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# Mitigating greenhouse gases: The importance of land base interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices

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A B S T R A C T

The forest sector can contribute to atmospheric greenhouse gas reduction, while also providing other environmental, economic, and social benefits. Policy tools for climate change mitigation include carbon-related payment programs as well as laws and programs to impede the loss of agricultural and forest lands to development. Policy makers will base their expectations of the effectiveness of these strategies to some degree on anticipated land use impacts. We examine a number of scenarios about carbon prices, urban development rates, and potential future land transfers between forestry and agriculture to provide information about the potential effectiveness of policies to address climate change in the U.S. Because large areas of land can move between forestry and agricultural uses, we used the Forest and Agriculture Sector Optimization Model-Greenhouse Gases model to examine responses between sectors as part of GHG policy analysis. The model projects changes in land uses, has full carbon accounting for both forestry and agriculture, and can examine a broad range of adaptation and climate change mitigation options. Modeling results suggest that receipt of carbon-related payments by landowners in forestry and agriculture can have substantial impacts on future land use patterns, levels of terrestrial carbon sequestration, forest resource conditions, agricultural production trends, and bioenergy production.

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## 1. Introduction

Policy makers are examining a wide array of alternatives for climate change mitigation. The forest sector can potentially provide significant contributions both by preventing emissions through fossil fuel replacement and by sequestering greenhouse gases, while also providing other environmental, economic, and social benefits. Policy tools that could affect forests include payments for carbon sequestration to stimulate more storage of greenhouse gases (GHGs) and measures to slow or reduce losses of forest area to developed uses and agriculture and thereby reduce forest-based GHG emissions. Deforestation globally released an estimated 136 billion tonnes of carbon or 33% of the total emissions between 1850 and 1998 (Watson et al., 2000), exceeding any other anthropogenic activity besides energy production. The United States likewise has substantial deforestation, and preventing GHG emissions from deforestation as an avoided land-use change is receiving increased attention (e.g., Society of American Foresters, SAF, 2008). In the United States between 1982 and 1997, more than 9 million ha were deforested in total, with more than 4 million ha converted to developed uses (USDA Natural Resources Conservation Service, 2000). Between 1992 and 1997, the rate of deforestation increased and the proportion of forest converted to urban and developed uses increased to 55% of the total, with more than 400,000 ha converted annually.

This study is intended to inform policy makers about the effectiveness of forest-related policy alternatives for climate change mitigation. We examine scenarios that differ on three dimensions of potential policy control: (i) rates of deforestation for developed uses (land lost to urbanization), (ii) carbon price, and (iii) the extent of land use change between forestry and agriculture. Our concern is with the interaction of these several policy variables (some combination of carbon price, land loss to urbanization, and land shifts among forestry and agriculture), not just the effects of each policy in isolation as has been the case in most past studies. For each scenario we project the following impacts on the U.S. forest sector: (i) forest area; (ii) amounts of forest carbon sequestered, (iii) production and prices in traditional forest industries, and (iv) agricultural prices and levels of bioenergy production. To capture interactions between sectors, we employ the Forest and Agriculture Sector Optimization Model-Green House Gases (FASOM-GHG) model (Adams et al., 1996, 2009; Lee et al., 2007), which projects changes in land uses involving forestry and agriculture and has a comprehensive carbon accounting system for the U.S. private forest and agricultural sectors including final products and disposal. The following sections describe our policy simulation model and the methods used to examine the several mixes of policy actions, our results for the four impact areas noted above, and a final section discusses the policy implications of our findings.

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## 2. Methods

The FASOM-GHG modeling system simulates both economic (market) and biophysical systems in the U.S. forestry and agricultural sectors. FASOM-GHG uses a multi-period market surplus optimization approach with the two sectors linked via the market for land that can be used in either sector. Market models in both sectors consider product transformation processes from crop or forest stand initiation through multiple market levels to wholesale demand for processed products. Private land suitable for either use flows to the sector that promises the highest land value. Product markets include both domestic and external supplies and demands, some exogenous (such as rest of world demand for agricultural products) and some endogenous (such as Canadian export supply of timber products). Both sectors can also supply feedstocks to an array of bioenergy production options (ranging from biomass for wood-fired electricity generation to ethanol from corn). The model has nine forestry regions and ten agricultural regions and operates on a five-year time step.

### 2.1. Land markets

Modeling land markets in FASOM-GHG allows some portion of the land base in the forestry or agricultural sectors to be shifted to an alternative use at the extensive margin. Land can transfer between sectors based on its potential profitability across all alternative forest and agricultural uses over the time horizon of the model. At the intensive margin, land management investment decisions are also endogenous, such as for harvest timing in forestry, so that they are based on the expected profitability of timber and carbon sequestration if both are valued monetarily. By accounting for land competition and landowner response to changing relative prices for products and services, the model provides a comprehensive assessment of net market impacts associated with increased demand for land, whether for production of bioenergy feedstocks, conversion to developed uses, or other uses. Interrelated decisions that are modeled include crop switching, changes in livestock production, movements between cropland and pastureland, movements between forest land and agricultural land, and changes in quantities and prices of agricultural and forestry commodities.

A key capability of the FASOM-GHG model is to be able to examine deforestation, reforestation, and afforestation on private lands, based on maximizing net returns to different land uses (Alig et al., 1998), and linkage of land-use changes and land management (e.g., forest thinning). Future forest area lost to deforestation for developed uses is exogenous, drawing upon projections of developed land for the 2010 Resources Planning Act Assessment (Alig et al., 2009). Developed use projections are based on National Resource Inventory land-use data collected by the USDA Natural Resources Conservation Service (2000). Deforestation for agricultural use is modeled endogenously. Afforestation is the conversion of agricultural land to forest land. Reforestation is the replanting or natural regeneration of cutover timberland. Both are modeled endogenously. Land is afforested or reforested using commercial species, such as loblolly pine (*Pinus taeda*) in the southern United States.

