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ARTICLE

Projected US timber and primary forest product market impacts of climate change mitigation through timber set-asides

Prakash Nepal, Peter J. Ince, Kenneth E. Skog, and Sun J. Chang

Abstract: Whereas climate change mitigation involving payments to forest landowners for accumulating carbon on their land may increase carbon stored in forests, it will also affect timber supply and prices. This study estimated the effect on US timber and primary forest product markets of hypothetical timber set-aside scenarios where US forest landowners would be paid to forego timber harvests for 100 years to increase carbon storage on US timberland. The scenarios featured payments to landowners of $0 (business-as-usual (BAU)), $10, and $15 per each additional metric ton (t) of carbon dioxide equivalent (CO_2e) sequestered on the set-aside timberlands, with maximum annual expenditures of $3 billion. For the set-aside scenarios, reduction in timberland available for harvest resulted in increased timber prices and changes in US domestic production, consumption, net export, and timber market welfare. Economic analyses indicated that the scenario with more area set aside and the largest carbon mitigation benefit (lower carbon price, $10/t CO_2e) would result in the largest decrease in market welfare, suggesting that climate change mitigation policies and programs would need to consider such impacts when evaluating the costs and benefits of climate change mitigation strategies in the forest sector.

Résumé : Alors que la mesure d'atténuation des changements climatiques consistant à payer les propriétaires forestiers pour accumuler du carbone sur leurs terres peut augmenter la quantité de carbone emmagasiné dans les forêts, cette mesure aura aussi un effet sur le prix et l'approvisionnement en bois. Cette étude avait pour but d'évaluer l'effet, sur le bois produit aux États-Unis et sur les marchés de produits forestiers primaires, de scénarios hypothétiques de mise en réserve de terrains forestiers productifs en vertu desquels les propriétaires forestiers américains seraient payés pour renoncer à récolter du bois pendant 100 ans afin d'accroître le stockage de carbone sur les terrains forestiers aux États-Unis. Les scénarios comprenaient des paiements aux propriétaires de 0 (maintien du statu quo), 10 et 15 $ pour chaque tonne métrique (t) additionnelle d'équivalent dioxyde de carbone (CO_2e) séquestré sur les terrains forestiers mis en réserve, jusqu'à ce que la dépense annuelle atteigne un maximum de trois milliards de dollars. Dans le cas des scénarios de mise en réserve de terrains forestiers productifs, la perte de terrains forestiers disponibles pour l'exploitation a entraîné une augmentation des prix du bois et des changements dans la production domestique, la consommation, l'exportation nette et la santé des marchés du bois aux États-Unis. Les analyses économiques ont indiqué que le scénario qui comportait la plus grande superficie de terrains forestiers mis en réserve et le bénéfice d'atténuation du carbone le plus élevé (le prix du carbone le plus bas, 10 $/t CO_2e) entraînerait la plus forte détérioration de la santé des marchés, ce qui indique que les politiques et les programmes d'atténuation des changements climatiques devraient tenir compte de tels impacts lorsqu'il s'agit d'évaluer les coûts et bénéfices des stratégies d'atténuation des changements climatiques dans le secteur forestier. [Traduit par la Rédaction]

Introduction

Forests and wood products have important roles in climate change mitigation because trees capture carbon dioxide (CO_2), and carbon captured in trees can be stored for a long time in forests or long-lived products. Because of its large forest carbon stock (Heath et al. 2010; US EPA 2011) the United States has substantial potential for management changes that would contribute to climate change mitigation (Adams et al. 2011; Ryan et al. 2010). Currently, US demand for forestry-based carbon offsets is low, and carbon-dedicated forest management is not considered a viable option at prevailing US carbon prices (Latta et al. 2011; Nepal et al. 2012*a*; Ryan et al. 2010). A management shift to increased use of forests for climate change mitigation could have economic effects on the local, regional, and national economy through its effects on the conventional timber supply and forest product markets and trade. Understanding the potential economic effects on the US forest products sector of anticipated climate change policy will be important in evaluating the effectiveness of potential programs aimed at increasing forest carbon mitigation and in strategic planning within the forest products sector.

This study aims to evaluate the projected timber and primary forest product market impacts of hypothetical future payments to forest landowners for carbon accumulation on timberland that they voluntarily set aside as carbon reserves. The evaluation is performed by comparing market projections that include timber set-aside payments to a business-as-usual (BAU) projection without timber set-aside payments. Specific objectives are to project economic effects of the timber set-asides on (*i*) remaining timberland area available for harvest; (*ii*) timber inventory available for harvest; (*iii*) timber harvest quantity; (*iv*) timber stumpage price; (*v*) production, consumption, and net trade of timber and primary forest products; (*vi*) timber and primary forest product revenues; and (*vii*) consumer plus producer surplus (net market welfare) in timber and primary forest products markets. Estimates of potential changes in timber and forest product markets and their welfare impacts may help to provide policy guidance by providing

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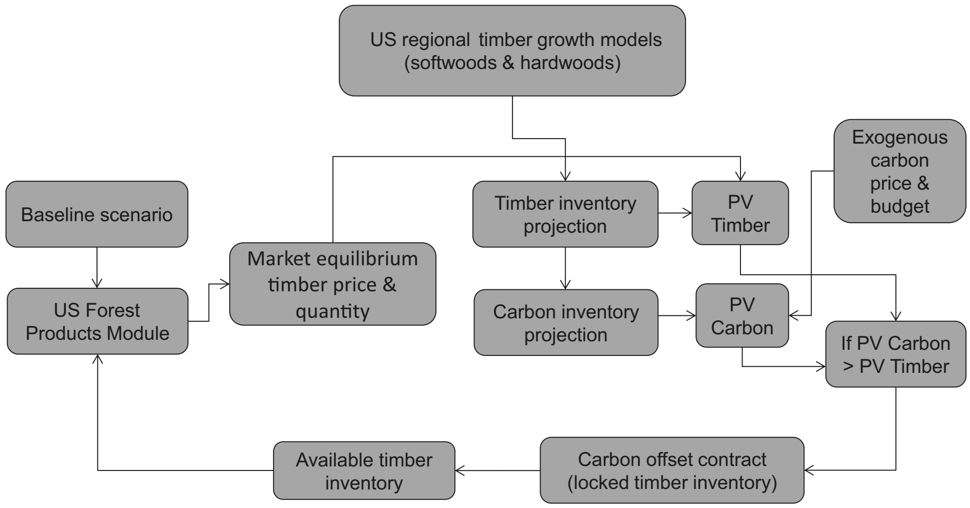
Fig. 1. Flow chart summarizing individual model components and their flow in evaluating timber and forest product market implications of carbon payment involving timber set aside in the United States.



information on the costs and benefits of climate change mitigation strategies in the forest sector.

