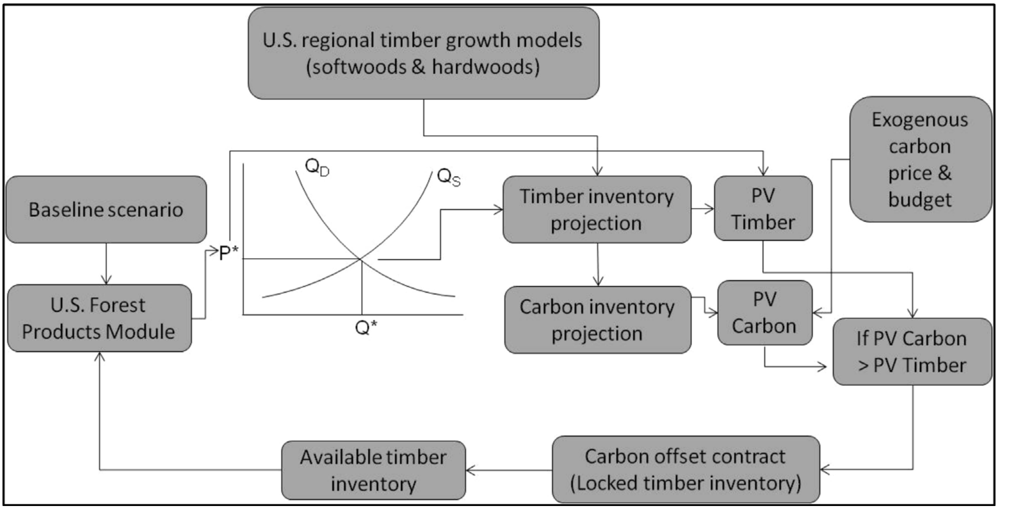

Fig. 2. Flowchart summarizing individual model components and their flow in evaluating climate change mitigation and forest product market implications of carbon reserve scenarios in the United States.

timber growing stock harvest quantity from the inventory on the available portion of timberland as follows:

$$AI_t = AI_{t-1} + GAI_t - H_t - SA_t \tag{1}$$

where AI_t is the current year available inventory, AI_{t-1} is last year's available inventory, GAI_t is the annual increment of timber growth for available inventory (net of mortality), H_t is the timber harvest from available inventory, and SA_t is volume of inventory on timberland that is set-aside because of carbon payments and becomes unavailable for harvest. Inventory in the set-aside timberland (unavailable for harvest) was projected using the following equation:

$$UI_t = UI_{t-1} + GUI_t + SA_t \tag{2}$$

where UI_t is the current year total inventory that is unavailable for harvest, UI_{t-1} is last year's unavailable inventory, GUI_t is the annual timber growth for the set-aside unavailable inventory, and SA_t is the volume of inventory set-aside due to current year carbon payments. The annual timber growth (net of mortality) for timber growing stock was predicted as a non-linear function of regional timber growing stock density (timber inventory divided by timberland area) as described in Nepal et al. (2012a) and Turner et al. (2006):

$$G_i = (\alpha + \alpha_1 P_i)(S_i)^{\gamma} + u_i \tag{3}$$

where G_i is net annual growth (net of mortality) as percentage of growing-stock inventory (%/yr) in county i, S_i is growing-stock density (m^3/ha) (growing-stock inventory divided by timberland area) in county i; P_i is proportion of area in plantations in county i; α and γ are parameters; and u_i is an error term. Because the growth model in Eq. (3) predicts average timber growth by species groups, it assumes that forests of each tree species group in each region are homogenous. However, the heterogeneity in site productivity and age classes is represented by the growing stock density parameter (S_i) that changes each year due to changes in inventory, growth and timberland area. Functional parameters for this timber growth model were estimated by region using cross-sectional county-level data on percentage annual growth and growing stock densities as described in Nepal et al. (2012a). The estimated parameters are presented in Appendix 1 (Table A1).

In addition, projected changes in total U.S. regional timberland area were exogenously applied to our model and were based on forest land area projections of USDA Forest Service 2010 RPA summary report (USDA Forest Service, 2012)[3]. The land area projections indicate gradually declining forest area in all U.S. regions over the next 50 years, primarily as a result of suburban encroachment and land development. Thus, our analysis assumes a gradually declining overall U.S. forest land base, and within that receding forest land area we project the shares of timber growing stock inventory that would be set aside in carbon reserve contracts and the growing stock that would remain available for harvest. In addition, we assumed an expansion in pine plantation area in the U.S. South to 21 million ha by 2060 from a current level of about 16 million ha, as projected for A2 scenario in USDA RPA summary report (USDA Forest Service, 2012).

Projecting market equilibrium timber harvest quantity and price

The annual market equilibrium timber harvest quantities and timber stumpage prices were projected using the USFPM/GFPM model (Ince et al., 2011a,b). The USFPM is a sub-model of the U.S. forest sector and regional U.S. timber markets that operates within the larger partial market equilibrium framework of the GFPM (Buongiorno et al., 2003). Within the USFPM/GFPM modeling framework, the market equilibrium timber harvest quantity and price for a given year are estimated by maximizing total producer and consumer surplus of the entire forest sector, based on Samuelson's optimization approach to regional market modeling (Ince et al., 2011a,b; Buongiorno et al., 2003). For a particular year, timber supply in USFPM/GFPM is estimated using a Cobb–Douglas functional form defined by the following equation (Buongiorno et al., 2003):

$$S_{ik} = S_{ik}^{*}\left(\frac{P_{ik}}{P_{(ik-1)}}\right)^{\gamma_{ik}} \tag{4}$$

where S^* is current timber supply at last period's timber price (P) and γ is price elasticity of supply (Table A2). Timber supply curve shifts over time, with the level of inventory and other specified variables, and their corresponding supply elasticities. In this study, the supply curve is shifted using an inventory elasticity of 1.0 based on the logic that supply of timber is proportional to physical volume of timber inventory available in the forest, which is consistent with several other studies (e.g., Abt et al., 2012; Ince et al., 2011b). The price elasticity of supply in USFPM/GFPM was estimated for four categories of timber (softwood sawtimber, softwood non-sawtimber, hardwood sawtimber, and hardwood non-sawtimber) in each of the three U.S. regions (North, South, and West) using methods described in Ince et al. (2011a). Briefly, for the South, supply functions were constructed by summarizing several simulations of harvest responses as modeled by an econometric model of harvest choices (Forest Dynamics Model, FDM), for all FIA plots in 13 southern states (Polyakov et al., 2010). The FDM estimates the probability of harvest as a function of potential revenue for harvest or for delaying harvests. Such regional harvest response obtained from several simulations is then aggregated using constant elasticity models for each period to provide estimates of the aggregate South-wide timber supply elasticities (Ince et al., 2011a). For the North and the West the price elasticities were derived using a time-series model of timber harvest as a function of timber stumpage price and other 'shifter' variables (Ince et al., 2011a).