### 2.2. Model structure

The dynamic FASOM-GHG model solves jointly for the multi-market, multi-period equilibrium in the linked agricultural and forestry sectors in a nonlinear programming framework. A solution reflects price and quantity equilibria established in each sector in each period, where producers and consumers have perfect knowledge of market conditions in all periods (Alig et al., 1998). Land, water, labor, and natural and other resources (e.g., fertilizer, capital) are used by forest, crop (including bioenergy feedstock), and livestock production. The raw primary commodities are then produced, and some move directly to markets, while others are used as inputs to processing activities generating secondary commodities (including bioenergy), in direct livestock feed, or are used in blended livestock feeds. The primary and secondary commodities, bioenergy, blended feeds, and imports go to meeting household demand, other domestic demand, livestock feeding, and exports.

The FASOM-GHG model is unique in its modeling of multiple forest-related markets, including both logs and mill processed products. Sawtimber, pulpwood, and fuelwood are included in log markets, and sawn lumber, plywood, reconstituted panel products, and pulp are modeled in product markets. The forest sector modeling is based in part on a family of models supporting the USDA Forest Service's Forest and Rangeland Renewable Resources Planning Act (RPA) assessments (Adams and Haynes 2007), which was linked to the Agricultural Sector Model (ASM, starting with Baumes (1978) and other studies reviewed in Adams et al. (2009)). The ASM model is a spatially disaggregated model of the agricultural sector representing the United States in terms of 63 production regions and 10 market regions, depicting trade with 37 foreign regions.

The FASOM-GHG model was expanded and enhanced in the 2000s on both the forestry and agricultural sides. Products were added on the forestry side, along with an increased number of forest types and silvicultural management options (e.g., for the southern United States, planted pine is distinguished from natural pine and other types, and there are seven planted pine management intensity classes). Extensive modifications on the agricultural side (Adams et al., 2009) included improvement of agricultural carbon sequestration dynamics, expansion of the scope of agricultural sector GHG emission source and mitigation strategy coverage, and bioenergy modeling.

FASOM-GHG includes all states in the conterminous United States, broken into 11 market regions. The 11-region breakdown reflects the existence of regions for which there is agricultural activity but no forestry, and vice versa. Forestry production is included in 9 of the market regions (all but Great Plains and Southwest), whereas agricultural production is included in 10 of the market regions (all but Pacific Northwest–West side). The Great Plains and Southwest regions are kept separate because of important differences in agricultural characteristics. Likewise, important differences exist for the two Pacific Northwest regions (PNW-Westside and PNW-Eastside, relative to the crest of Cascade Mountains) for forestry, so they are maintained separately, although only the Eastside is considered a significant producer of agricultural commodities tracked in the model.

### 2.3. GHG modeling

The FASOM-GHG model has comprehensive carbon accounting in the forest and agricultural sectors, including movements of carbon from forests to pools of final products and disposal. In the forest sector, carbon can be sequestered in soils, standing trees, other vegetation, and wood products. Sequestration refers to storage for more than one year. The forest carbon accounting component of FASOM-GHG tracks forest carbon in four pools: tree (live and dead), soil, forest floor, and understory vegetation. The accounting process is largely derived from the Forest Carbon (FORCARB) modeling system (Birdsey et al., 2000). In the case of deforestation to developed uses, carbon is tracked on developed land after exiting the forest land base, reflecting a reduced stocking of trees on residential land.

The carbon fate of harvested wood is tracked in the FASOM-GHG model, simulating dynamics for use as products, emissions in processing and use, and disposal. Harvested logs removed from site are converted into three types of outputs through primary manufacturing processes: wood and paper products, mill residues, and fuel wood. The distribution of product carbon changes over time, and FASOM-GHG tracks the fate of product carbon for each end use using two pools: carbon remaining in-product (e.g., paper) (Skog and Nicholson 1998) and carbon leaving the product. Carbon that leaves

**Table 1**
Land use changes projected relative to base levels in 2050 across scenarios.

| | Forest area (million ha) | | | Afforestation (million ha over 50 years) | | | Cropland (million ha) | | | Pasture (million ha) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $0 | $25 | $50 | $0 | $25 | $50 | $0 | $25 | $50 | $0 | $25 | $50 |
| *Endogenous land transfers* | | | | | | | | | | | | |
| 1/2 base development | 5.1 | 15.4 | 35.0 | (1.0) | 10.1 | 29.4 | 0.7 | (5.2) | (19.7) | 0.3 | (4.5) | (8.8) |
| Base development | – | 9.4 | 29.0 | – | 10.0 | 29.4 | – | (4.9) | (19.7) | – | (4.6) | (8.9) |
| Twice base development | (10.6) | (2.5) | 16.8 | 1.7 | 9.8 | 29.3 | (1.0) | (4.7) | (19.6) | (0.5) | (4.7) | (8.9) |
| *Fixed land bases* | | | | | | | | | | | | |
| 1/2 base development | 9.4 | 9.4 | 9.4 | 3.4 | 3.4 | 3.4 | (2.4) | (0.9) | 0.2 | (0.2) | (1.5) | (2.4) |
| Base development | 3.3 | 3.3 | 3.3 | 3.4 | 3.4 | 3.4 | (2.4) | (0.9) | 0.2 | (0.2) | (1.5) | (2.4) |
| Twice base development | (8.9) | (8.9) | (8.9) | 3.4 | 3.4 | 3.4 | (2.3) | (0.9) | 0.2 | (0.2) | (1.5) | (2.4) |

Note: Three columns labeled 0, 25, and 50 under each section refer to $CO_2$ price per tonne. A dash indicates base case.

the product ultimately makes its way to emissions or is permanently sequestered in landfills.

### 2.4. Policy scenarios

To evaluate the potential impacts of policy instruments available for climate change mitigation, we built scenarios based on three strategies: carbon pricing, development rates (land loss to urbanization), and the extent of land use changes between forestry and agriculture. Unlike past studies which focus more on a range of potential levels of one policy, we examine alternate levels of three policies and focus on their interaction.

The $CO_2$ pricing scenarios in the present analysis include a base case with no $CO_2$ price, the \$25/tonne, and \$50/tonne $CO_2$ price. The \$25/tonne price comes from Murray et al. (2005), who argue that costs of mitigation actions in forestry and agriculture would range from \$15 to \$25/tonne of $CO_2$. We also simulate a scenario with \$50/tonne to investigate effects of a higher $CO_2$ price.