Previous studies used forest sector models to understand impacts of climate change policies including carbon sequestration and bioenergy expansions on the forest products sector. The most recent examples include the use of an intertemporal optimization model of the US forest and agriculture sectors (FASOM GHG, e.g., Adams et al. 2011; Baker et al. 2010; Latta et al. 2011), a global model of forests and land use (Sohngen and Mendelsohn 2003), and the Sub Regional Timber Supply Model (SRTS, e.g., Abt et al. 2012). Another forest sector model that has been updated to analyze carbon sequestration and bioenergy policy is the US Forest Products Module within the Global Forest Product Model (USFPM/GFPM; Ince et al. 2011*a*, 2011*b*; Nepal et al. 2012*b*, 2012*c*). The general finding of these studies was that the implementation of climate change mitigation policy would impact forest sector markets through reduction in timber supply, higher timber prices, reduced forest product output, higher product prices, and increased imports. The general approach in many studies is to simulate competition between traditional and alternative use of forests for climate change mitigation, and allow the model to determine market equilibrium quantity and prices for timber products and forest carbon accumulation given a series of exogenously specified carbon prices. Carbon supply could be estimated for each of the series of exogenously specified carbon prices. These analyses are a market-based approach where demand for carbon offset is determined endogenously and there is no limit on expenditure for carbon offset purchases. However, an expenditure cap may be relevant for a government program and there is limited funding to provide payments for forest carbon accumulation. Although our analysis is similar to previous modeling in allowing competition between traditional timber markets versus a market for timber set-asides to increase carbon sequestration, it focuses on evaluating a program-based approach where payments are provided up to an expenditure limit each year (details are in the Methods section). Our study also differs in that it has certain guidelines for purchasing carbon accumulation that are similar to those in the Climate Action Reserve (CAR) forest project protocol (CAR 2010).

The type of policy we envision is similar to the US federal Conservation Reserve Program (CRP; Babcock et al. 1996; Osborn et al. 1995; Plantinga et al. 2001; Reichelderfer and Boggess 1988) that was applied during the 1980s and 1990s, where eligible farmers could submit bids to enroll their erodible farmland for 10–15 year set-aside contracts. 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 the annual rent 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 assume that a rational landowner will enroll timberland for timber set-aside contracts if the expected present value of the carbon payments would exceed the expected present value of timber revenue. For our analysis, we pose possible price levels the government may pay for carbon accumulation. The government would accept bids for 100 years' worth of carbon accumulation on given land areas at the specified carbon price until the expenditure cap (e.g., $3 billion) is exhausted for a particular year. The $3 billion could be placed in a fund and used to make payments for carbon accumulation over 100 years on the land that is set aside in the current year. It is assumed that the fund could provide a constant real dollar payment per ton of carbon accumulated over the 100 years. Because there is an annual expenditure cap, a higher carbon price would result in less timberland area enrolled in a given year (more quickly using the budget). We compare our results with past studies and explain differences and similarities.

Methods

Assessment of the economic effects of hypothetical timber set-asides on US timber and forest product markets required development of a BAU scenario and alternative set-aside scenarios, and the use of forest sector models to simulate the competition for use of forest resources to produce timber for harvest or carbon reserves (long-term timber set-aside). The study used four models including (1) the US regional timber growth and inventory projection model (Nepal et al. 2012*b*) for projection of timber growth and inventory, (2) the USFPM/GFPM (Buongiorno et al. 2003; Ince et al. 2011*a*, 2011*b*) for projection of equilibrium annual timber harvest quantities and prices, (3) a timberland allocation model to determine the area of timberland set-aside as carbon reserve at specified carbon prices, and (4) a US regional tree biomass carbon stock projection model (Nepal et al. 2012*c*) for projecting carbon accumulation on US timberland (Fig. 1).

BAU and alternative carbon payment scenarios involving timber set-asides

The BAU scenario includes the effects of the recent 2008–2009 global economic recession and decreased US housing demand. The BAU scenario incorporated (*i*) the projections of US and global GDP, population and currency exchange rates, from the USDA Economic Research Service (ERS) global macro outlook (USDA ERS 2012) from 2006–2030 extended to 2060 and (*ii*) a projection of US housing starts (based on convergence to the long-run trend line similar to industry forecasts) from 2010 to 2060. US housing starts were assumed to rebound from a recent low level to a long-term logarithmic trend line amount of 1.1 million by 2015.

The two alternative scenarios assumed an expenditure (in constant 2006 dollars) of up to \$3 billion each year for carbon reserves (up to \$1 billion for each US region), with the scenarios using either \$10 or \$15 per metric ton (t) of carbon dioxide equivalent (CO_2e), "Carbon-10," and "Carbon-15," respectively. The \$3 billion annual budget constraint adopted for analytical purposes does not relate to any proposed government program or policy. To provide a perspective, the assumed expenditure level of \$3 billion could likely generate about 30% or 20% of the allowed domestic offset credits in the recently debated climate bill if carbon prices were \$10 or \$15/t CO_2e, respectively. The climate bill, which was approved by the US House of Representatives, but not passed by the US Senate, would have allowed US capped entities to use up to two billion tons of emission offset credits annually, half of the which (1 billion t) would have to come from domestic offset projects (US EPA 2009).

Similar to the CRP mechanism, this analysis assumes that forest landowners will enroll land in carbon reserves and receive government payments for carbon accumulation if they perceive that the expected present value of carbon payment for a given carbon price is higher than the expected present value of timber harvest. Once the government accepts offers to enroll the timberland in the carbon reserve contract, landowners would maintain the contract for 100 years by withholding timber harvests. The government accepts enrollees until the budget is exhausted and will allocate the available annual budget (\$3 billion) in a trust fund to ensure annual payments to landowners for the duration of 100 years at the given carbon price levels (\$10 or \$15/t CO_2e). If more landowners are willing to participate than the annual budget can accommodate, the government could implement a lottery system to select landowners from among those willing to participate in the set-aside program. Although the selected carbon price levels are consistent in magnitude with forest carbon economics literature (e.g., Adams et al. 2011; Latta et al. 2011; US EPA 2009), they are hypothetical payments to forest landowners. The assumed budget of \$3 billion per year would allow for less timberland area to be set aside at the higher carbon price (\$15) than what would be set aside at the lower carbon price (\$10), because the budget will stretch farther and achieve more timber set-asides at a lower carbon price so long as that price would still be attractive to landowners.

Projecting timber growth and inventory

An exogenous spreadsheet model was linked to the USFPM/GFPM market model to project timber growth and inventory on US timberland for three regions (North, South, and West) and two species group categories (softwoods and hardwoods). The timber inventory available for harvest in a given year was projected using the following equation:

$$\text{[1]} \qquad \mathrm{AI}_t = \mathrm{AI}_{t-1} + \mathrm{GAI}_t - H_t - \mathrm{SA}_t$$

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 the volume of inventory set aside because of carbon payments that becomes unavailable for harvest. Inventory in the set-aside timberland (unavailable for harvest) was projected using the following equation:

$$\text{[2]} \qquad \mathrm{UI}_t = \mathrm{UI}_{t-1} + \mathrm{GUI}_t + \mathrm{SA}_t$$

where UI_t is the current year total inventory that is unavailable for harvest, UI_{t-1} is last year's unavailable inventory, and GUI_t is the annual timber growth for the set-aside unavailable inventory.

