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Implications of Alternative Land Conversion Cost Specifications on Projected Afforestation Potential in the United States

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Abstract

The Forestry and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG) has historically relied on regional average costs of land conversion to simulate land use change across cropland, pasture, rangeland, and forestry. This assumption limits the accuracy of the land conversion estimates by not recognizing spatial heterogeneity in land quality and conversion costs. Using data from Nielsen et al. (2014), we obtained the afforestation cost per county, then estimated nonparametric regional marginal cost functions for land converting to forestry. These afforestation costs were then incorporated into FASOMGHG. Three different assumptions for land moving into the forest sector (constant average conversion cost, static rising marginal costs, and dynamic rising marginal cost) were run in order to assess the implications of alternative land conversion cost assumptions on key outcomes, such as projected forest area and cropland use, carbon sequestration, and forest product output.

Introduction

Global land-use sectors have the potential to provide greenhouse gas (GHG) abatement through activities that decrease land clearing, reduce emissions from crop and livestock production activities, and increase carbon sequestration on working croplands or through afforestation. Afforestation, or extensive margin expansion of forestland, has long been recognized as a key potential mitigation strategy in regions, such as the United States, where land is relatively fungible between forests and alternative uses, and productivity of planted forest systems is high. Several studies have evaluated the mitigation potential of afforestation in the United States and elsewhere, applying a wide range of economic frameworks (Lubowski, Plantinga, & Stavins, 2006; Nielsen, Plantinga, & Alig, 2014; Tian, Sohngen, Baker, Ohrel, & Fawcett, 2018). These studies typically represent economic and natural resource systems by adopting key biophysical functions and/or data inputs to characterize the economic returns to forestry and/or agriculture activities. However, the underlying economic assumptions vary widely across studies, especially those considering land conversion costs. Cost assumptions about land-use change are a key consideration for economic analyses that seek to project potential afforestation on alternative land uses under alternative policy or market scenarios.

Incorporation of land-conversion costs into an economic analysis varies depending on the methodology. In reduced form or econometric frameworks such as Lubowski et al. (2006), and Nielsen et al. (2014), costs are often based on observed land-use change and differences in rental rates. These studies apply estimated regression coefficients to simulate land-use change under exogenous policy assumptions. General equilibrium models and integrated assessment models often rely on land supply elasticities and/or land-use change cost parameters, simulating endogenous land-use change across policy alternatives (e.g., Palatnik & Roson, 2012; Wise, Calvin, Kyle, Luckow, & Edmonds, 2014; and Havlik et al. 2014). Partial-equilibrium models assume constant or rising conversion costs (e.g., Baker et al., 2010), or land rental functions (e.g., Tian et al., 2018). Regardless of the assumed form, these functions are typically aggregated to relatively large spatial regions or forest-type aggregates. Such aggregation ignores spatial heterogeneity in land-conversion or management costs within regions, which can lead to biased projections of afforestation or environmental benefits of increased forest area (e.g., GHG mitigation). Within a partial equilibrium framework, dynamic simulations often assume the same cost structure in each simulation period, ignoring endogenous changes in land-conversion costs as land-use change occurs at the extensive margin. Disregarding such temporal dependency in land conversion costs can also bias mitigation cost estimates for afforestation in dynamic economic analyses.

In this study, we apply a detailed partial-equilibrium model of the US forestry and agriculture sectors to assess the relative importance of alternative afforestation cost assumptions. Specifically, three alternative cost specifications are included in this study: the first assumes an average cost of land conversion within each model region; the second assumes static rising regional marginal costs based on spatially explicit information depicting intra-region heterogeneity of land productivity; and the final scenario assumes dynamic rising regional marginal cost functions. The dynamic marginal cost considerations assume continuously increasing marginal costs throughout the simulation horizon, as opposed to the static supply curves, which begin at the same reference point in each simulation period. Using baseline macroeconomic assumptions and multiple hypothetical GHG mitigation policy scenarios, we assess the implications of alternative land conversion cost assumptions on key outcomes. The results of this study are focused on projected forest area and cropland use, carbon sequestration, and forest-product output. Simulation analysis for this study is performed using an updated 2018 version of the Forest and Agriculture Sectors Optimization Model with Greenhouse Gases (FASOMGHG). Recent changes to the model include updated historical agricultural factors included production, trade, and prices and an updated forest-sector model based on the Land Use and Resource Allocation (LURA) model framework described by Latta, Baker, and Ohrel (2018). One of the benefits of

FASOMGHG is the market and land-use interactions across the forest and agriculture land-use sectors. This partial-equilibrium model endogenously allocates land to either forestry or agriculture based on maximizing the net present value of the future stream of benefits.