The scenarios related to rates of development loss include a base level, twice the rate of loss in the base, and one-half the rate of loss in the base. Policy related to development can either accelerate or impede conversion of forest and agricultural land to developed use. The projected base level of forest converted to development is approximately 15 million ha over 50 years, drawn from recent studies by Lubowski et al. (2006) and Alig et al. (2009).

The policy scenarios related to intersectoral land transfers involving forestry and agriculture include the "market" case, with endogenous determination of the forest and agricultural land allocation within the FASOM-GHG model. This would be a policy of no restrictions on the market determined shifting of land to the use promising the highest rent. A second case envisions a policy that fixes the land base allocation with no land shifts between forest and agriculture.

The full set of scenarios involves 18 unique combined runs. There are nine each for the endogenous and fixed land-use sets. Descriptors for each scenario are comprised of three elements (e.g., C50_D2_E): $CO_2$ price (\$0, 25, and 50) per metric tonne, level of development relative to the base case (.5, 1, 2), and whether land transfers are endogenous (E) or the forest and agricultural land bases are fixed (F). For policy analysis, we report the first 50 years of the projections for 80-year runs, including differences from the base case.

### 2.5. Modeling assumptions

Timber demand, timber inventory data, and other information about the forest sector were taken in large part from the 2005 RPA Timber Assessment Update (Adams and Haynes 2007). Timber harvests on public timberlands are exogenous inputs in the FASOM-GHG modeling of timber markets, drawn from the Timber Assessment as well. Other exogenous assumptions for the base case include 13 million ha of land kept in CRP,[1] regional corn yields increase at a rate of 1.4% annually over time, and energy prices over time are equal to the base Annual Energy Outlook 2008 (EIA, 2008) projections (e.g., real gasoline price of \$2.36 per gallon in 2022). Production targets for bioenergy are in line with the national Renewable Fuels Standard as imposed by the 2007 Energy Independence and Security Act. The Renewable Fuels Standards level of bioethanol production is primarily set by constraints, with 114 billion liters of renewable fuels produced in the base projections.

## 3. Results

### 3.1. Forest area changes

Projections of forest area across the scenarios demonstrate the relative potential influence of policies regarding loss of forest to development, land transfers with the agricultural sector, and $CO_2$ payments available to landowners. Forest area is highest under scenarios where $CO_2$ payments are available to landowners and with endogenous afforestation levels (Table 1). By 2050, the range in projected forest area is from approximately 106 million ha under twice the base level of deforestation and no $CO_2$ prices, to more than 154 million ha with \$50 $CO_2$ prices and one-half the base rate of projected loss of forest area to developed uses (Fig. 1).

Under base case assumptions, forest area is projected to decline by 12% over the projection period. A policy to prevent loss of forest to agriculture (C0_D1_F) would increase forest area by 3% compared to the 2050 base level. Combining that policy with one to reduce the rate of deforestation for developed uses by half the base rate (C0_D.5_F) would increase forest area by 9% by 2050 compared to the base level. Effects on forest area from those combined land use policies would approximate those from having a \$25 $CO_2$ price and no such land-use policies (C25_D1_E) (Table 1). If a \$50 $CO_2$ price is introduced (C50_D1_E), then the carbon policy could lead to a net increase in forest area relative to the base level of more than three times the area amount for the combined land-use policies.

Long term increases in forest area are only positive with \$50 $CO_2$ prices and endogenous land transfers with agriculture. For \$25 $CO_2$, the additional restriction of having reduced development of forests is also necessary to obtain a forest area total in 2050 not much lower than that in the first period (Fig. 1).

Projected afforestation under \$50 $CO_2$ prices with base level of development and endogenous land transfers boosts forest area by 25% in 2050 compared to the base case. A \$25 $CO_2$ price produces an 8% increase over the base level, and with the base level of deforestation to development, this leads in net to lower forest area than at the start of the projection (Fig. 1).

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[1] Based on the FASOM baseline estimate of about 15 million ha in CRP, placing a floor of 13 million ha in CRP implies that a maximum of 2.1 million ha of CRP land can revert to cropland under the Control Case.