Annual timber growth net of mortality was projected as a nonlinear function of average timber growing-stock density (timber inventory divided by timberland area) for three US regions (North, South, and West) and two species groups (softwoods and hardwoods). Details on these models are in Nepal et al. (2012*b*). Projected changes in total US regional timberland area were exogenously specified and taken from projections for the A1B scenario from the Resources Planning Act (RPA) forest assessment (USDA Forest Service 2012), which indicated gradual declines in timberland areas in all US regions, primarily because of urban encroachment and land development.

Projecting market equilibrium timber harvest quantity and price

The market equilibrium regional timber harvest quantities and timber stumpage prices were projected for each of the three scenarios using the USFPM/GFPM timber market model (Ince et al. 2011*a*, 2011*b*), with timber inventory and supply adjusted for timberland set-aside in carbon reserves. The USFPM is a submodel of the US forest sector and regional US timber markets that operates within the global partial market equilibrium framework of the GFPM (Buongiorno et al. 2003). The market equilibrium timber harvest quantities and prices for a given year are estimated in the USFPM/GFPM by maximizing total producer and consumer surplus of the entire forest sector, based on Samuelson's optimization approach to regional market modeling (Buongiorno et al. 2003; Ince et al. 2011*a*, 2011*b*). The USFPM/GFPM, like most similar long-range projection models, operates with constant real dollar values. Thus, the changes in timber prices are real prices, ignoring inflation. Real timber prices change endogenously in the model over time in response to projected changes in timber demands and timber supply (influenced by set-asides for the carbon reserve).

Calculating timberland area set aside as carbon reserve

A spreadsheet-based timberland allocation model was used to simulate the choice US timberland owners have each year to accept carbon payments and withhold timber harvest for 100 years or to retain timber harvest rights. Our analysis has certain requirements for landowner's participation in the carbon reserve program that are similar to those of the CAR Forest Project Protocol (CAR 2010). Each has a commitment period (100 years) and allows credits for carbon additions for land where stocking density is at or above a regional average. The CAR program allows landowners to harvest after enrolling with appropriate reductions or repayment of carbon credits, whereas our analysis does not allow for harvest because our focus is on assessing the effect of 100 year timber set-asides.

The choice between the two options (maintain harvest rights or set aside timber and forego harvest) was modeled on the basis of landowners' rational expectations about potential revenue from timber harvest versus potential revenue from carbon accumulation (Sohngen and Brown 2008; Van Deusen 2010). In theory, landowners would enroll if they believe that the discounted value of the carbon payments is higher than the discounted value of future timber harvests. The timberland set-aside analysis computes the possible carbon accumulation over 100 years using projected timber growth using regional average growing-stock densities for land not yet set aside. The use of average regional stock densities approximates the requirement of the CAR forest project protocol (CAR 2010), where credit for carbon accumulation is only given when initial carbon stocks are above "Common Practice," defined as the average aboveground live carbon stocks on similar lands within the project's assessment area.

For a given year, we compared the present values of timber harvests and expected carbon payments by region for a 100 year period using a discount rate of 5% with all values expressed in 2006 US dollars. We used two potential payment levels ($10 and $15/t CO_2e). In an actual program it is likely that landowners would place bids for carbon payments so the expected value of carbon revenues would exceed the expected value of timber revenue. The government would accept bids until the budget ($3 billion) is exhausted. The government would set aside funds that could make payments (that include increases for inflation) for expected carbon accumulation over 100 years. Once the landowner is enrolled, he (or) she is ensured payment for carbon accumulation as it occurs over 100 years. Similar analysis is conducted for each budget year through 2060 with the last years planning period going from 2060 to 2160. The carbon prices are specified in 2006 dollars but would increase at the rate of inflation. The models make projections using real dollars.

In summary, the interlinked models are estimating, by successive approximation through iteration, the yearly decisions of all landowners over the projection period about participation in carbon set-asides and harvest level from available timberland. Harvest level is influenced by use of the set aside option in a given run of the model. The use of set-asides is determined by successive approximation through iteration as follows. An initial estimate of set-asides and land available for harvest over the projection period is made using the choice model and BAU scenario projections of timber prices. This projection of available inventory is used to shift timber supply in the next iteration of USFPM/GFPM, which determines revised harvest levels and timber price levels over time. The harvest levels and timber prices from USFPM/GFPM are used by the choice model to generate a revised estimate of inventory that is set aside, which in turn is used by USFPM to shift timber supply curves and generate a revised estimate of harvest. The iterations continue until the two models converge on a matching projection of harvest levels and timberland area set aside over time. The converged projection is one where harvest decisions have been influenced by the level of set aside land and the decision about the level of set-aside land has been influenced by harvest level and associated timber price. This type of iterative procedure has been used in other forest sector models where submodels exchange projections and converge to stable solutions (e.g., Haynes et al 2006).

Estimating and projecting tree biomass carbon

The projected increase in timber inventories in the BAU and alternative scenarios were used to estimate tree biomass carbon accumulation on US timberland for the corresponding scenarios. The total tree biomass carbon includes 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 does not include foliage biomass (Miles 2012). The projected timber inventory was converted to total tree biomass mass using regional average ratios of total dry mass biomass to timber growing-stock volume (Nepal et al. 2012*c*), using data from the FIA database on dry mass of tree biomass and growing-stock inventory volume on US timberland (Miles 2012). The estimated dry mass of biomass was multiplied by 0.5 to estimate carbon mass and then converted to the CO_2 equivalent based on molecular weight (US EPA 2011).

Estimating timber and primary forest product markets welfare impacts of timber set-asides

Finally, we describe our approach to estimating consumer plus producer surplus (net market welfare) impacts of alternative forest carbon payment scenarios involving timber set-asides on timber and primary forest products markets. Consumer surplus (CS) was estimated by integrating the area under the demand curve between baseline price (P_0) and new price (P_1) as follows:

$$[3] \qquad \Delta \text{ in CS} = \int_{p0}^{p1} AP^{-a}\mathrm{d}P$$

$$[4] \qquad \rightarrow \Delta \text{ in CS} = \frac{Q_0}{p_0^{-a}}\left(\frac{p^{1-a}}{1-a}\right)\Bigg|_{p_0}^{p_1}$$

where $Q_D = AP^{-a}$ is the demand function, $P = \frac{Q_0}{p_0^{-a}}$ is the inverse demand function, Q_0 and P_0 are equilibrium demand quantity and price in the BAU scenario, P_1 is the equilibrium price in alternative scenario, α is the elasticity of product (timber or primary forest product) demand with respect to its own price (Table 1), and A is a constant. Note that timber does not have a specified elasticity of demand in the USFPM/GFPM, as the demands for timber are derived from demands for primary forest products based on the estimated input–output coefficients (timber inputs to primary forest products). For the purpose of estimating timber consumer surplus, we assumed a proxy demand elasticity of 0.5 for all timber products in all regions (Table 1).