Enrollment in carbon reserve contracts reduces timber inventory available for harvest, shifting timber supply curve to the left. We developed a spreadsheet based timber growth and inventory submodel (described in Section "Determining amount of timberland area set aside as carbon reserve") to estimate the reduction in available timber inventory due to carbon reserve contract, which was linked to the USFPM/GFPM via iterative solution procedure. The iteration procedure involved using projected U.S. regional timber harvests from USFPM/GFPM in the spreadsheet-based timber growth and inventory submodel, which in turn provided updated regional timber inventory projections to shift regional timber supply curves in the USFPM/GFPM (using an inventory elasticity of 1.0). The models were run iteratively in this manner until they converge on stable equilibrium solutions for projected harvest and inventory (usually requiring less than a dozen iterations). This iterative procedure has

[3] We used the land area projections of the 2010 RPA A1B scenario to adjust our regional timberland area.

been used in other forest sector models where submodels exchange projections and converge to stable solutions (e.g., Haynes et al., 2006).

Determining amount of timberland area set aside as carbon reserve

We modeled the choice of U.S. timberland owners to retain timber harvest rights or to forego harvest for carbon sequestration payments on the basis of rational expectations of future revenues and relative opportunity costs (Van Deusen, 2010; Sohngen and Brown, 2008). The opportunity cost for timber set-aside by carbon reserve contract is the present value of future timber harvests foregone. In theory, a rational landowner would choose to enroll in a carbon contract only if the landowner believes that the expected present value of entering the carbon contract is higher than the expected present value of future timber harvests.

For a given year, the present value of expected future timber harvests and carbon sequestration payments are computed for a 100-year period ahead, based on average initial timber growth rates and harvest levels for each U.S. region. Similarly, the present value to the landowner of projected carbon reserve payments are computed for a 100-year period ahead, based on the additional carbon accumulation above baseline regional average carbon stocks. The analysis used a discount rate of 5% and the values are expressed in real 2006 U.S. dollars.

Our analysis of landowner choices approximates the guidelines of the leading forest carbon protocol in North America (the Climate Action Reserve Forest Project Protocol (CAR, 2010)). Under the CAR protocol, the forest landowner receives carbon sequestration credit only for carbon accumulation that is above a baseline carbon stocking level called the "common practice" baseline, which is defined specifically as the average standing above-ground live carbon stocks on similar lands within the project's assessment area or region. Accordingly, our analysis of landowner choice and projected carbon payments are for projected carbon accumulation above baseline carbon stocks that are the regional average stocking levels.

For this comparison, we projected average timber harvest quantities per hectare 100 years ahead using a trendline of the immediate past 20 years of timber harvest quantity along with the USFPM/GFPM projected timber stumpage prices based on the logic that landowners would anticipate future harvest volumes similar to recent past trends, and prices similar to those projected by the economic model. The 100-year carbon payments were estimated based on projected net annual timber growth and carbon accumulation above the baseline average stocking levels, with our growth formula taking into account average rates of natural mortality and natural forest disturbances (such as wildfire), thus ensuring a degree of permanence to the projected carbon sequestration. The resulting additional carbon sequestration above baseline levels on set-aside lands was priced at one of three exogenous payment levels ($5, $10, or $15 per t of additional CO_2e sequestered on the set aside land, depending on the scenario), with an overall annual expenditure limit of up to $3 billion, assumed to be available for carbon purchase each year. This $3 billion budget limit was equally distributed among each U.S. region (up to $1 billion per year). The range of carbon payment levels ($5 to $15 per t$CO_2$e) is consistent with carbon prices used in the economic analyses of forest carbon by other researchers (Nepal et al., 2012b; Latta et al., 2011; Adams et al., 2011; U.S. EPA, 2009; Huang and Kronrad, 2006). The $3 billion annual budget constraint ($1 billion for each U.S. region) is simply a hypothetical assumption that we adopted for analytical purposes, and does not relate to any actual or proposed government program or policy. The budget constraint limits the amount of timberland that can be enrolled in set-aside contracts each year. An expenditure constraint is realistic, because funding for any carbon reserve program will undoubtedly be limited to some extent, and it is necessary also to limit the purchase of timberland set asides because without an expenditure constraint the model would immediately enroll all available timberland for set asides whenever it is economical to do so.

The enrollment in carbon reserve contracts and the carbon payment mechanism envisioned in this study is similar to the U.S. federal Conservation Reserve Program (CRP; Plantinga et al., 2001; Babcock et al., 1996; Osborn et al., 1995), a program implemented during 1980s and 1990s where eligible farmers could submit bids to enroll their erodible farmland for 10-15 year set-aside contract. The acreage would be maintained in a conservation use with appropriate vegetative cover and no commercial crop harvest, grazing, or hay production. Landowners would receive annual rent payments specified in the accepted bid. Our analysis assumes a similar program where landowners would have a choice to enroll in the long-term timber set-aside for carbon sequestration at given carbon price levels or to retain timber harvest rights, with their decision based on their expected timber revenue and carbon payments for the next 100 years. We assumed for simplicity of analysis that once timberland became enrolled in the timber set aside carbon reserve program, it would not be available for timber harvest for the remainder of the projection period (at least 100 years). The government would accept low bids for 100 years' worth of carbon accumulation on given land areas (e.g., \$5/tCO_2e, \$10/tCO_2e, and \$15/tCO_2e) until the expenditure cap (e.g., \$1 billion in each U.S. region) is exhausted for a particular year. The \$3 billion could be placed in a fund and used to make annual payments for carbon accumulation over 100 years on the land that is set aside in the current year. The carbon prices are specified in 2006 dollars but would increase at the rate of inflation. The models make projections using real dollars. The annual expenditure cap will allow less timberland area to be enrolled in a given year at a higher carbon price. With a limited budget, a higher carbon price would more quickly exhaust the available budget, consequently allowing fewer acres to be enrolled compared to the case when carbon prices were lower.

Given the timber inventory volumes that are set aside for carbon sequestration under the hypothetical carbon reserve program, the spreadsheet model then determines how much timber inventory remains available for harvest after the set aside and after other projected changes in forest land area due mainly to urbanization. The loss of forest land area to urbanization and other land uses in the baseline scenario is an exogenous projection that remains the same across all of the alternative carbon payment scenarios, since urbanization is driven primarily by overall economic growth assumptions that are the same in all of the scenarios. The net changes in available timber inventory estimated by spreadsheet inventory model, in turn, are linked to USFPM/GFPM that shifts the USFPM/GFPM timber supply curves in U.S. regions (using an inventory elasticity of 1.0). Through a series of iterations with the spreadsheet inventory model, and the USFPM/GFPM market model, we obtained market equilibrium timber harvest, inventory, and prices for each year.

Estimating and projecting tree biomass carbon

This study projected the total quantity of carbon sequestered in tree biomass on all U.S. timberland[4] for the baseline scenario and for the three alternative scenarios (with carbon sequestration payments). Total tree biomass carbon represents all standing live and dead above- and belowground tree biomass carbon in trees larger than 2.5 cm diameter at breast height (dbh) on timberland. In the context of carbon analysis, the total tree biomass carbon pool on timberland is most relevant to consider because this pool accounts for the largest share of total carbon stock in U.S. forests, about 60% (McKinley et al., 2011; Ryan et al., 2010) and also because the existing carbon offset protocols recognize tree biomass carbon as eligible for carbon offset credit[5].

The merchantable timber growing stock volume was converted to total tree biomass weight using regional average ratios of total biomass weight to merchantable volume (Nepal et al., 2012c), based on data from the FIA database (Miles, 2011) on total tree biomass weight and growing stock volume in U.S. timberlands.