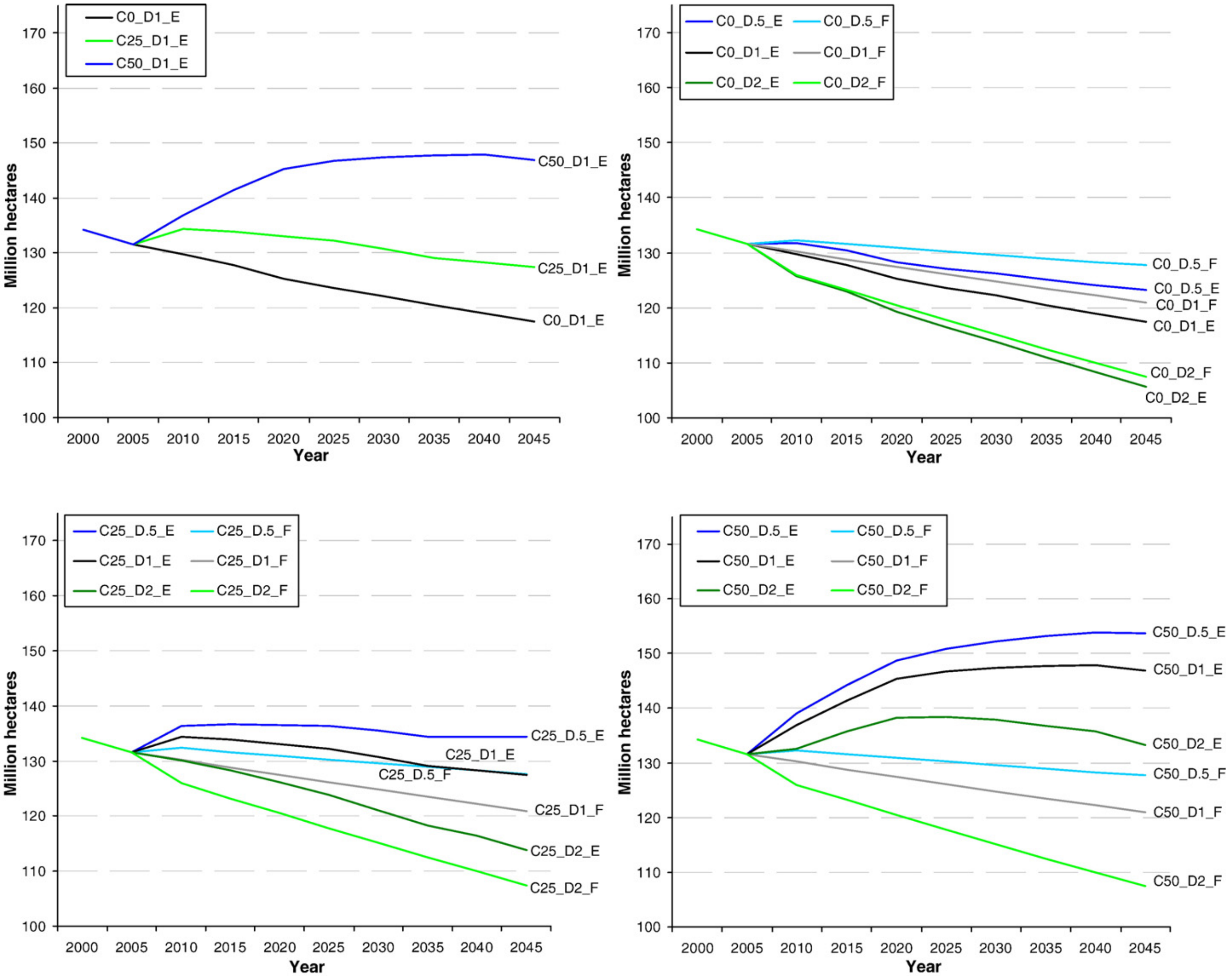

**Fig. 1.** Forest area projections under different scenarios (million ha): a) \$0, \$25, and \$50 $CO_2$ price scenarios with base level of forest development; b) \$0 $CO_2$ price scenarios, c) \$25 $CO_2$ price scenarios; and d) \$50 $CO_2$ price scenarios.

With afforestation area sensitive to $CO_2$ prices, projected net change in forest area involving land exchanges with agriculture (afforestation area minus area deforested to agriculture) is positive with a \$50 $CO_2$ price, base level of development, and endogenous forest and agricultural land exchanges (Fig. 2). In contrast, net change levels without a $CO_2$ price are negative. Afforestation dominates deforestation to agriculture over much of the projection period with \$25 $CO_2$, but is exceeded by such deforestation in the 2030 decade.

Deforestation for conversion to agricultural use is also sensitive to the $CO_2$ price assumption. Deforestation to agriculture is reduced to about two-fifths the base area amount with \$25 $CO_2$ prices. With \$50 $CO_2$, the amount of deforestation to agriculture drops essentially to zero over the first two projection decades. However, even with \$50 $CO_2$ prices, the deforestation for agricultural use does increase later in the projection period, given the expanded forest area and changes in land prices across the two sectors.

Fig. 1 also shows that effects on forest area of restricting transfers between forest and agriculture are sensitive to carbon prices. At \$0 $CO_2$ price, forest area is higher under restricted transfers than under endogenous transfers at all development levels. Without restrictions, more land would be deforested for agriculture. However, at \$25 and \$50 $CO_2$ prices, the case is reversed. Restrictions lead to less forest area

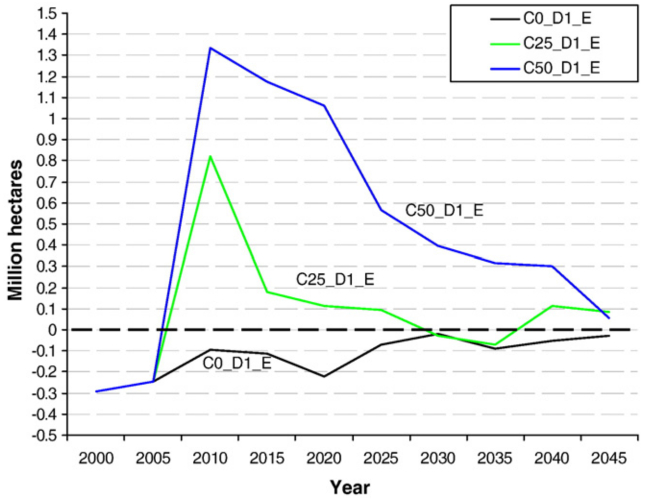

**Fig. 2.** Projected annual net change in forest area across scenarios due to land exchanges with agriculture, where net change equals gain to forestry from agriculture (afforestation) minus deforestation of forest to agriculture (million ha).