Because the shifts in timber and primary forest product supply curves are different among the scenarios, it requires separate estimates of total producer surplus in the BAU as well as in the alternative scenarios. The change in producer surplus is then estimated by taking the difference in values between two scenarios. Estimating producer surplus also requires an estimate of the intercept of the supply curve. However, because USFPM/GFPM uses only segments of the demand and supply curves around the equilibrium point (Buongiorno et al. 2003), we can only approximate the intercept of the supply curve. For simplicity, we assumed that the supply curve has a zero intercept. This assumption allows for approximate estimation of producer surplus for each scenario. Producer surplus (PS) for a given scenario is the area between equilibrium price (P^*) and supply curve between $Q = 0$ and $Q = Q^*$ (equilibrium quantity). Mathematically,

$$[5] \qquad \text{PS} = \int_0^{Q^*}\left[P^* - \left(\frac{Q_S}{B}\right)^{\frac{1}{\beta}}\right]\mathrm{d}Q$$

$$[6] \qquad \rightarrow \text{PS} = Q_S\left[P^* - \frac{\beta\left(\frac{Q_S}{B}\right)^{\frac{1}{\beta}}}{1+\beta}\right]\Bigg|_{Q}^{Q^*}$$

where $Q_S = BP^{\beta}$ is the supply function and $P = \left(\frac{Q_S}{B}\right)^{\frac{1}{\beta}}$ is the inverse supply function, β is the elasticity of the product (timber or primary forest product) supply with respect to price (Table 1), and B is a constant. Substituting $\frac{Q^*}{(p^*)\beta}$ for B in eq. [4] and simplifying, we obtain

$$[7] \qquad \text{PS} = Q^*P^*\left(\frac{1}{1+\beta}\right)$$

Primary forest products do not have elasticity of supply in the USFPM/GFPM model because the supply of primary forest products is

Table 1. Assumed demand and supply elasticities with respect to price for timber and forest products used in this study for estimation of welfare impacts of projected shifts in demand and supply.

	Elasticity of supply with respect to price				Elasticity of demand with respect to price			
Commodity	North	South	West	US	North	South	West	US
Timber products								
SW sawtimber	0.50	0.22	0.34		–0.50*	–0.50*	–0.50*	
SW nonsawtimber	0.50	0.31	0.34		–0.50*	–0.50*	–0.50*	
HW sawtimber	0.48	0.19	0.34		–0.50*	–0.50*	–0.50*	
HW nonsawtimber	0.64	0.26	0.34		–0.50*	–0.50*	–0.50*	
Primary forest products								
SW lumber				0.50†				–0.14
HW lumber				0.50†				–0.10
SW veneer/plywood				0.50†				–0.65
HW veneer/plywood				0.50†				–0.28
OSB				0.50†				–0.65
Industrial particleboard				0.50†				–0.28
Fiberboard				0.50†				0.00
Newsprint				0.50†				–0.46
Printing and writing paper				0.50†				–0.68
Other paper and paperboard				0.50†				–0.42

Note: OSB, oriented strand board; SW, softwood; HW, hardwood.

*Timber does not have a specified elasticity of demand in the US forest products module within the Global forest product model (USFPM/GFPM), as the demands for timber in the model are derived from demands for primary forest products based on the estimated input–output coefficients (sawtimber and nonsawtimber supplies are converted into timber product outputs such as sawlogs or veneer logs and pulpwood that are inputs to primary forest products). For the purpose of estimating the timber consumer surplus, we assumed a proxy demand elasticity of 0.5 for sawtimber and nonsawtimber in all regions.

†Primary forest products do not have specified elasticity of supply in the USFPM/GFPM model, since the supply of primary forest products are derived from the estimated input–output coefficients (timber and nonsawtimber inputs to primary forest products), timber prices, and other costs of manufacturing primary forest products. For the purpose of estimating primary forest products producer surplus, we assumed a proxy supply elasticity of 0.5 for all primary forest products.

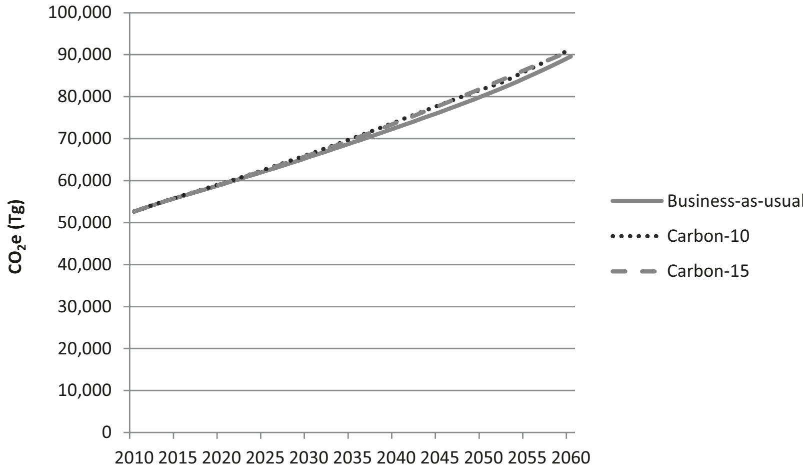
derived using estimated input–output coefficients (timber and nonsawtimber inputs to primary forest products), timber prices, and other costs of manufacturing primary forest products. To approximate the primary forest product supply curves and their producer surpluses, we assumed a proxy supply elasticity of 0.5 for all 10 primary forest products (Table 1). This approach to estimating primary forest product producer surplus could involve double counting because the primary forest product producers are also the timber consumers. Just et al. (2004) showed that when there is a close relationship between the product producer and factor consumer surpluses, there is a risk of double counting. We therefore acknowledge that our estimate for the primary forest product producer surplus may have been overestimated because of the estimation of producer surplus in both the product and factor markets.