Biomass dry weight was multiplied by 0.5 to estimate carbon weight (dry wood biomass is approximately 50% carbon) and then we converted to CO_2 equivalent based on molecular weight (U.S. EPA, 2011). The above- and belowground tree biomass estimates include tree bole, tops and limbs, saplings, stump, bark, and coarse root biomass of all live and standing dead trees above 2.5 cm dbh but do not include foliage biomass (Miles, 2011).

[4] Timberland is forest land that is open to commercial timber harvesting and is capable of a minimum timber growth rate (Smith et al., 2009).

[5] Although carbon stored in harvested wood products is also eligible for credits under CAR, we do not consider payments for harvested wood products carbon in this study because the set-aside lands are assumed to be fully withdrawn from harvests.

Determining cost effectiveness of alternative scenarios

Cost-effectiveness analysis (CEA) was used here to evaluate cost effectiveness of the carbon reserve payments as climate change mitigation policy alternatives, taking into account the estimated carbon leakage effects (Section "Estimating leakage effect"). CEA is a general technique used for computing costs per unit of benefit for activities producing physical benefits that are difficult to measure precisely in economic terms, such as human health benefits of medical activities (Gold et al., 1996). In this case, CEA is used to determine the policy scenario that offers lowest monetary costs per unit of physical climate change mitigation benefits ($/t$CO_2$e) (ICRA, 2012). The cost-effectiveness ratio (CER) is relevant here (rather than a benefit/cost ratio) because the CER compares the mitigation costs of alternative scenarios per unit of increased CO_2 sequestration (ICRA, 2012). This CER was calculated as follows (ACP, 2000):

$$\mathrm{CER} = \frac{C_\mathrm{A} - C_\mathrm{B}}{E_\mathrm{A} - E_\mathrm{B}} \qquad (5)$$

where C_A and C_B represent total costs of alternative (A) and business-as-usual (B) scenarios, respectively, and E_A and E_B are total carbon accumulation effects (additional net forest carbon sequestration) of alternative and business-as-usual scenarios, respectively. There is no carbon payment in the business-as-usual scenario, and therefore C_B is zero.

Estimating leakage effect

Timber set asides exert more pressure to harvest timber (to meet the relatively unchanged demand for forest products) on the remaining timberland that is not within the carbon reserve. This increased harvest on available timberland would reduce the net carbon benefit of the set aside program. Such reduction in the intended carbon benefit is positive leakage and can be estimated, by comparing the level of carbon set aside price per ton of CO_2e ($5, $10, and $15) to the cost-effectiveness ratio in each scenario (50 year cumulative cost divided by 50 year additional cumulative carbon benefit). Mathematically,

$$L = \left(1 - \frac{P_C}{CER}\right) \qquad (6)$$

where L is leakage in percentage, P_C is carbon set aside price, and CER is cost-effectiveness ratio (Eq. (5)). If there were no leakage, the CER would be equal to the given carbon set aside price, but in our analysis the CER is generally higher than the carbon set aside price because there is significant carbon leakage (due to increased harvest of timber on land that is not within the carbon reserve).

Results and discussion

CO_2 mitigation benefits of baseline and alternative scenarios

Fig. 3 compares projected quantities of total tree biomass carbon accumulated on all U.S. timberland in the baseline and three alternative carbon reserve scenarios over the next 50 years. In 2010, the starting year of the projection, about 52,600 TgCO_2e was sequestered in total tree biomass on U.S. timberland in all scenarios. Our economic analysis indicated that 89,559 TgCO_2e would be accumulated in total tree biomass on timberland by 2060 in the baseline scenario without any carbon policy in place to purchase carbon offsets. Carbon is projected to be accumulated on U.S. timberland in the baseline scenario because projected net annual growth of timber exceeds growing stock harvest by a wide margin. The projection continues the historical pattern of carbon accumulation on U.S. timberlands in recent decades.

The alternative carbon reserve scenarios, featuring different levels of carbon set aside prices ($5, $10, and $15/t$CO_2$e) and fixed annual carbon expenditure ($3 billion/year), resulted in various levels of CO_2 sequestration on timberland, with generally higher projected carbon accumulation than the baseline (business-as-usual) scenario over the projection period 2010–2060. The largest climate

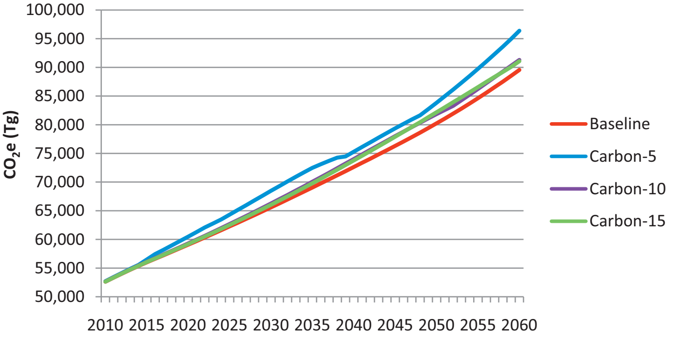

Fig. 3. Cumulative total tree biomass carbon accumulation ($TgCO_2e$) on U.S. timberland under baseline and alternative carbon reserve scenarios, 2010–2060.

change mitigation benefit was offered by the alternative scenario Carbon-5, which featured carbon set aside payments of just $5/$tCO_2e$, accumulating 96,369 $TgCO_2e$ in total tree biomass on timberland by 2060, representing an additional accumulation of 6810 $TgCO_2e$ (8%) relative to the baseline scenario. The alternative scenario Carbon-10, featuring carbon set aside payments at $10/$tCO_2e$, accumulated 91,302 $TgCO_2e$, by 2060, representing additional accumulations of 1743 (2%) relative to the baseline scenario. The alternative scenario Carbon-15, with carbon set aside price of $15/$tCO_2e$, sequestered 91,072 $TgCO_2e$, which was 1513 $TgCO_2e$ more (2%) than the baseline scenario.

The relative increases in carbon accumulation of the alternative scenarios can be translated into an average annual carbon accumulation rate (flux) over the 50-year projection period (2060 accumulation minus 2010 accumulation, divided by the number of years in the projection period). For example, during 2010–2060, the baseline scenario sequestered at an average annual rate of 739 $TgCO_2e$/year. Alternative scenarios Carbon-5, Carbon-10, and Carbon-15 sequestered at the rates of 875, 774, and 769 $TgCO_2e$/year, representing additional average annual CO_2e influx of 135 (18%), 34 (5%), and 30 (4%) $TgCO_2e$/year above the baseline scenario. These projected quantities of carbon sequestration on timberland in the baseline and the alternative scenarios refer to total tree biomass carbon on all U.S. timberland, including both available and unavailable (set-aside) portions of timber inventory. Although increases in carbon accumulation in the set-aside portions of the timber inventory (the carbon reserves) were substantial for all three alternative scenarios, net increases across all timberlands were reduced by increased harvests and depleted timber inventories on the available portion of the inventory. This kind of market adjustment that reduces effectiveness of carbon set-asides (in this case a shift in timber harvest from land under carbon contract to other land not under contract) is a “leakage effect”.