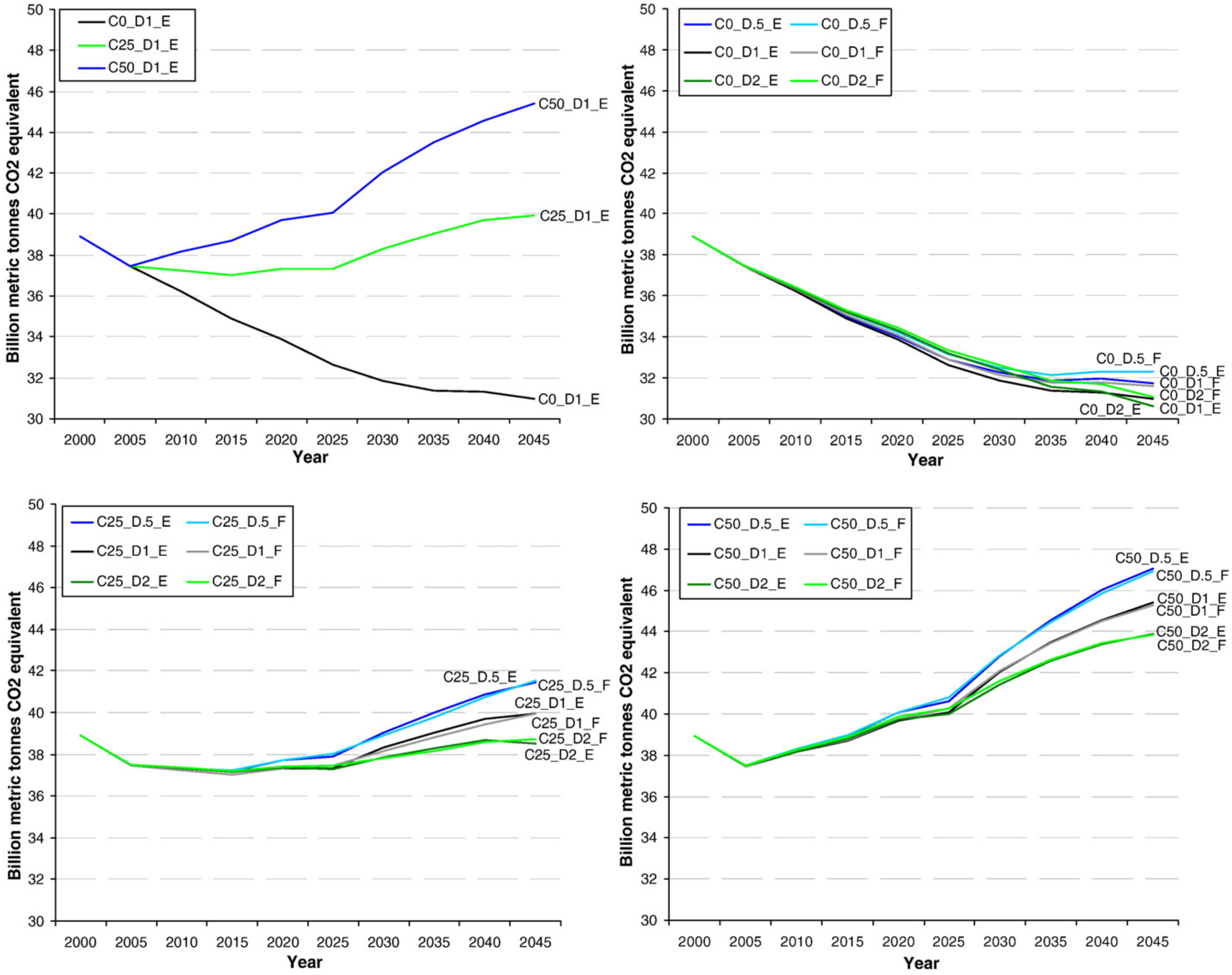

**Fig. 3.** Carbon storage in forest ecosystems under different scenarios (billion metric tonnes $CO_2$ equivalent): a) \$0, \$25, and \$50 $CO_2$ price scenarios with base level of forest development; b) \$0 $CO_2$ price scenarios, c) \$25 $CO_2$ price scenarios; and d) \$50 $CO_2$ price scenarios.

than endogenous transfers at all development levels, where restrictions now preclude afforestation.

### 3.2. Forest-related carbon

Carbon sequestration by the forest sector in the base case follows a declining trend over the 50 year projection (Fig. 3). The amount sequestered in forest ecosystems drops by approximately 20% over the business as usual projection (C0_D1_E). The only scenarios with lower forest carbon in 2050 are with no $CO_2$ prices and twice the base amount of deforestation to developed uses (Table 2), with the largest drop about 1% from the base level for the C0_D2_E scenario.

Increases in projected forest-based carbon are highest with the availability of $CO_2$ payments (Table 2). The largest increase by 2050 compared to the base case would be 82% with a \$50 $CO_2$ price, reduced deforestation for developed uses, and endogenous land transfers

**Table 2**
Projected changes in forest carbon sequestration pools (million metric tonnes $CO_2$ equivalent) from the base case in 2050 across scenarios, for three $CO_2$ prices (\$0, \$25, and \$50 per tonne) and three land development assumptions (.5, base level, and double the base level).

| | Forest management | | | Forest products | | | Total carbon accounts | | |
|---|---|---|---|---|---|---|---|---|---|
| | \$0 | \$25 | \$50 | \$0 | \$25 | \$50 | \$0 | \$25 | \$50 |
| *Endogenous land transfers* | | | | | | | | | |
| 1/2 base development | 751.0 | 13,208.7 | 26,315.0 | 55.8 | (349.1) | (857.3) | 1216.9 | 18,943.2 | 36,256.4 |
| Base development | – | 11,582.6 | 24,641.0 | – | (352.2) | (859.1) | – | 16,705.5 | 33,942.8 |
| Twice base development | (367.3) | 10,112.6 | 23,011.4 | 144.2 | (273.5) | (761.0) | (433.4) | 14,804.2 | 31,787.5 |
| *Fixed land bases* | | | | | | | | | |
| 1/2 base development | 1106.7 | 10,261.7 | 15,673.3 | 65.6 | (392.0) | (967.5) | 2797.4 | 15,632.5 | 24,035.7 |
| Base development | 425.2 | 8687.3 | 14,014.8 | 46.7 | (398.5) | (972.8) | 1455.8 | 13,408.8 | 21,730.5 |
| Twice base development | (69.8) | 7463.7 | 12,592.0 | 149.6 | (333.1) | (885.2) | 489.5 | 11,674.7 | 19,821.5 |

(C50_D.5_E). The smallest increase with a \$50 carbon price would be 39% if the land bases in forestry and agriculture were fixed in combination with a double loss of forestland to developed uses (C50_D2_F). Without land transfers, the largest increase with a \$50 CO2 price is a 49% increase over the base level in 2050 with reduced rate of deforestation to developed uses (C50_D.5_F).

In terms of amounts of forest carbon sequestered, having land transfers between forestry and agriculture allows substantially more forest carbon to be sequestered with afforestation. The additional periodic increment in forest carbon sequestered by 2050 is more than 10 billion metric tonnes. In comparison, a policy to reduce deforestation to development is projected to add about 1.7 billion tonnes relative to the base level, and about 3 billion tonnes relative to a double deforestation rate.

The boost in forest carbon amounts from allowing land transfers between forestry and agriculture in the \$50 $CO_2$ price case is similar in magnitude, but somewhat less, to that in moving from \$25 to \$50 $CO_2$ prices. Increases of approximately 13 billion tonnes or more are projected with endogenous land transfers across development scenarios (Table 2). With fixed land bases in forestry and agriculture, the largest increase when moving to such higher $CO_2$ prices would be less than half the amount when land can move between forestry and agriculture.

Storage of carbon among pools in the forest sector can be affected by policies. Compared to base levels, availability of $CO_2$ prices boosts forest management carbon in all cases (Table 2). In contrast, carbon in forest products is reduced with a carbon payments policy compared to base levels. Forest products carbon could increase compared to the base in the absence of carbon payments as more forest land is converted to developed uses and harvested timber contributes to the products pool.