Results and discussion

Impacts of timber set-asides on carbon accumulation

The timber set-aside scenarios, Carbon-10 and Carbon-15, featuring two carbon price levels ($10 and $15/t CO_2e) along with fixed annual carbon expenditures ($3 billion/year) were projected to result in a modest increase in carbon accumulation compared to the BAU scenario over the projection period 2010–2060 (Fig. 2). For example, the cumulative carbon additions on US timberland between 2006 and 2060 for the BAU scenario were projected to be 89 559 Tg CO_2e. The Carbon-10 scenario accumulated 1743 Tg CO_2e more, and the Carbon-15 scenario accumulated 1513 Tg CO_2e more by 2060. The relatively modest boost in carbon accumulation (about 2%) was due to leakage of harvest that would have occurred on set-aside lands to other lands that remain available for harvest. In our analysis, estimated leakage (estimated as one minus the ratio of the given carbon price to the actual per unit cost of carbon) ranged from 88% (for a carbon price of $10/t CO_2e) to 85% (for a carbon price of $15/t CO_2e). This translates the actual cost of carbon sequestration to $83/t CO_2e and $101/t CO_2e over the projection period for the Carbon-10 and Carbon-15 scenarios, respectively. Our leakage estimate is similar to or somewhat higher than other studies. Murray et al. (2004) estimated up to 68% leakage from a hypothetical forest set aside program in the southcentral US and up to 93% leakage from hypothetical avoided deforestation project in the Lake State region in the US, whereas Wear and Murray's (2004) study of the effects of reductions in federal timber sales in the western US showed a leakage of 58% for the US and 84% for North America. Similarly, a carbon mitigation and cost analysis by Sohngen and Brown (2008) for 12 southern states estimated that set-asides could be viable only when the carbon price exceeds $40/$CO_2$e, and it could be as high as $55/t CO_2e for productive timberlands. Our estimates for the entire US indicated the set-aside costs of $83/t CO_2e and $101/t CO_2e for the evaluated carbon prices of $10/t CO_2e and $15/t CO_2e, respectively, because of our high estimated leakage rates. The leakage estimates from our analysis could be lower if we knew the minimum carbon price needed each year to induce landowners to participate in the carbon offset program, but our analysis assumed fixed carbon prices and a fixed program budget. On the other hand, Latta et al. (2011) compared the effects of mandatory participation with voluntary participation in a hypothetical carbon offset sales program in the US with an unlimited budget. For a voluntary system (which is similar to our analysis), they estimated that payments of $45/t CO_2e would yield about 100 Tg CO_2e/year from management of existing forests during their 50 year projection. We estimated an average mitigation benefit of 35 and 30 Tg CO_2e/year for an average cost of $83/t CO_2e and $101/t CO_2e, respectively, during 2010–2060. Thus, our estimates of mitigation costs are somewhat higher per unit of carbon, with higher leakage. Our study differs from that of Latta et al. (2011) in that their model considered land use competition between forest and agriculture (our study covers the forest sector only), they did not have a fixed budget, and they allowed timber harvest on contracted land if the landowner paid a penalty. The differences in our results with other studies can be

Fig. 2. Cumulative total tree biomass carbon accumulation (Tg CO_2e) on US timberland under business-as-usual and alternative carbon payment scenarios, 2010–2060.



attributed to differences in carbon budget assumptions and model structure (different responsiveness of domestic and foreign timber suppliers to timber price change and responsiveness of consumers to changes in product prices), endogenous land use competition between forestry and agriculture (our study used exogenous land use projection), and the assumption about timber harvest on contracted land (our study assumed no harvest).

Impacts of timber set-asides on timber and primary forest product markets

Direct payments to forest landowners for timber set-asides substantially reduced the projected timberland area and timber inventory available for timber harvests. Between 60 and 49 million ha of US timberland area would be set aside for a net carbon sequestration cost of \$83/t CO_2e and \$101/t CO_2e by 2060 in the Carbon-10, and Carbon-15 scenarios, respectively (Figs. 3 and 4). These numbers represent 31% and 25% of the 193 million ha of US timberland area available in the BAU scenario in 2060. Our estimates for the area of timberland enrolled in set-asides is much higher than Sohngen and Brown (2008)'s estimate, which indicated that about 1 million ha of timberland area would be set aside for a cost of \$55/t CO_2e in the southeastern US, but it is close to an estimate by Latta et al. (2011), who reported that about half of the private timberland area or one-third of all timberland would be enrolled in voluntary carbon offsets and sales programs at a cost of \$30/t CO_2e. The reduction in overall timberland area coupled with timber set-asides and a higher harvest-to-growth ratio on the available timberland (than the BAU case) led to large projected reductions in timber inventory available for harvest in the alternative scenarios (Fig. 5). Over the 50 year period, available timber inventory would be decreased by more than half (25 billion m^3 or 55%) in the Carbon-10 alternative scenario and by just less than half (21 billion m^3 or 45%) in the Carbon-15 alternative scenario, relative to the available inventory in the BAU scenario (46 billion m^3).

The cumulative timber harvest from US timberlands (Fig. 6) in the Carbon-10 and Carbon-15 scenarios was projected to be reduced by 3 billion m^3 (10%) and 2 billion m^3 (7%) during 2010–2060, relative to the cumulative harvest for the BAU scenario (29 billion m^3). Adams et al. (2011) reported that carbon pricing at \$30/t CO_2e would reduce US softwood harvests up to 6% per year during 2010–2060, a projected harvest reduction lower than ours even though they used a higher carbon price. Again, the reason for the differences could be differences in model structure, carbon budget, and carbon market assumptions, and consideration of land use competition between agriculture and forestry.

Stumpage prices increased for both sawtimber and nonsawtimber in both softwood and hardwood species groups because of the reduction in available timber inventory resulting from timber set-asides (Fig. 7). By 2060, even with timber set-asides, timber prices converge close to the BAU price levels except for hardwood nonsawtimber, where prices were notably higher than for the BAU scenario. For hardwood nonsawtimber, the stumpage price was up to 50% higher than the BAU price for the Carbon-10 scenario and up to 37% higher than the BAU price for the Carbon-15 scenario by 2060. The price levels for other products in 2060 (hardwood sawtimber, softwood sawtimber, and softwood nonsawtimber) were up to 7% higher in price than the BAU price. However, the timber prices in the alternative scenarios were higher for all products during the period 2020–2050, after which the carbon payments for timber set-asides were not sufficiently attractive and no new area was set aside. This is similar to the result from Latta et al. (2011) and Adams et al. (2011) who reported that total harvests and product prices would converge to BAU levels in the projection because of lower marginal returns from carbon payments, declining rate of carbon sequestration, and increased harvest to take advantage of higher timber prices.

The projected increases in timber prices owing to timber set-asides had a substantial effect on primary forest products production, consumption, net trade, and net market welfare. The Carbon-10 and Carbon-15 scenarios resulted in 8% and 5% lower cumulative revenue, respectively, from timber harvest by 2060 relative to the BAU scenario (\$677 billion of cumulative stumpage revenue by 2060). The cumulative revenue generated from the output of primary forest products including lumber, structural and nonstructural panels, and paper and (or) paperboard was reduced by \$114 billion and \$69 billion in the Carbon-10 and Carbon-15 scenarios, respectively, by 2060, relative to the cumulative revenue of \$5006 billion in the BAU scenario. These losses in primary forest product revenues are mainly due to reduced domestic production and lower net exports caused by higher domestic timber prices. For example, relative to the BAU scenario, US production of lumber declined at 13 and 7 million m^3/year on average in Carbon-10 and Carbon-15 scenarios, respectively, during 2010–2060. Similarly, the average production of paper declined about 1 million t/year for both Carbon-10 and Carbon-15 scenarios during 2010–2060.