Taking into account the leakage effect, we computed the cost effectiveness of the hypothetical timber set aside programs in terms of climate change mitigation benefit (measured by increased carbon sequestration on timberland). Our models account for the carbon flux on all U.S. timberlands, including both the lands set aside in the carbon reserve and remaining lands not in the carbon reserve. Thus, we can account for the leakage effect in terms of carbon losses on other lands relative to additional carbon sequestration on set-aside lands, and we compute the actual effectiveness of the hypothetical timber set asides in terms of net gain in total forest carbon sequestration. For example, in alternative scenario Carbon-5 (carbon price $5/$tCO_2e$, and carbon budget of $3 billion/year), $117 billion would be spent over the 2010–2060 period, and we estimate that it would achieve climate change mitigation benefits of 6810 $TgCO_2e$ relative to the business-as-usual scenario (without any carbon purchases), taking into account carbon sequestration on all timberland (land in the carbon reserve and lands not in the reserve). Thus, on average, the cost effectiveness of mitigating a ton of CO_2e emissions in alternative scenario Carbon-5 was $17.18. Or, in other words, the $5/$tCO_2e$ set aside payment to landowners in the Carbon-5 scenario results in a net carbon sequestration gain of only 0.29 ton of CO_2e (a cost effectiveness of only 29%). This corresponds to a leakage effect of 71% (the increase in carbon emitted on other U.S. timberlands relative to carbon sequestered on contracted set-aside timberlands). In other words, while the contracted landowners were paid for carbon accumulation on their land at \$5/tCO_2e, the actual cost of the program in terms of effectively offsetting a ton of CO_2e was more than several times higher (\$17.11) because of the leakage effect.

With higher carbon prices and the same carbon expenditure limit (\$3 billion per year), the total expenses during 2010–2060 in alternative scenario Carbon-10 (carbon price \$10/tCO_2e) and Carbon-15 (carbon price \$15/tCO_2e) were \$145 and \$153 billion, respectively, with corresponding additional CO_2 mitigation benefits of 1743, and 1513 TgCO_2e, respectively. Thus, the cost effectiveness was much less at the higher carbon prices, as the total costs of offsetting a ton of CO_2e in alternative scenarios Carbon-10 and Carbon-15 were \$83.19 and \$101.15, respectively. The corresponding leakage effects were higher also, at 88% and 85%, respectively, meaning that the \$10 to \$15 payments to landowners for carbon reserves would be only 12% to 15% effective in terms of mitigating a ton of CO_2e after taking into account net changes in carbon stocks on all timberland. These estimated costs are not marginal costs and therefore cannot be used to derive a carbon supply curve, because we have a fixed budget constraint in this analysis.

The total payment of \$117 billion in Carbon-5 scenario is substantially lower than the total available budget during 2010-2060 (\$3 billion/yr times 51 yr = \$153 billion). This occurred because the carbon price of \$5/tCO_2e did not provide an economic incentive for enrollment in carbon reserve contracts in the later years of projections (after 2038 in the West, after 2048 in the North, and after 2059 in the South). In general, higher carbon prices provided better economic incentives to landowners for enrollment in carbon reserve contracts throughout. However, the limited budget allowed fewer areas to be enrolled in these scenarios as the available budget was more quickly exhausted with higher carbon price. In Carbon-5 scenario, 68 million ha of timberland area was enrolled in carbon reserve contract with a total cost of \$117 billion, whereas 60 and 49 million ha of timberland area were enrolled, with total costs of \$143, and \$153, in Carbon-10, and Carbon-15 scenarios, respectively.

Intuitively, one might expect the leakage effect would increase with the area of timber set-asides. In our analysis the largest area was set aside in Carbon-5 scenario (68 million ha), followed by Carbon-10 (60 million ha), and Carbon-15 (49 million ha). However, the expectation that higher leakage would occur with larger set-aside area would be valid when only harvest effects were considered in estimating leakage between the scenarios. Our analysis includes not only the harvest effects but also the overall cost-effectiveness in terms of nominal carbon price per unit of carbon set aside versus actual payments per net unit of increased carbon. The carbon-5 case was the most cost-effective carbon reserve scenario within the hypothetical budget constraint of \$3 billion per year. It has the lowest leakage effect, but still very substantial leakage at 71%. In general, our CEA shows that a budget-constrained forest carbon reserve program will be more cost effective if lower prices are paid for carbon sequestration, provided that the price (e.g., \$5 per t of additional CO_2e sequestered on set aside lands) is still sufficient to cause rational forest landowners to forego future timber harvests, as it was in this case. However, the CEA also shows substantial leakage effects, and even in the most cost-effective scenario (Carbon-5) the carbon payment to forest landowners for sequestering a t of carbon is only 29% effective in terms of sequestering a t of CO_2e on timberland (at 71% leakage) because of shifts in timber harvest to non-reserve lands. Our estimates of leakage (71–88%) are roughly consistent with Murray et al. (2004) who estimated up to 68% leakage from hypothetical forest set- aside program in the United States. Our analysis computes the leakage effects solely in terms of net carbon change on U.S. timberland, and does not account for forest carbon change in other countries. However, because of reduced U.S. wood product net exports in the alternative carbon reserve scenarios, there would likely also be some additional global carbon leakage due to increased timber harvest and possibly reduced timber inventories in foreign countries.

Although U.S. timberland area and timber inventory available for timber harvest were decreased due to timber set-asides in the alternative scenarios, the relatively inelastic U.S. and global demands for forest products did not change. Thus, smaller available U.S. timber inventories in the alternative scenarios had to meet the same inelastic demands for forest products as in the baseline scenario, resulting in depleted timber inventory (and depleted tree biomass carbon) on the timberlands that remained available for timber harvest outside of the set-aside carbon reserve lands. The climate change mitigation benefit is thus generally much smaller than the carbon accumulation in carbon reserves, despite a large accumulation of carbon in timber inventory on carbon reserve lands.

Policy implications and discussion

The findings of our analysis convey some important general policy implications related to climate change mitigation efforts using timber set-asides. First, due to the relatively inelastic demand for forest products, climate change mitigation benefits are diminished by substantial leakage in the form of increased timber harvest and reduced carbon stock on remaining available timberland. Second, efforts to mitigate climate change using timber set- asides can have other broad economic impacts on the forest sector resulting from reduced timberland area, reduced timber inventory, reduced timber supply, and increased timber price (discussed in Section "Estimating leakage effect").

We compared our results on costs to mitigate climate change with other studies. These comparisons, however, are indirect in that our modeling framework is different from most other studies in terms of overall approach and scope of the study. For example, cost estimates for climate change mitigation from most previous studies were based on estimates of marginal cost of carbon supply (willingness of landowners to accept carbon contracts). Our study is technically not a marginal cost study, because we specified fixed carbon prices and we constrained carbon reserve expenditures to $3 billion/year, which results in less forest area set aside (not more) when carbon price is increased, because of our assumed budget constraint.