FASOMGHG has been used extensively to project agricultural and forest land management across different market, policy, and environmental change scenarios. A seminal report by Murray et al. (2005) projected GHG mitigation potential from the US land-use sectors across a wide range of mitigation price scenarios and found a large portion of abatement (>400 $TgCO_2e$ at mitigation prices about $\$30/tCO_2$ or about 30 percent of total US mitigation potential) from afforestation of cropland and pasture. Baker et al. (2010) quantified the implications of climate and renewable energy policy incentives on net farm income and found that incentivizing afforestation through offset payments can provide large economic welfare benefits to farmers. Alig et al. (2010) used FASOMGHG to examine afforestation and forest management changes under mitigation policies combined with alternative urban development scenarios. Latta, Adams, Alig, and White (2011) evaluated afforestation under voluntary GHG mitigation incentives, and Latta, Baker, Beach, Rose, and McCarl (2013) explored land-use dynamics across alternative hypothetical biomass electricity policy scenarios.

In these previous analyses, the FASOMGHG model relied on constant average cost assumptions for afforestation on cropland, cropland pasture (meaning managed land suitable for crop production that is currently being used as pasture but could be converted to crop production or forestland), and pasture. This cost specification is limited in that it does not reflect the heterogenous quality of agricultural lands and the costs of converting these lands to forestry. This analysis seeks to add to the rich literature on agriculture and forest-sector interactions using economic modeling frameworks by improving the representation of marginal land conversion costs—both spatially and temporally. We develop non-parametric, upward sloping marginal cost curves, specific to US regions and agricultural land-use types. We use this information to inform a scenario analysis designed to evaluate the relative importance of afforestation cost specifications on projections of land-use change and management under different policy assumptions.

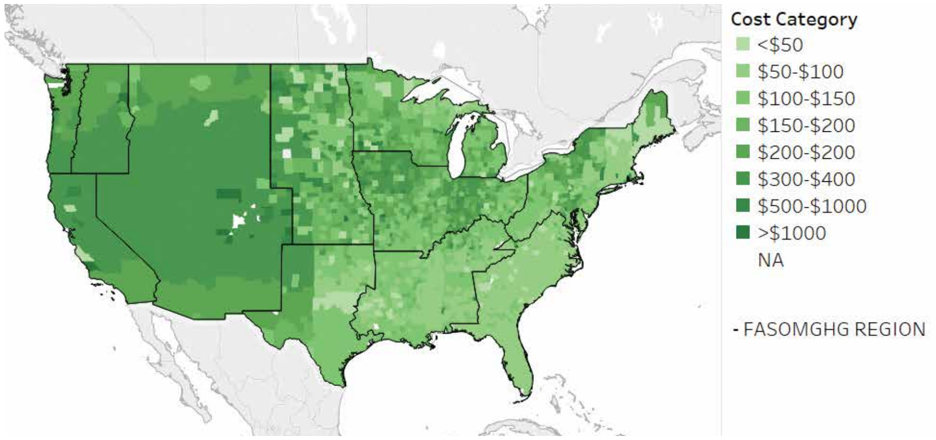
Data

To create regional supply curves for individual land types moving into forestry, the quantity of land available for conversion across varying prices is needed. The primary data used to create the supply curves in this analysis are from Nielsen et al. (2014), who report county-level cost estimates for converting land to forestry from alternative agricultural land uses. Nielsen et al. (2014) base their land conversion cost estimates on data from the Conservation Reserve Program (CRP), a federal conservation initiative administered by the US Department of Agriculture Farm Service Agency designed to encourage land owners to set aside marginal agriculture and grazing land or to fully convert it to forestry. In return, land owners receive yearly rental payments and early adopters of the program also received subsidies up to 50 percent of the cost of initial planting. The goal of the program is to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat. The program also provides co-benefits of increasing carbon storage through the expansion of forestland.