The increased timber prices owing to timber set-asides had a negligible effect on projected US consumption of primary forest

Fig. 3. Cumulative set-aside timberland area (million ha) and cumulative costs (billions of dollars) under alternative carbon payment scenarios, 2010–2060.

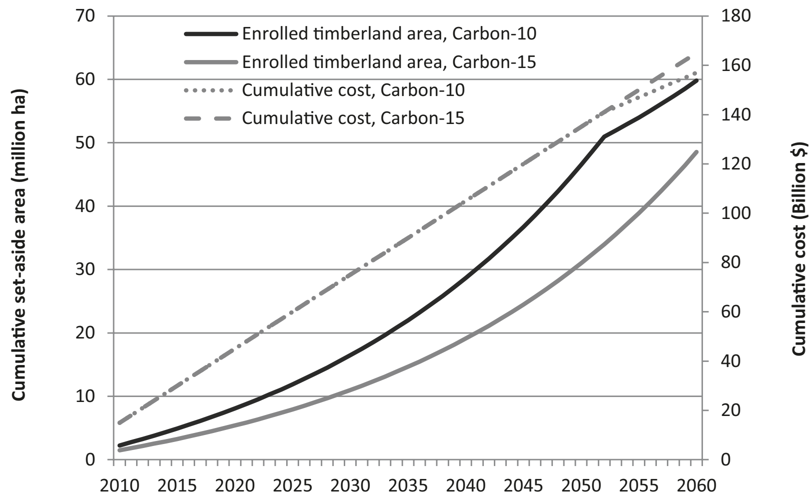


Fig. 4. Available US timberland area (million ha available for timber harvest) under business-as-usual and alternative carbon payment scenarios, 2010–2060.

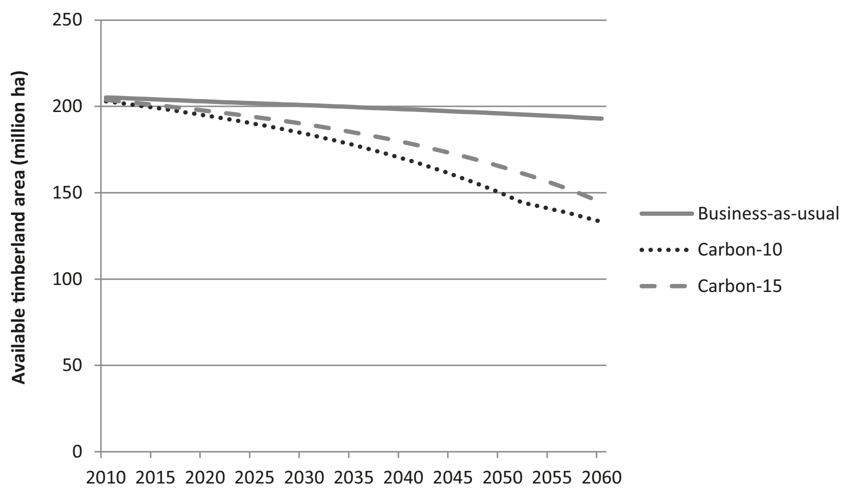


Fig. 5. Available timber inventory (billion m^3) for harvest on US timberland under business-as-usual and alternative carbon payment scenarios, 2010–2060.

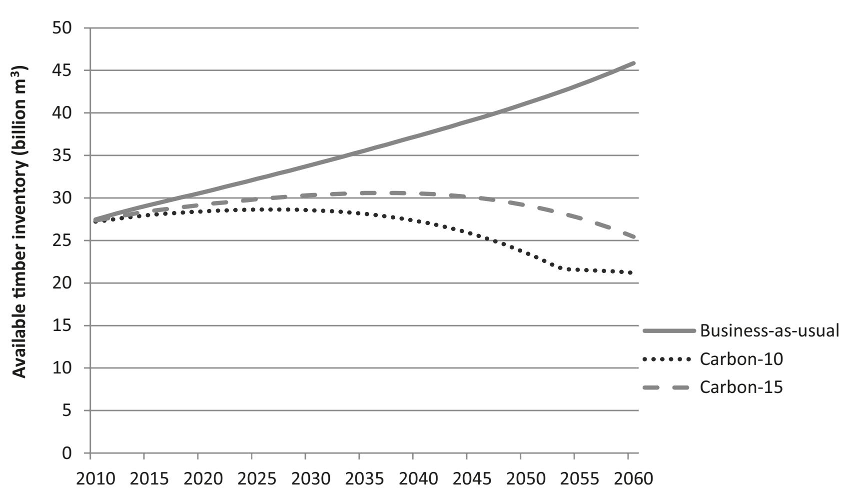


Fig. 6. Total timber harvests (million m³) from US timberland under business-as-usual and alternative carbon payment scenarios, 2010–2060.

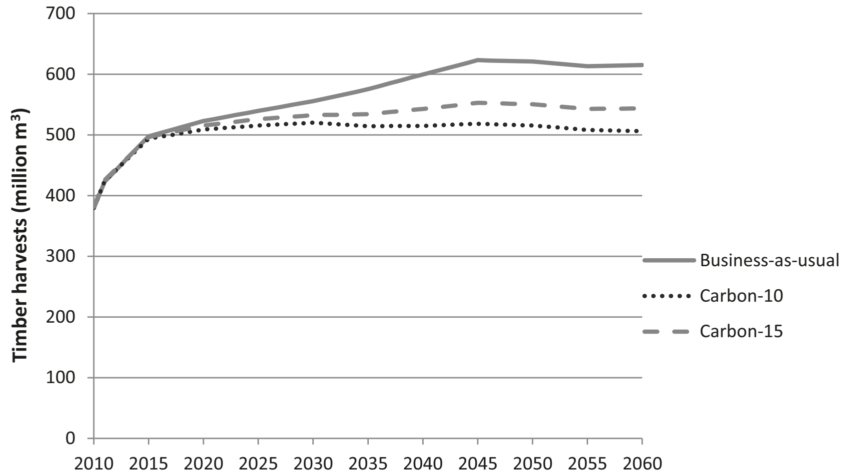
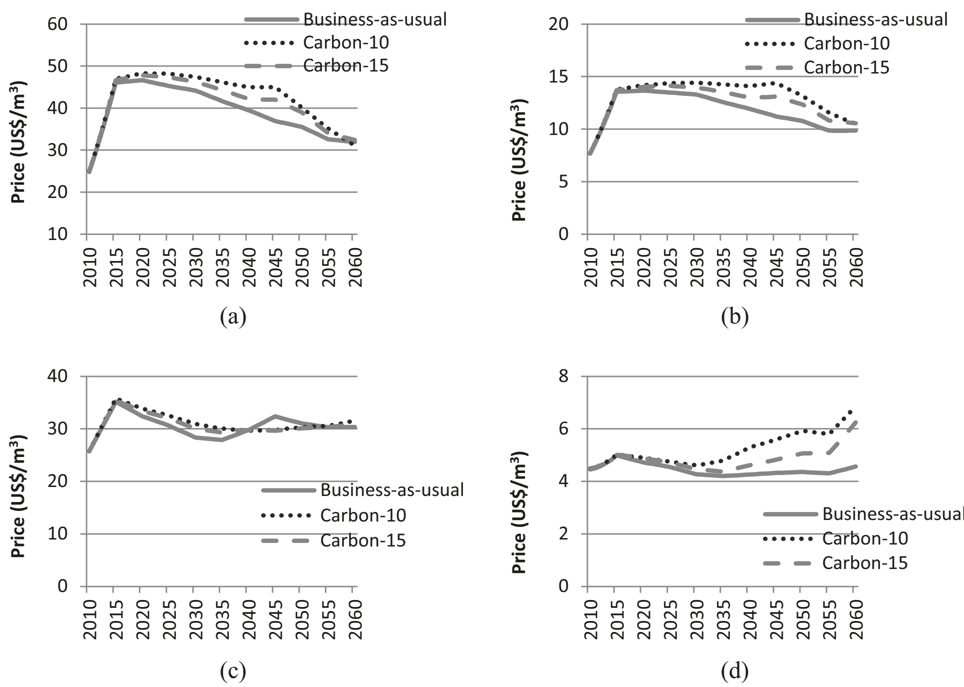