In addition, our study focused only on the effects of timber set-asides (without considering effects of other possible climate change mitigation strategies, such as afforestation or forest management activities, that are analyzed in other studies). Similarly, our study focuses on the timber market and forest sector impacts within the United States (using the same exogenous assumptions about major land use changes, such as shifts from forest land to urban land use, in the baseline and alternative scenarios). A comparable study by Latta et al. (2011) used the FASOM GHG model to compare effects of mandatory incentives (tax/subsidy applied to all eligible lands) to the effects with voluntary participation. Their results for voluntary participation are somewhat comparable to our study, in that both models used a theory that landowners would decide to participate in carbon offset contracts based on a comparison of expected value of timber harvests versus expected value of carbon offset payments. However, our study differs in that their model considered land use competition between forest and agriculture (our study covers the forest sector only) and they allowed timber harvest on contracted land if the landowner paid a penalty. Their estimates indicated that payments of about $20/tCO_2e$ would achieve climate change mitigation benefits of 50 $TgCO_2e$/year. We estimated an average mitigation benefit of 134 $TgCO_2e$/year for an average cost of $17.11/tCO_2e$ during 2010–2060. Our estimate of mitigation cost is thus somewhat lower. However, the version of the FASOM-GHG model used considerably higher projected timber demands associated with higher U.S. housing starts (based on the 2005 RPA forest assessment), whereas the 2012 baseline scenario that we used in USFPM/GFPM has much lower projected U.S. housing starts, very little projected growth in U.S. timber harvest, and declining long-run trends in real timber prices. The lower timber demand outlook leads to lower projected U.S. timber prices and greater likelihood of forest landowner participation in carbon set aside programs. The implication of this finding is that projections of forest product and timber market trends are important in projecting the consequences of mitigation programs that involve payments to landowners for carbon offsets. The demands for forest products drive the price of timber and in turn the price of carbon reserve payments that would be needed to compete for timber harvest rights.

A study by Sohngen and Brown (2008) analyzed carbon mitigation and cost implications of extending forest rotations in 12 southern states. Based on marginal cost analysis of these 12 southeastern states, they reported that timber set-asides could be a viable option only when a carbon price (cost) exceeds $40/CO_2e$, and that about 1 million ha of land would be set aside with carbon price (cost) of $55/tCO_2e$. Our estimates indicated that about 1.36 million ha would be set aside per year (68 million ha during 2010–2060) with a carbon price of $5/tCO_2e$ and the mitigation cost of $17.11/tCO_2e$. Again, this may reflect the fact that the 2012 baseline scenario in USFPM/GFPM has very little projected growth in U.S. timber demand, which tends to dampen projected timber price appreciation and increases the feasibility of landowner participation in carbon set-aside contracts.

U.S. EPA (2005) estimated the future potential for climate change mitigation benefits from the forest sector, including benefits of afforestation and forest management (lengthened timber harvest rotations, increased forest management intensity, forest preservation and avoided deforestation) over

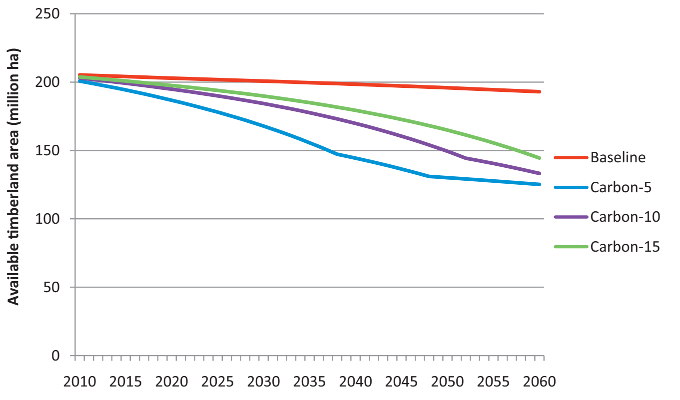

Fig. 4. Available U.S. timberland area (million ha available for timber harvest) under baseline and alternative carbon reserve scenarios, 2010–2060.

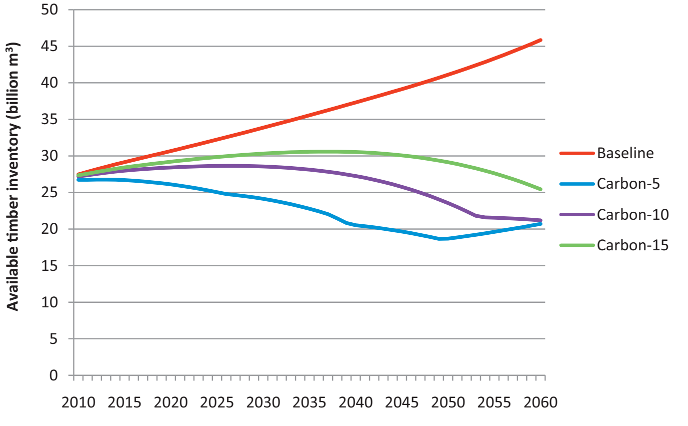

Fig. 5. Available timber inventory (billion m^3) for harvest on U.S. timberland under baseline and alternative carbon reserve scenarios, 2010–2060.

the next 100 years (2010–2110). Their estimates ranged from 107.4 $TgCO_2e$/year at the price (cost) of $5/$tCO_2e$ to 1208 $TgCO_2e$/year at the price (cost) of $50//$tCO_2e$. Our results suggested similarly a mitigation potential of 134 $TgCO_2e$/year (through timber set asides) at the effective cost of $17.11/$tCO_2e$ annualized over 50 years (2010–2060). However, with higher carbon prices, our study showed smaller mitigation potential because our study constrains total carbon expenditure to $3 billion/year, which allows for less timber set asides as carbon price increases.

Impact of timber set aside payments on available timberland area, timber inventory, timber supply, timber price, and forest product revenues

Our analysis suggested a number of types of effects of timber set asides via carbon payment scenarios, including impacts on available timberland area (Fig. 4), timber inventory (Fig. 5), timber supply (Fig. 6), and sawtimber stumpage prices (Fig. 7). Fig. 4 shows timberland area that is available for harvest in the baseline and alternative scenarios. The available timberland area in the baseline scenario is projected to gradually decline even without a carbon reserve program because of projected urban expansion and land development (our projections follow the projections of forest land area developed for the 2010 RPA forest assessment (USDA Forest Service, 2012). Results of our economic analysis suggested that about 68 million ha of U.S. timberland area would be set aside for carbon

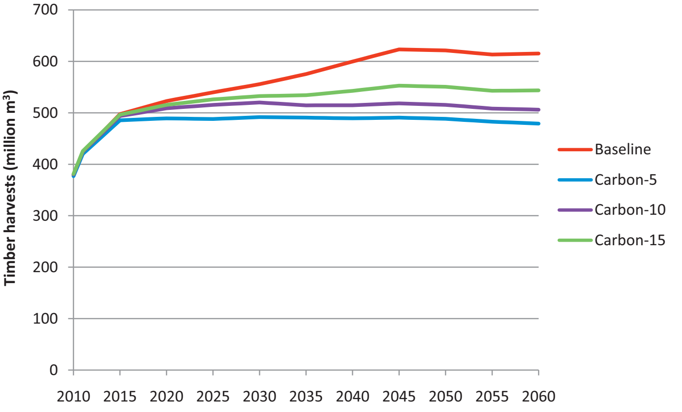

Fig. 6. Total timber harvests (million m^3) from U.S. timberland under baseline and alternative carbon reserve scenarios, 2010–2060.

reserves during 2010–2060 in the Carbon-5 scenario. This amounts to 35% of the projected 193 million ha of U.S. timberland area in 2060, after adjusting for losses of timberland area to urbanization and development.