Using the payout information from the CRP, Nielsen et al. (2014) estimated the average cost of planting forestland per county. The initial goal of the CRP was to enroll large areas of erodible cropland, while over time, the focus moved to a more targeted approach to identify parcels with the potential to increase environmental benefits. Because of this, Nielsen et al. (2014) chose to limit observations from the CRP to its early years (1986–1993). It was assumed that each landowner received the full 50 percent subsidy toward the cost share of trees, and the authors calculated the average CRP payment within a county (which was then doubled to estimate the full cost associated with conversion). For counties with no available data, the authors used a two-stage Heckman model to regress the CRP payments on physiographic variables to estimate the cost of land conversion across the nation (see Figure 1). Combining these regression results with CRP payment data, county-level afforestation costs across the nation can be estimated.

To estimate the amount of land available for conversion to forestry, Nielsen et al. (2014) used data on the total amount of private land within each county currently used as cropland, pasture, and rangeland, as classified by Holdridge Life Zones (Holdridge, 1967).

Figure 1. Estimated per acre cost of afforestation



Source: Adapted from Nielsen et al. (2014).

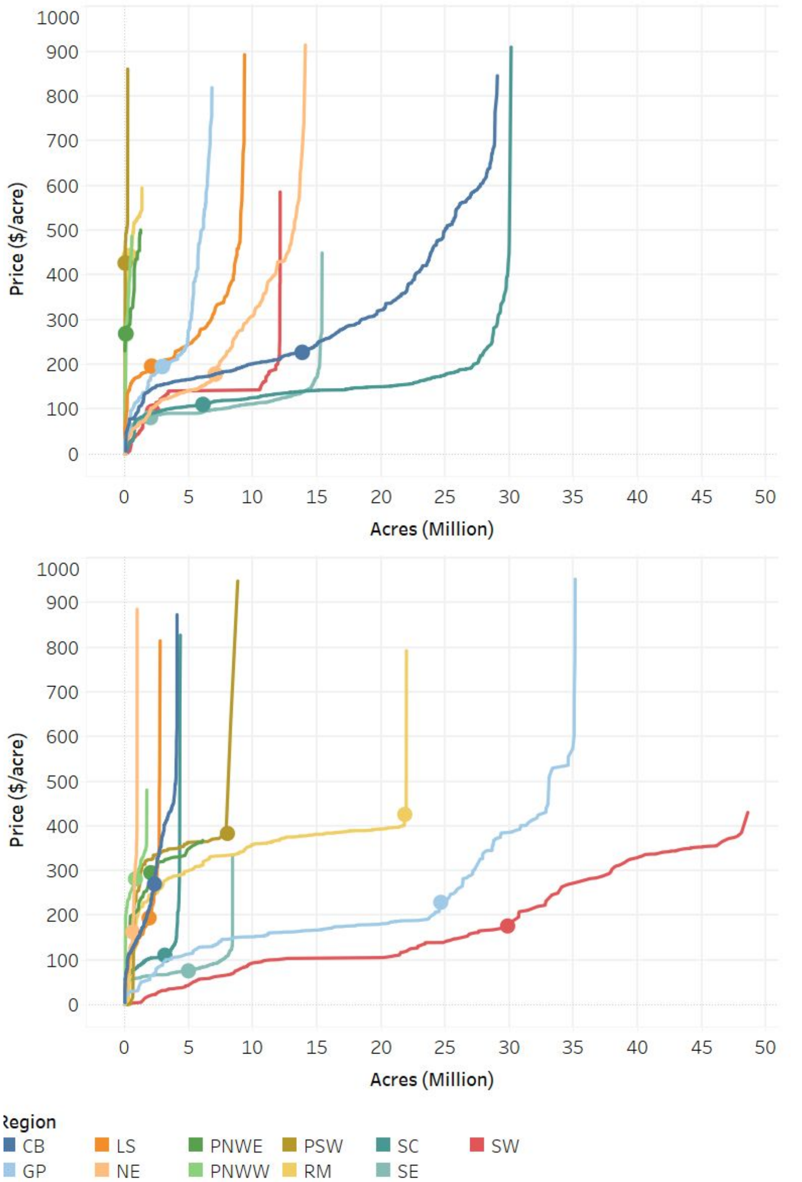
Methods

Combining the county-level estimates of land available with the estimated afforestation costs by county, we created spatially explicit afforestation supply curves. Then, we assigned land conversion costs for each county for both cropland and pasture, respectively, to one of the 11 primary agroforestry regions in FASOMGHG (described in Beach et al., 2010). For each region, we arranged county-level conversion cost estimates from low to high price to create stepwise afforestation supply curves. Using each county as an incremental step in the supply function, we horizontally summed all acres available for conversion at each price increment, creating a nonparametric supply curve. Operationally, each nonparametric supply curve was incorporated into FASOMGHG using separable programming techniques. All conversion costs were inflated to reflect 2010 US dollars, to be consistent with other commodity and input prices in FASOMGHG. Figure 2 presents regional supply curves for cropland, and other agriculture lands.

Establishment costs across all FASOMGHG regions and land-use types range from approximately $0 to $5,606 per acre with this updated method. In the previous version of the model, average conversion and planting costs for establishing forest on cropland and pasture ranged from $38 to $240 per acre. Although the cost of forest establishment has a much higher ceiling price using the data from Nielsen et al. (2014), total afforestation potential is still high at prices below the previous maximum of $240 per acre (approximately 65 million acres). Given increased market demand for forest products or policy incentives that encourage afforestation, large areas of cropland, and other agricultural lands could potentially convert to planted forest with this new rising marginal cost specification. In addition to reflecting the rising opportunity costs of land conversion, rising marginal costs of afforestation offer an implicit market-driven upper bound on the amount of land available to be converted to forestry.