Fig. 7. Projected weighted average US stumpage prices (US$/m³) for the business-as-usual and alternative carbon payment scenarios, 2010–2060 for (*a*) softwood sawtimber, (*b*) softwoods nonsawtimber, (*c*) hardwood sawtimber, and (*d*) hardwood nonsawtimber.



products because of relatively inelastic product demands. As US prices for timber and wood products increased under the timber set-aside scenarios, US imports were projected to increase and net exports to decrease. Figures 8 and 9 show the substantial cumulative loss in producer surplus, consumer surplus, and net market welfare in US timber and primary forest products markets as a result of the hypothetical carbon payment for timber set-asides relative to the BAU scenario during 2010–2060, although producer surplus per hectare of available timberland area was higher for landowners retaining harvest rights. The projected cumulative effect on primary forest product producer surplus (Figs. 8*a* and 9*a*) ranged from –\$20 to –\$30 billion and from –\$52 to –\$93 billion by 2060, respectively, with a larger reduction for the lower carbon price (\$10/t CO_2e) scenario because more timberland area would be placed in carbon reserves over time (Fig. 3). These cumulative producer welfare losses do not include gains in welfare for forest landowners who receive timber set-aside payments nor do they include welfare gains of foreign producers who export more wood products to the US. An estimate of change in welfare for landowners receiving timber set-aside payments requires the estimate of a carbon supply curve, which was not possible to derive in our model because of the constrained carbon reserve budget. Nevertheless, a rough estimate could be the projected payments to those landowners for carbon additions (timber growth on set-aside land times carbon payment per ton) minus their loss of timber revenues for the set-aside payments. Cumulative expenditure for timber set-asides by 2060 was \$157 billion and \$165 billion for Carbon-10 and Carbon-15 scenarios, respectively. The loss in cumulative timber revenue was \$51 and \$34 billion, respectively. Thus, the approximate gain in welfare to forest landowners who received set-aside payments was \$106 billion for the Carbon-10 scenario and \$131 billion for the Carbon-15 scenario.

The market welfare for consumers of timber and primary forest products was also decreased by higher stumpage prices. The cumulative losses in consumer surplus for timber and primary forest products were –\$28 and –\$19 billion for a price of \$15/t CO_2e

Fig. 8. Projected cumulative changes in (*a*) timber producer (landowners retaining harvest right) surplus, (*b*) timber consumer (primary forest products industry) surplus, and (*c*) net timber market welfare (sum of changes in timber producer and timber consumer surplus), in billions of dollars, for the alternative carbon payment scenarios, 2010–2060. Note that this market welfare does not include the direct carbon payments (up to $3 billion/year paid for additional carbon in set-asides), which goes exclusively to those forest landowners who elect to receive timber set-aside payments.

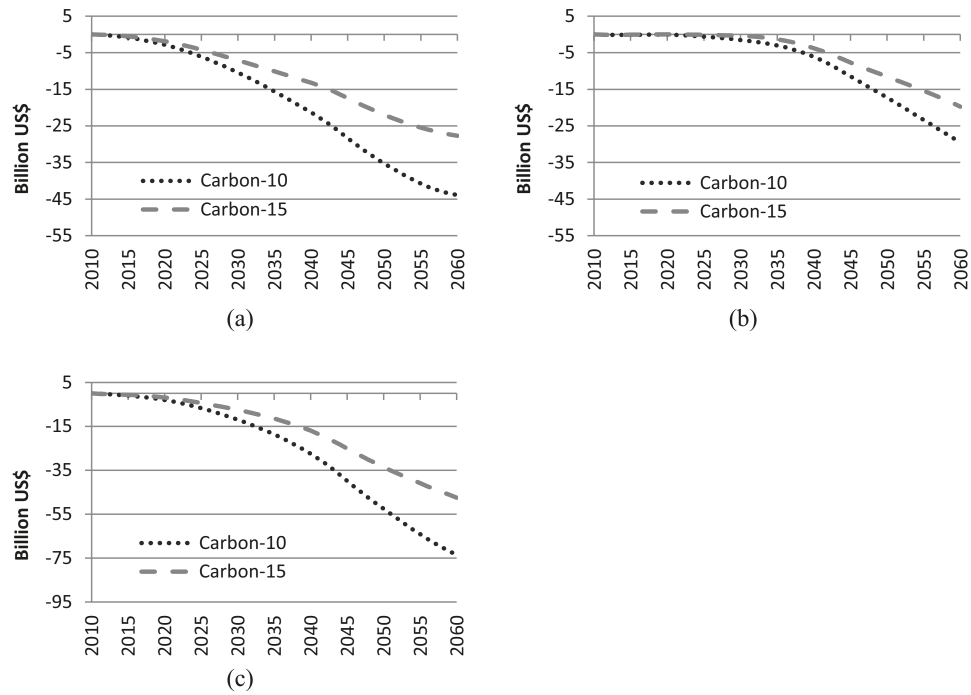
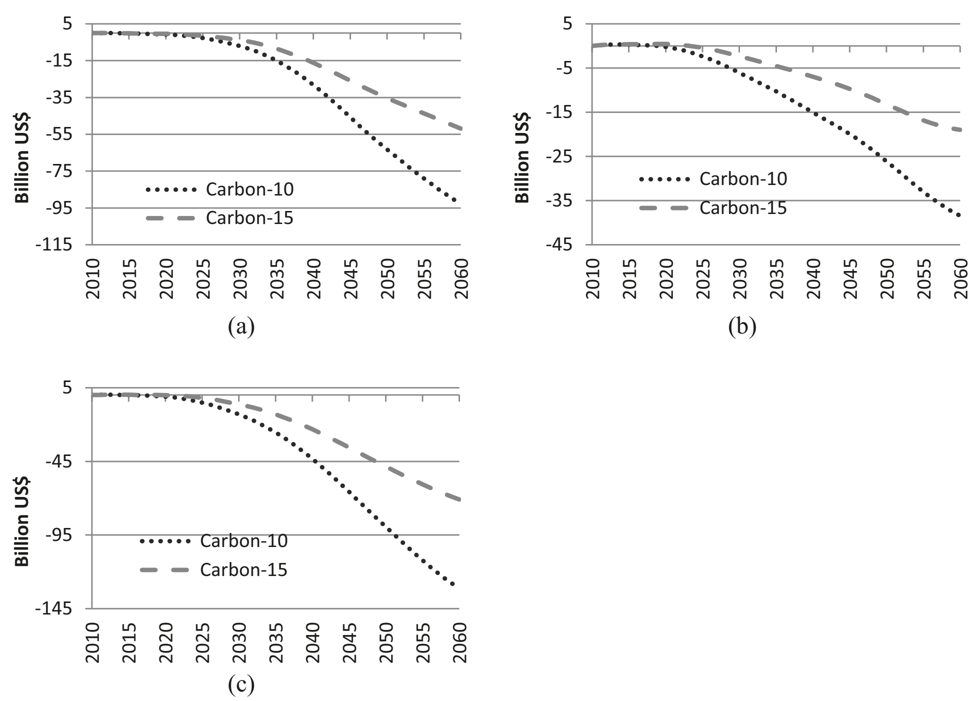