With higher carbon prices in alternative scenarios Carbon-10 and Carbon-15, less timberland area was set aside. This was because the implicit cost per hectare increased with higher carbon prices and therefore less timberland area could be set aside with the fixed budget ($3 billion per year). For instance, the timberland areas set aside during 2010–2060 were 60 (31%) and 49 (25%) million ha in alternative scenarios Carbon-10 and Carbon-15, respectively.

Although scenario Carbon-5 has only 12% more timberland area being set aside as carbon reserve than scenario Carbon-10 by the end of the projection, it has higher cumulative climate change mitigation benefit (75% more) over the projection period because more timberland area (and carbon inventory) was set aside during the early years in this scenario. The huge difference in the estimated carbon benefits between scenarios Carbon-5 and Carbon-10 were caused by the fact that low carbon price in Carbon-5 scenario allowed more timberland area to be set aside early in the projection period. Eventually, timber prices begin increasing and it became financially less attractive to enroll land under the Carbon-5 scenario. In contrast, less area is set aside in alternative scenario Carbon-10 in the early years because of the fixed budget, although enrolling in carbon contracts is financially more attractive to landowners with a higher carbon price in this scenario. One of the general policy implications of this result is that the effect of carbon reserve on timber price in a particular year depends on the total area of forests that are set aside up to that year. Increasing the area set aside in the beginning of the program would, each year, increase the opportunity cost of timber revenue that would need to be overcome by carbon payments obtained by enrollment.

Fig. 5 compares projected timber inventory available for harvest during 2010–2060 for the baseline scenario and alternative carbon reserve scenarios. The impact of carbon reserves on available timber inventory was similar to the impact on available timberland area, except that the percentage reduction in available timber inventory was greater than the percentage reduction in timberland area. For example, over the 50-year projection period, available timber inventory would be decreased by more than half (25 billion m^3, or 55%) in alternative scenarios Carbon-5 and Carbon-10, and by less than half (21 billion m^3, or 45%) in alternative scenario Carbon-15, relative to the available inventory in the baseline scenario (46 billion m^3). The large reductions in available timber inventory in the alternative scenarios were due to several factors, including the placement of large fractions of timberland area into carbon reserves, the losses of timberland area due to urbanization and development, and also proportionately higher harvest-to-growth ratio on the diminishing areas of available timberland. This occurs because available timberland area and timber inventory were reduced but growth in demands for forest products remained relatively unchanged, inducing proportionately higher removals than

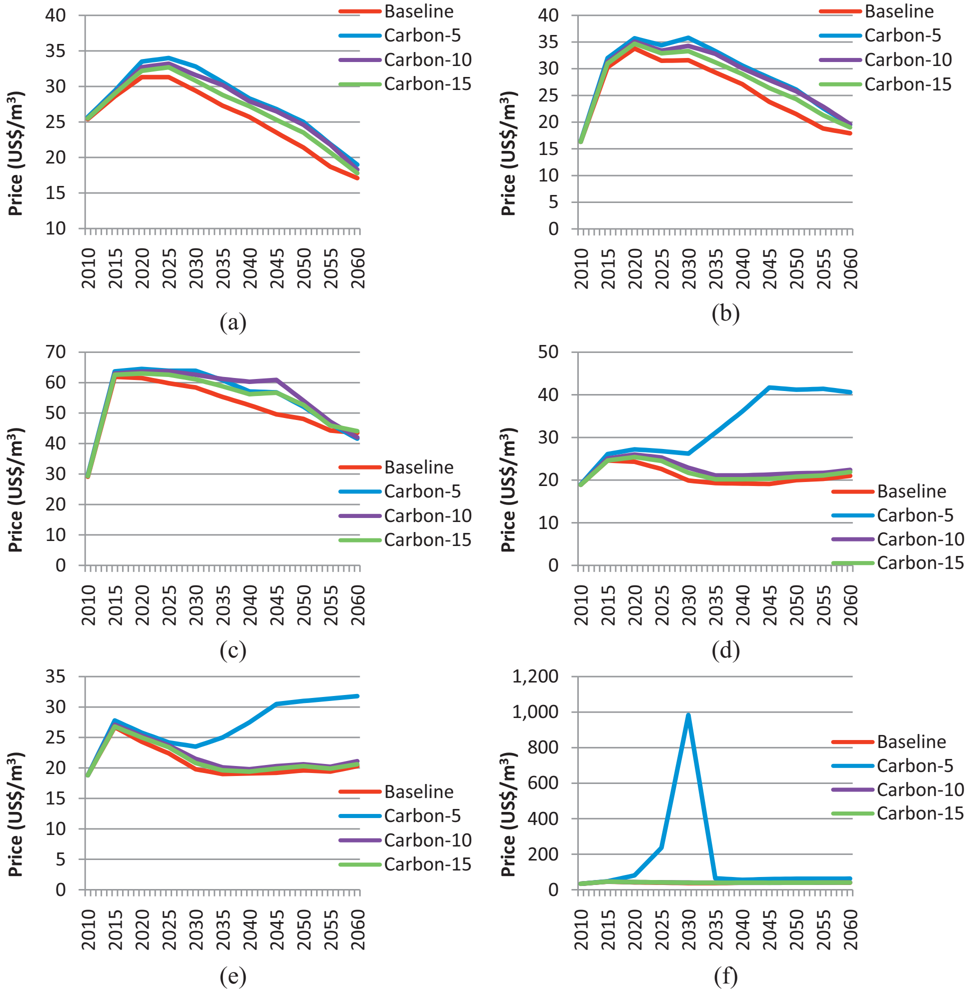

Fig. 7. Projected sawtimber stumpage prices (US$/m^3) for the baseline and alternative carbon reserve scenarios, 2010–2060: (a) softwoods, North, (b) softwoods, South, (c) softwoods, West, (d) hardwoods, North, (e) hardwoods, South, and (f) hardwoods, West.

growth on available timberland, although the U.S. timber harvest was decreased somewhat relative to the baseline scenario because of higher timber prices with the decrease in available timber inventory (Fig. 5).

The market responses to reduced availability for harvest of timberland area and timber inventory are reflected in lower projected timber harvests (Fig. 6) and higher sawtimber stumpage prices (Fig. 7). As an aside, the near-term increase in timber harvest from 2010 to 2015 in all cases (Fig. 6) is a reflection of the assumed rebound in U.S. housing construction and corresponding rebound in timber demands by 2015. The 2010 U.S. timber harvest level is very depressed (actually down by about 30% relative to recent historical peaks). Projected future growth in timber harvest beyond 2015 is relatively modest, and much of the projected growth in timber harvest is for wood energy (which was projected to roughly double by 2060 in the baseline scenario). The reduction in the available inventory due to timber set-asides effectively shifts the regional timber supply curves to the left relative to the baseline scenario (Fig. 1) and results in higher projected saw timber stumpage prices (Fig. 7) and reduced timber harvests (Fig. 6). The average annual U.S. timber harvests in alternative scenarios Carbon-5, Carbon-10, and Carbon-15 are reduced by 83 (14%), 60 (10%), and 40 (7%) million m^3 during 2010–2060, relative to average annual harvest of the baseline scenario (575 million m^3/year). These reductions in U.S. timber harvest are relatively small compared to corresponding reductions in available timber inventory (up to 55% reduction by 2060). Again, this was because forest product demands are relatively inelastic with respect to price, and the drivers of demand growth such as GDP growth in alternative scenarios remain the same as in the baseline scenario. The result is that percentage reductions in harvest were less than percentage reductions in available timber inventory.