With $CO_2$ prices, forestry activities that contribute most to the boost in forest management carbon are expanded forest area, along with longer timber rotations. $CO_2$ prices provide incentives for landowners to build up forest inventories and forest carbon stocks. This includes less reforestation area, due to reduced harvested area and less timber harvest volume than in the base case with $CO_2$ prices.

With \$25 and \$50 per tonne $CO_2$ prices and less timber harvest, forest inventories build up markedly over time compared to the base case. By the end of 50 years and with a \$50 $CO_2$ price, total private timberland inventories (softwoods and hardwoods) are 64% larger than in the base case. For a \$25 $CO_2$ price, aggregate timber inventory volume increases 35% compared to the base level. This is in contrast to essentially no change in the level of aggregate timber inventory in the base case, given the influence of opportunity costs of carrying additional inventory without $CO_2$ prices.

With less timber harvest projected for the $CO_2$ price scenarios compared to the base case, this results in less reforestation area. Projected total area of reforestation for the 50-year projection with a \$50 $CO_2$ price is 17% lower than the base case. For the \$25 case, reforestation area is 6% lower.

Carbon payment policies would lead to increases compared to the base case for total carbon accounts in both the forestry and agricultural sectors (Table 2), except for the case of no carbon prices, intersectoral land transfers, and twice the base development of forests. The largest increases for the total carbon accounts are produced by carbon payment scenarios. The largest portion of the increase in the total carbon accounts is contributed by forest carbon sources. For the endogenous land transfers set and a \$50 $CO_2$ price, forestry's contribution is more than 70%, while for the fixed land bases set the contribution exceeds 60%.

### 3.3. Timber harvest and prices in forest sector

Scenarios with $CO_2$ payments have the largest effect on forest sector prices. Increased incentives to leave trees longer in the woods to increase forest carbon storage means that quantity of timber supply will be reduced in the near term. Fig. 4 shows projections of reductions in timber harvest volumes from private timberlands when owners can receive \$25 or \$50 $CO_2$ prices compared to \$0 in the base, with endogenous land transfers between the forest and agriculture sectors and an assumed base level of forest loss to development. With \$50 $CO_2$ prices (C50_D1_E), cumulative timber harvest volume over the first 50 years would drop 15% compared to the base case, 13% for softwood harvests and 26% for hardwood harvests. Not allowing land transfers with agriculture would reduce timber harvest further, approximately 2% (C50_D1_F vs. C50_D1_E); increased deforestation to developed uses would increase timber harvest by about 1% compared to a base level of development (C50_D2_E vs. C50_D1_E).

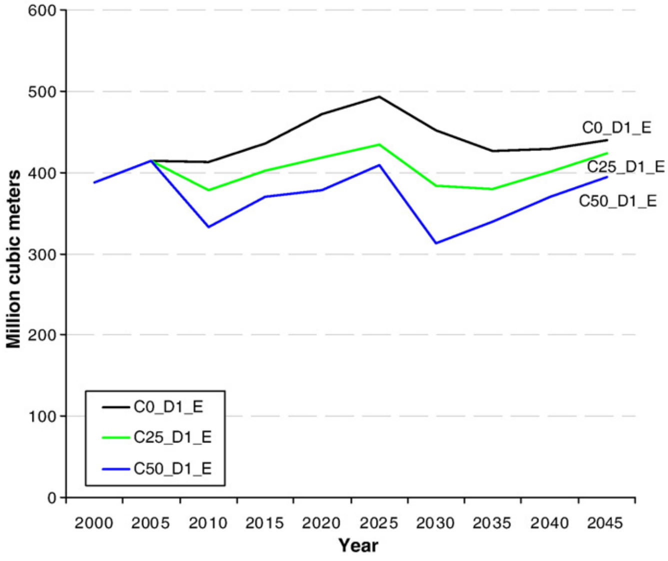

**Fig. 4.** Projected volumes of timber harvest from private timberland over the projection period, for three $CO_2$ prices (\$0 (base), \$25, and \$50 per tonne) and base level of land development.

Soil expectation values (SEV) represent the discounted future costs and revenues of a bare hectare of land placed into timber production. Across all scenarios for development and endogeneity of land transfers, SEV values go up 40% and 136% on average for $CO_2$ prices of \$25 and \$50, respectively (Table 3). The SEV values in Table 3 show approximately three times the impact as for softwood sawlog prices, while the impact is eleven times greater than that for softwood lumber price. The increase in value above and beyond the usual commodities used to determine forest land price is because of the new

**Table 3**
Projected percentage changes from the base case for selected land and forestry prices across scenarios, for three $CO_2$ prices (\$0, \$25, and \$50 per tonne) and three land development assumptions (.5, base level, and double the base level).

| | 2010 soil expectation value | | | 2050 softwood sawtimber | | | 2050 softwood lumber | | |
|---|---|---|---|---|---|---|---|---|---|
| | \$0 | \$25 | \$50 | \$0 | \$25 | \$50 | \$0 | \$25 | \$50 |
| *Endogenous land transfers* | | | | | | | | | |
| 1/2 base development | (4) | 96 | 256 | (3) | 31 | 86 | (2) | 7 | 20 |
| Base development | – | 99 | 259 | – | 32 | 88 | – | 7 | 20 |
| Twice base development | (25) | 86 | 243 | (3) | 30 | 83 | (1) | 7 | 18 |
| *Fixed land bases* | | | | | | | | | |
| 1/2 base development | (36) | 85 | 247 | (5) | 40 | 98 | (2) | 9 | 25 |
| Base development | (34) | 80 | 267 | (2) | 41 | 98 | (0) | 9 | 25 |
| Twice base development | (47) | 78 | 238 | (4) | 41 | 96 | (1) | 9 | 24 |