Fig. 9. Projected cumulative changes in (*a*) primary forest products producer surplus, (*b*) primary forest products consumer surplus, and (*c*) net market welfare (sum of changes in primary forest products producer and consumer surplus), in billions of dollars, for the alternative carbon payment scenarios, 2010–2060. Note that this market welfare does not include the direct carbon payments (up to $3 billion/year paid for additional carbon in set-asides), which goes exclusively to those forest landowners who elect to receive timber set-aside payments.



and –\$44 and –\$38 billion for a price of \$10/t CO_2e by 2060. For timber markets, the loss in combined producer and consumer surplus ranged from –\$48 billion at \$15/t CO_2e to –\$74 at \$10/t CO_2e by 2060 (Fig. 8c). For primary forest product markets, the losses in combined producer and consumer surplus ranged from –\$71 billion at a price of \$15/t CO_2e to –\$131 at a price of \$10/t CO_2e by 2060 (Fig. 9c).

In summary, forest landowners who retained their timber harvest rights obtained higher timber prices as a result of the timber set-asides, but they experienced reduced overall harvest levels because of reduced domestic timber consumption (demand quantities declined and product imports increased at higher timber prices). Thus, timberland owners who received payments for timber set-asides achieved welfare gains, whereas those who retained harvest rights had welfare losses. Forest product producers and consumers sustained unambiguous net losses in market welfare (higher timber and wood product prices and higher imports) as a result of timber set-asides. Of course it is expected that society as a whole would experience some net welfare gain from climate change mitigation in the long run (otherwise the carbon offset program would not make sense economically), but evaluating the climate welfare effect of set-asides is beyond the scope of this paper. Nevertheless, such welfare trade-offs would be important components for evaluating the costs and benefits of government policies and programs. For example, previous work on the welfare effects of climate policy in the agricultural sector shows that trade-offs within a given sector are an important component of weighing the collective costs and benefits of a climate change mitigation policy (Baker et al. 2010).

Limitations

Our study has a number of limitations. First, we estimated welfare impacts of carbon payments only for US timber and primary forest product markets. Additional estimates of welfare impacts on forest landowners supplying carbon through timber set-aside and final forest product consumers (e.g., consumers of housing, furniture, etc.) would provide a more complete picture of market welfare impacts. Next, our results assumed that timberland enrolled for set-aside payments remains locked up for 100 years with no option of regaining harvest rights prior to 100 years. However, a requirement that landowners leaving the program buy credits from other landowners who would join the program may have a similar effect of maintaining set-aside acreage. Another limitation is that our forest growth and inventory model does not simulate timber stand conditions, productivity classes, or age classes for individual owners or by ownership category. Instead, projected timberland set-aside area and carbon accumulation of such acres was determined using average regional growing-stock density and average timber growth, but that is similar to the Common Practice baseline requirement of the CAR forest project protocol. Similarly, our results do not account for the effects of projected climate change on timber growth and inventory, which was beyond the scope of our analysis. In addition, although we used an exogenous assumption of a gradual decline in overall timberland area, based on the RPA land use projections, we acknowledge that our model does not estimate land exchange between agriculture and forestry that might also result because of timber set-asides. This might marginally affect forest product markets and overall system carbon gains or losses through afforestation in response to timber set-asides. Finally, an evaluation of the broader social costs and benefits should account for net welfare impacts resulting from climate change mitigation owing to the policy. Despite these limitations, the timber and primary forest products market impacts of carbon payment for timber set-asides provided in this study indicate the approximate magnitude of effects of a policy involving voluntary payments to forest landowners to set aside timberland for carbon reserves.

Summary and conclusion

This study contributes to understanding the approximate impacts that payments for timber set-asides, as a means for mitigating climate change, would have on timber markets and the use of timber resources. The results provide an understanding of the linkage and trade-offs between forest sector climate change mitigation efforts and forest sector economic well-being. The study has shown that payments to landowners for timber set-asides could affect conventional timber stumpage markets and primary forest products markets substantially. The projected increase in stumpage price reduced domestic production and generally increased imports of primary forest products, but had relatively smaller effects on consumption. Increases in timber prices were projected to be passed on to the producers and consumers of primary forest products and resulted in reduced producer and consumer surplus relative to the BAU scenario.

The analysis suggests that the most effective timber set-aside scenario (in terms of carbon mitigation benefit) under the fixed annual expenditure budget would be one with the lowest acceptable carbon price because it would allow a larger area of timberland to be set aside as carbon reserves. Our analysis showed that plenty of timberland would likely be enrolled at the lower price (\$10/t CO_2e in this case). Thus, the government should preferably try to set the carbon price at a level that would maximize long-term carbon storage benefit. This result reinforces the findings of Babcock et al. (1996), who concluded that the government should purchase land with higher benefit-to-cost ratios to maximize the environmental benefits of CRP contracts.

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