The price impacts of changes in available timber inventory and timber supply can be different for hardwood and softwood species groups because our modeling framework projected separate regional timber prices for softwoods and hardwoods. In addition, we used the same nationwide carbon price for all regions and species, but hardwoods and softwoods differ in wood density (and carbon content per unit volume). Thus, depending on the outcome of economic analysis, it is theoretically possible that hardwood timber inventory in a particular region might be enrolled in carbon reserves while softwood timber inventory may not be. For instance, if the present value of softwood harvest in a given region for a given year were higher than the present value of the carbon reserve payments, then softwood inventory will not be chosen to be enrolled in the carbon reserve contract that year. Our results showed varying region-wide timber price impacts (generally price increases) among the carbon reserve scenarios, especially in the middle part of the projection years. However, at the end of the projection period, the overall long-range price impact in all regions was similar (and modest) except for hardwood in the U.S. West, where an extreme outcome was projected for hardwood inventory and price in the Carbon-5 scenario. Virtually all available hardwood timber inventory in the West was set aside in carbon reserves by around 2025, with no available inventory left to sustain demands for hardwood timber, resulting in a sharp but unrealistic price increase for hardwood timber in the U.S. West in the Carbon-5 scenario (Fig. 7f). In actuality, hardwood timber in the U.S. West accounts for only a very small share of total U.S. timber harvest (less than 3%), and the price spike for hardwood in the West in the Carbon-5 scenario should be regarded as an anomaly of our modeling system and not a likely or expected outcome.

Despite a fairly stable harvest level during the projection period, the baseline scenario resulted in decreasing softwood timber prices due to projected increase in softwood inventory in this scenario (Fig. 5). In all three U.S. regions, the projected changes in softwood sawtimber prices in the alternative scenarios followed roughly the same trajectory as the baseline scenario but remained at slightly higher levels (Fig. 7), reflecting the effect of inward shift in supply curve due to reduction in available inventory due to set-asides. For example, in the baseline scenario, the overall price changes for softwood sawtimber during 2010–2060 were −0.79%/year, +0.19%/year, and +0.81%/year for the U.S. North, South, and West, respectively. Softwood sawtimber prices for the Carbon-5 case for the U.S. North and South were higher in 2060 than the base case by 10% and 7%, respectively. For the West, it was lower than the base case by 3%. Lower price impacts were observed for the other alternative scenarios. The relatively modest impacts on softwood timber price in all alternative scenarios were due to relatively less softwood inventory purchased for set-asides (because of higher expected present value of softwood timber harvest than their corresponding carbon offset values). By contrast, greater impact was observed in hardwood sawtimber inventory and price in all regions, especially in alternative scenario Carbon-5. The impact was extreme for the U.S. West. However, by the end of the projection, these extreme prices were stabilized as the timber supply remained fixed at a smaller level because of the depleted resource base (little available timber inventory).

The baseline hardwood sawtimber price changes in the U.S. North, South, and West during 2010–2060 were +0.21%/year, +0.15%/year, and +0.37%/year, respectively. Hardwood sawtimber prices for the Carbon-5 case for the U.S. North, South, and West were higher in 2060 than the base case by 100%, 62%, and 114%, respectively. The impact on non-sawtimber price of alternative scenarios was also similar to the sawtimber price (not reported here).

Thus, results of the region-wide economic analyses indicated a greater impact on hardwood timber inventory and timber price in all regions, primarily because of lower projected prices for hardwood timber during the initial years of the projection period. The resulting effect was that more hardwood timber inventory was set aside in early years, with less available inventory and timber supply in

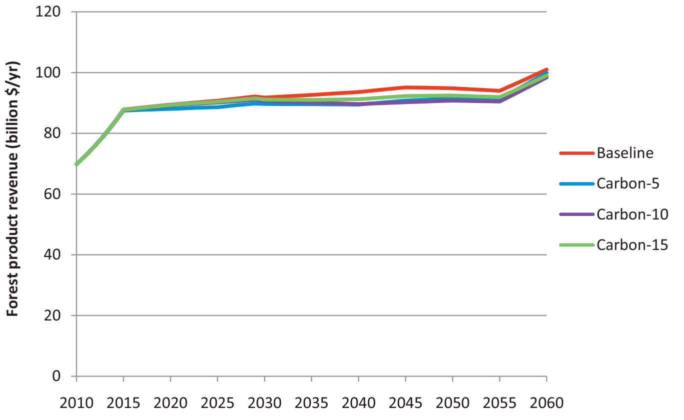

Fig. 8. Projected undiscounted annual primary forest product revenues (billion dollars) for the baseline and alternative carbon reserve scenarios, 2010–2060.

the subsequent years, leading to relatively higher price increases for hardwood timber relative to softwood timber. By contrast, with less softwood timber inventory set asides, the projected increases in softwood timber prices were relatively small. In addition, softwood timber prices were largely driven by projected softwood inventory in the South, where it was projected to increase even in all carbon reserve scenarios (not shown in figure). Even though area is set aside in the U.S. South the loss in available inventory is less than timber growth on available land which includes expansion in pine plantation area (21 million ha by 2060) Expanding inventory and falling prices in the South offsets the effect of reduced softwood inventory in the North and the West. This explains the declining softwood timber price (Fig. 7a–c) despite relatively stable total harvests in the alternative scenarios.

These findings suggest an important implication for carbon offset programs for the entire forest sector. The implication is that payments to forest landowners for carbon sequestration in timber set asides would lead to increased timber prices that would be passed on to consumers through increased product prices, impacting the cost and affordability of wood products. In addition, higher timber prices would affect cost competitiveness of U.S. forest product producers and negatively impact projected U.S. forest product production and net trade. For example, the average annual undiscounted revenue from primary forest products including lumber, panels, paper/paperboard, and wood fuel feedstock was projected to be $93.20 billion from 2010 to 2060 in the baseline scenario (measured in constant 2006 dollars). However, for alternative scenarios, increases in real timber prices due to set-asides and reduced timber harvests resulted in a net loss of primary forest product revenues. Relative to the baseline scenario, the average annual losses in primary forest product revenues, from 2010 to 2060, were $2.43 billion, $2.28 billion, and $1.37 billion for Carbon-5, Carbon-10, and Carbon-15 scenarios, respectively (measured in constant 2006 dollars). Fig. 8 shows these changes in average annual revenues for primary forest products for the baseline and alternative scenarios. The losses in forest product revenues are mainly attributable to lower net exports and reduced domestic production under the carbon offset scenarios as a result of higher domestic timber prices. Another likely economic response to increases in timber prices would be more investment in intensive forest management and/or new plantation establishment, which could have additional impacts on forest carbon stocks, although our analysis does not attempt to quantify that response.

Our study addressed also the issues of additionality, permanence, and leakage of carbon for our hypothetical forest carbon reserve scenarios. Additionality means that a climate change mitigation action specifically taken to increase carbon sequestration must result in additional carbon sequestration above the level of carbon sequestration that would occur anyway in a baseline scenario. We address the issue of additionality by counting the projected carbon stock increases on all timberland in our carbon reserve scenarios relative to the carbon stock projections of a fully developed "business-as-usual" baseline market scenario, which has no carbon reserve payments (e.g., Fig. 3).