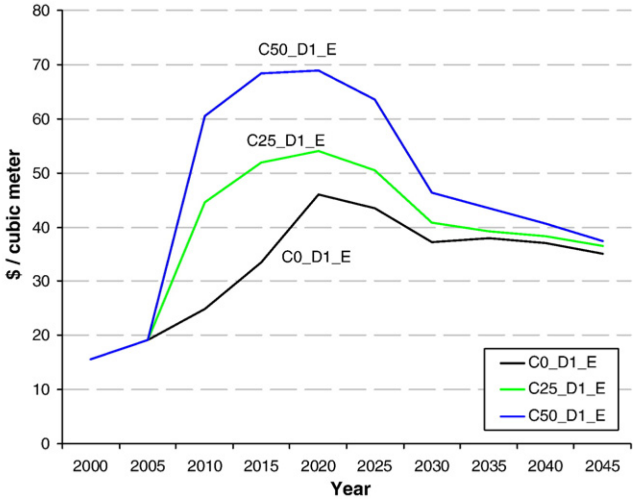

**Fig. 5.** Projected pulpwood prices over the projection period ($ per cubic meter), for three $CO_2$ prices ($0 (base), $25, and $50 per tonne) and base level of land development.

revenue stream created through the $CO_2$ market. The double development scenarios have smaller impacts on forest prices due to non-$CO_2$ price policies. Combining the double forestland development assumption with both endogenous land transfers and a fixed land base serves to dampen the $CO_2$ price impacts on SEV estimates. In general, $CO_2$ price impacts on sawlog, pulpwood, and lumber prices are also substantially higher when land transfers between the agriculture and forest sectors are fixed.

Projected differences by 2050 from the base for scenarios are generally larger for softwood sawtimber prices as compared to softwood lumber prices (Table 3). With $CO_2$ prices, competition for trees between uses as standing forest carbon and raw materials in timber markets puts upward pressure on sawtimber prices. Compared to base levels (with no $CO_2$ prices), softwood sawtimber prices are 91% higher on average across scenarios with a $50 $CO_2$ price, and 36% higher with a $25 $CO_2$ price. Softwood lumber prices experience smaller differences from base estimates, projected to be 22% higher in 2050 on average across scenarios with $50 $CO_2$ prices, and 8% higher with $25 $CO_2$ prices.

Projected pulpwood prices are also substantially influenced by availability of $CO_2$ prices (Fig. 5). With a $50 $CO_2$ price beginning in 2010, projected pulpwood prices are twice as high as base level prices through 2015, reflecting more competition for raw materials for pulp mills as timber harvest levels drop. Timber producers would have welfare gains with $CO_2$ prices, while consumers of timber such as mills face higher prices and would have losses in economic welfare. The projected competition is most intense over the first 25 years of the projection. Projected pulpwood prices under the $CO_2$ price scenarios then tend around 2030 to drop and converge toward base price levels. Differentials in projected prices under the $CO_2$ price scenarios compared to base levels persist longer in the sawtimber case. Compared to the sawtimber log case, the shorter rotations for pulpwood production represent smaller time periods for adjustment.

### 3.4. Agricultural crop prices and bioenergy production

Corn is an important part of meeting the Renewable Fuels Standard requirements of the Energy Independence Security Act of 2007, particularly during the early part of the projection period. Corn prices peak in the 2010 period with the adoption of the $CO_2$ price policy (Fig. 6), then decline slower with a higher $CO_2$ price. Cellulosic ethanol production plays a larger role later in the projection in meeting the Renewable Fuels Standard requirements. Projected prices for associated raw materials for cellulosic ethanol production, such as switchgrass, peak later than corn.

Corn prices are highest during peak periods for scenarios with $50 $CO_2$ prices and when land can move freely between the forest and agricultural sectors. With the corn price gap between the base case and $50 $CO_2$ price scenario rising for the first 25 years of the projection, the price difference is about $0.70 per bushel in 2035, approximately a 32% difference.

Corn prices generally decline after the peak periods, because the ethanol part of the Renewable Fuel Standard requirement is unchanged after 2025. By 2050, corn prices in the base case are at levels close to or below the initial year values. The same general pattern over time holds for switchgrass (Fig. 6); however, those price projections are much more sensitive to availability of $CO_2$ payments. The lowest switchgrass prices during peak periods are associated with scenarios without $CO_2$ prices. For example, the projected switchgrass prices with $50 $CO_2$ prices are more than 12 times higher than for the base case, while those under the $25 $CO_2$ price scenario are more than 6 times higher than base levels.

Projected levels of bioenergy would be substantially increased with $25 and $50 $CO_2$ prices. In the case of bioelectricity, about 8 times more could be produced by 2050 with $25 $CO_2$, compared to the base level. More than 11 times the base level could be produced with $50 $CO_2$ prices.

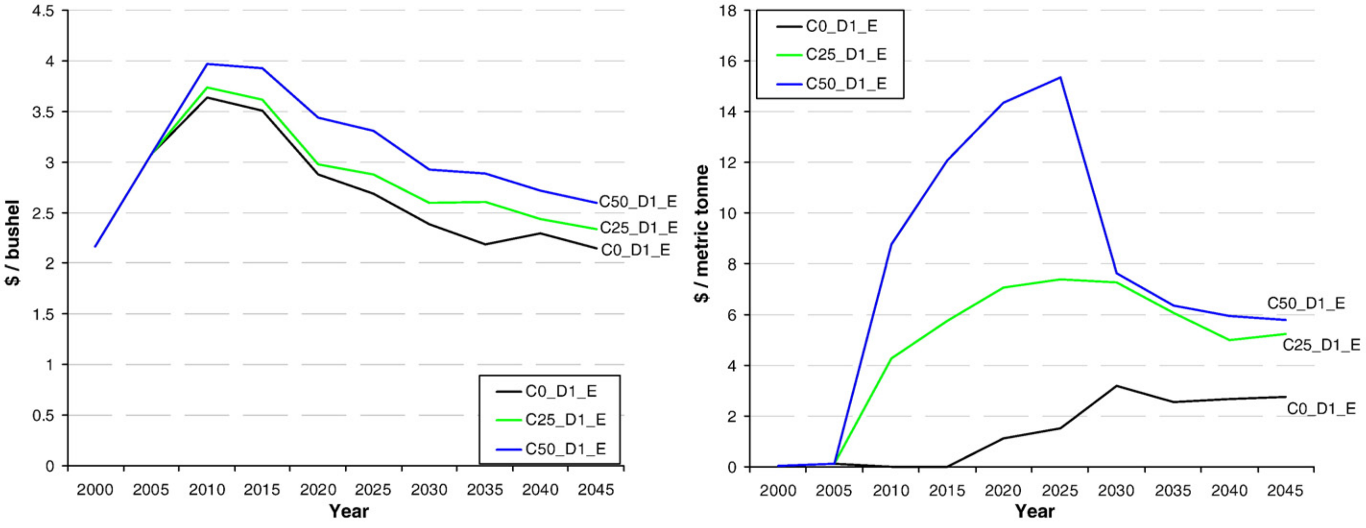

**Fig. 6.** Projected prices for corn and switchgrass over the projection period, for three $CO_2$ prices ($0 (base), $25, and $50 per tonne) and base level of land development.