The issue of permanence relates to the possibility that an accumulated forest carbon offset can be lost in a disturbance such as wildfire or timber harvest, or as a result of land use change. We ensured permanence of carbon storage on carbon reserve lands by excluding harvest for 100 years and by accounting for (deducting) an average rate of mortality that included the effects of fire and other natural disturbances, while we also accounted for projected losses of forest land to other land uses such as urban and developed land.

We also assessed the leakage that occurs because the setting aside of timberland in carbon reserves leads to increased harvest on other timberland, thus reducing carbon offset benefits of the timber set asides. In actual practice, the carbon offset payments to landowners would directly take into account such estimated leakage effects (as required in the CAR Forest Project Protocol, for example). However, in our analysis we did not pre-adjust the carbon reserve payments for the leakage effects, so that we could use the market model to estimate the leakage effects.

Our study has several limitations. This study did not take into account change in carbon stored in wood products made from wood harvests in the United States. If carbon accumulated in harvested wood products was included, the overall climate change mitigation benefit of the alternative scenarios would be slightly lower because of relatively lower harvest and lower forest product output in these scenarios relative to the baseline scenario. Similarly, our modeling framework was based on the assumption that once a tract of timberland is enrolled in the carbon reserve, it remains locked in the reserve for 100 years. However, in actual practice, some landowners might eventually find it attractive to breach their carbon contracts, paying any penalties, so they could sell timber at the higher timber prices resulting from reduced timber supply. Finally, the results do not account for the effects of projected climate change on timber growth and inventory, which was beyond the scope of our analysis.

Conclusions

We used the USFPM/GFPM market modeling system combined with a regional forest growth and inventory model and timberland allocation model to evaluate impacts of hypothetical carbon reserve scenarios on climate change mitigation (net carbon sequestration on timberland) and consequential impacts on forest products markets. Our analysis simulates competition that would occur hypothetically between billions of dollars of carbon payments to landowners for timber set asides and the demands of forest products for control and use of available timber resources. Results show how landowner decisions based on rational expectations would alter timberland area available for harvest, timber harvest level, timber inventory, change in timber prices and primary forest products revenues, and overall change in forest carbon (climate change mitigation benefit) under alternative carbon reserve scenarios. The evaluated alternative scenarios offer small to large climate change mitigation benefits depending on carbon price, carbon expenditure budget, and carbon leakage effects. Projected carbon storage leakage ranged from 71% to 88% of the purchased carbon accumulation on set aside lands. Under a fixed budget, lower carbon prices allow for more land to be set aside for the carbon reserve in early years of the projection, so long as the expected value of carbon offset payments is higher than the expected value of timber harvests. However, over the years, more timber set asides result in reduced availability of timber inventory for harvest, leading to higher stumpage prices, so late in the projection period the lower carbon price does not offer financial attractiveness over timber harvest and no new area would be set aside. This pattern of larger set asides early results in more carbon storage overall and less leakage than for cases that offer higher prices and lower storage early on. Under such a case, higher carbon price offers better financial attractiveness but less land would be enrolled in carbon reserves as the budget available for carbon purchase is fixed.

Among several alternative scenarios, with carbon purchase prices of $5, $10 and $15, and annual budget of $3 billion (in 2006 $), our economic analysis showed that a carbon price of $\$5/tCO_2e$ would provide the largest and most cost-effective climate change mitigation benefit during the next 50 years (135 $TgCO_2e$/year on average) with an average mitigation cost of $\$17.11/tCO_2e$ (after including the projected 71% leakage). However, the Carbon-5 scenario also induced large nationwide impacts on available timberland area, timber inventory, and timber prices (especially for hardwood timber), with likely negative social welfare consequences in forest sector employment and profitability, a topic not analyzed in detail in this study but an outcome that can be inferred from the large projected impacts on timber harvest, prices, and forest product revenues. Projected nationwide losses in forest product revenues ranged from $69 to $121 billion dollars cumulatively over the projection period from 2010 to 2060, mainly attributable to lower net exports and reduced domestic production with higher domestic timber prices. The study results can provide useful benchmark information to policy makers and other stakeholders interested in consequences of climate change mitigation through timber set aside.

The modeling framework described in this study was set up to analyze climate change mitigation costs and benefits of just one of the recognized major forest sector strategies to reduce GHG emissions – specifically decreased harvest intensity/avoided deforestation through purchase of timberland set asides. The modeling framework could be further adapted to assess forest sector outcomes and climate change mitigation costs and benefits of other forest sector mitigation strategies. For example, the carbon sequestration and forest sector impact of afforestation strategies could be analyzed by simulating rational decisions to increase forest area or to expand forest plantations in response to carbon payments, or there could be an assessment of the effect of payments that would alter management and increase forest growth rates. The effects of activities such as increased forest growth or increased forest thinning could be analyzed similarly by adjustment of timber supply and forest growth assumptions. We could also assess strategies related to increased carbon storage in forest products or decreasing emissions by substituting wood products for other products that generate more GHG emissions in manufacturing.

Acknowledgments

We acknowledge the assistance of Andrew D. Kramp (University of Wisconsin-Madison) who helped us in setting up the 2012 Baseline scenario in USFPM/GFPM. We thank two anonymous

Appendix A.

Tables A1 and A2

Table A1
Parameters used in timber growth and inventory models in Eq. (3).

Variable	Estimate[a]	Estimated 95% confidence limits	
		Lower	Upper
North, softwoods			
α	6.1323 (0.2314)***	5.6779	6.5867
γ	−0.2809 (0.0191)***	−0.3200	−0.2400
North, hardwoods			
α	23.2566 (1.4047)***	20.5001	26.0132
γ	−0.4648 (0.0152)***	−0.4986	−0.4390
South, softwoods[b]			
α	5.6224 (0.3274)***	4.9800	6.2649
α_1	22.8506 (2.8764)***	17.2060	28.4952
γ	−0.1453 (0.0220)***	−0.1885	−0.1021
South, hardwoods			
α	5.3815 (0.3932)***	5.0599	6.6031
γ	−0.1584(0.0171)***	−0.1920	−0.1248
West, softwoods			
α	9.3639 (0.5017)***	8.3763	10.3516
γ	−0.4097 (0.0265)***	−0.4619	−0.3574
West, hardwoods			
α	5.7107 (0.4185)***	4.8876	6.5337
γ	−0.1992 (0.0309)***	−0.2600	−0.1384

Source: Nepal et al., 2012a.

[a] Numbers in parentheses indicate approximate standard error.

[b] The model includes proportion of artificial regenerated area (proxy for pine plantation in the U.S. South) as an additional variable.

*** Statistically significant at 1% significance level.

Table A2
U.S. regional timber supply elasticities with respect to price used in this study.

Commodity	Elasticity of supply with respect to price		
	North	South	West
Timber products			
SW sawtimber	0.50	0.22	0.34
SW non-sawtimber	0.50	0.31	0.34
HW sawtimber	0.48	0.19	0.34
HW non-sawtimber	0.64	0.26	0.34

(Source: Ince et al., 2011a).

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