## 4. Discussion

Projections under the base case or business as usual scenario are that loss of forestland to other uses will be substantial (e.g., Alig et al., 2009), causing significant net release of GHGs (e.g., carbon dioxide) currently stored in those forests and also precluding much of their anticipated future GHG sequestration. The business as usual scenario has a declining amount of forest carbon sequestered over the projection period. Forest carbon sequestration for U.S. private forests can increase if landowners receive significant carbon-related payments. For $25 per metric tonne of $CO_2$, long-term increases in forest carbon sequestration are possible except for where development of forests is double that in the base case. For a $50 CO2 price, all scenarios we examined would result in an increase in long-term forest carbon sequestration. However, the deforestation for developed uses could notably reduce the long term potential.

Results for $25 and $50 per tonne $CO_2$ generally represent different groups or strata of projections for forest or agricultural-related activities. Examples are forest area (increasing), afforestation area (increasing), reforestation (decreasing), deforestation for agricultural use (decreasing), timber harvest area (decreasing), timber inventory volumes (increasing), forest commodity prices (increasing), agricultural commodity prices (increasing), and bioenergy production (increasing).

Responses to the availability of $CO_2$ payments also include changes over time in the projections that could be useful for policy deliberations. An example is the differential of timing of log price impacts for sawtimber versus pulpwood. An example in the agricultural sector is the sequencing of projected peaks in corn grown for mandated ethanol production as compared to other agricultural crops grown for cellulosic production (e.g., switchgrass). The cellulosic component of bioenergy production provides a larger portion of energy requirements later in the production period and associated crop prices peak after the ethanol-related corn prices.

Simulations of combinations of policy-related actions indicate the many possible interactions among land base changes, forest and agricultural crop production, forest and agricultural markets, energy production, and GHG sequestration. Some of the largest forest carbon gains or prevention of losses arise with the capability to afforest agricultural land when $CO_2$ prices are significant. The importance of modeling possible land exchanges between the forest and agricultural sectors is consistent with the findings of Alig et al. (1998) when they examined conservation and farm programs.

An important advance in this study is the modeling of the impacts of $CO_2$ prices on land-use changes, in contrast to early FASOM simulations of “forced amounts of afforestation,” obtained by adding associated constraints for related activities. The earlier research did demonstrate that although it is possible to increase carbon sequestration in forests through afforestation, the net effects on overall carbon sequestration from large-scale and short-fuse programs (without direct $CO_2$ prices) may not be as large as anticipated because land markets respond by moving some unprotected forests back into agriculture (i.e., deforestation) resulting in leakage (Alig et al., 1997). Murray et al. (2004) find similarly large leakage effects for some regions of the U.S., while Sohngen and Brown (2004) find smaller, though still potentially substantial, leakage effects for tropical regions. Our results here suggest that policies with $CO_2$ pricing could provide more net forest carbon sequestration, consistent with Sohngen and Mendelsohn (2003) and Murray et al. (2005).

One important implication of increasing net forest sequestration through the use of $CO_2$ pricing is that timber harvest (timber supply) will be reduced when timber inventories build up in the forest to sequester more carbon. In contrast, with direct land-use conversions, total timber harvest may not be affected substantially in the near term. For instance, total timber harvest is reduced less than 1% under the scenario with doubling of amount of forest area converted to urban and developed uses, because some timber is harvested from forestland converted to another land use.

Another aspect of climate change policy that could affect raw materials for the wood-using part of the forest sector is increased competition for raw material for wood processing mills from demands for bioenergy production. Mandated cellulosic production represents institutional influences on demand for land to grow woody biomass for bioenergy production. Increased competition for land along those lines was shown to substantially increase projected pulpwood prices, including large price movements for hardwoods during the first half of the projection.

## 5. Conclusions

This study examined the impacts of policies involving carbon prices, development rates (e.g., avoided deforestation), and land transfers between forest and agriculture. Results indicate that carbon payments, here in the form of $CO_2$ pricing, have the largest overall impacts on the forest and agricultural sectors. Changes in development rates or land transfers between forestry and agriculture can affect forest carbon sequestration, in combination with the carbon payments policy. When considered together with $CO_2$ prices, however, assumptions regarding land shifts can have a marked effect on projections. As future models are created and applied to climate change mitigation problems, examination of the treatment of intersectoral land transfers should be considered closely because of possible impacts on forest carbon projections.

Future studies with the FASOM-GHG model will focus more on larger variation in mitigation policy intensities for climate change, including more detail in reporting impacts to the various commodities in the different regions of the United States and Canada. Although results presented here focused on broad scale measures aggregated over regions or commodities, the underlying model output included detail on more than 50 raw and 40 processed agricultural and livestock commodities, more than 40 forest-based products, as well as a variety of production methods and feedstocks for bioethanol and bioelectricity, along with more than 50 GHG categories. With a broad array of alternatives offered to address climate change, including a number of forest management and product storage options (e.g., Society of American Foresters, SAF, 2008), it is important to examine broadly efficiencies and opportunity costs of different alternative strategies across sectors for addressing global climate change. Future research can also help address impacts from excluding or discounting certain offset practices because of uncertainty about measuring, monitoring, and verifying GHG reductions or because of concerns that land-based offsets could flood the market and reduce innovation in the capped fossil fuel intensive sectors of the economy. For example, limiting the eligibility of certain mitigation options such as soil carbon sequestration, forest management, and reducing non-$CO_2$ emissions from various agricultural practices could have large impacts on land use and associated forestry and agricultural carbon sinks. Future work can help inform policy makers about the effects of discounting some offsets to account for this uncertainty or to restrict the number offsets that are allowed if a cap and trade system is pursued, which will also influence landowners' incentives to adopt GHG mitigating practices across time.

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