These regional supply curves for cropland, rangeland, and pasture were incorporated into FASOMGHG. To compare afforestation results across alternative afforestation cost scenarios, we develop constant average cost (1), static rising marginal cost (2), and dynamic (or cumulative) rising marginal cost (3) specifications for each region and original land-use–type combination. Figure 3 presents a conceptual representation of these three specifications in a two-period example, where the green and red lines represent afforested acres in period 1 and 2, respectively. The constant average cost (1) specification uses a spatially weighted average cost of land conversion (P_t) for each region and is constant over the quantity converted in each period (Q_t) and across each period ($P_1 = P_2$). In the static rising cost (2) scenario, the marginal costs start at the same point (P_1) on the supply curve for each simulation period (t), regardless of land-use change

Figure 2. Land-use change supply curves for cropland to forest and other agriculture lands (range and pasture lands) to forest



Notes: Cropland to forest (top); other agriculture lands (range and pasture lands) to forest (bottom). The average cost scenario assumption is represented as the highlighted point along each curve.

in prior periods. This approach assumes that land is highly fungible and there is a constant supply of relatively cheap land available for afforestation at each time period. In this scenario, the price of land conversion in simulation period 1 (P_1) can be greater, equal, or less than the costs in simulation period 2 (P_2), depending on the amount of land converted in each period. If more land is converted at period 1 than period 2, the price of land conversion might be greater at period 1 than period 2. Conversely, if less land is converted at period 1 than period 2, the price of land conversion can be less in period 1 than period 2. Finally, the dynamic rising cost (3) specification uses the same supply curves as the static specification but assumes that marginal costs in each subsequent period do not start at the origin, meaning that the marginal cost of positive afforestation in every period will have a lower bound equal to the marginal cost in the previous period. In this scenario, P2> P1 over time if net afforestation is positive. Note that as a discount factor is included in the model for all types of land conversion cost, the discount factor will also be applied to the cost of afforestation in all specifications of the model.

To calculate consumer surplus for downward-sloping demand functions or producer surplus for upward-sloping supply functions we first produce a linear representation of the nonlinear function. We convert these nonlinear functions into linear representative functions using stepwise linear approximation through separable programming (McCarl & Spreen, 1997). For example, the afforestation cost in the model is represented as the stepwise linear approximation described as:

Objective function component:

$$\text{Cost} = \Sigma_{r,i,s,t}\, \widetilde{p_{r,i,s,t}}\, \widetilde{q_{r,i,s,t}}\, \lambda_{r,i,s,t}$$

$$\text{Identity: } Q_{r,i,t} = \Sigma_s\, \widetilde{q_{r,i,s,t}}\, \lambda_{r,i,s,t}$$

$$\text{Condition: } 0 \le \lambda_{r,i,s,t} \le 1,$$

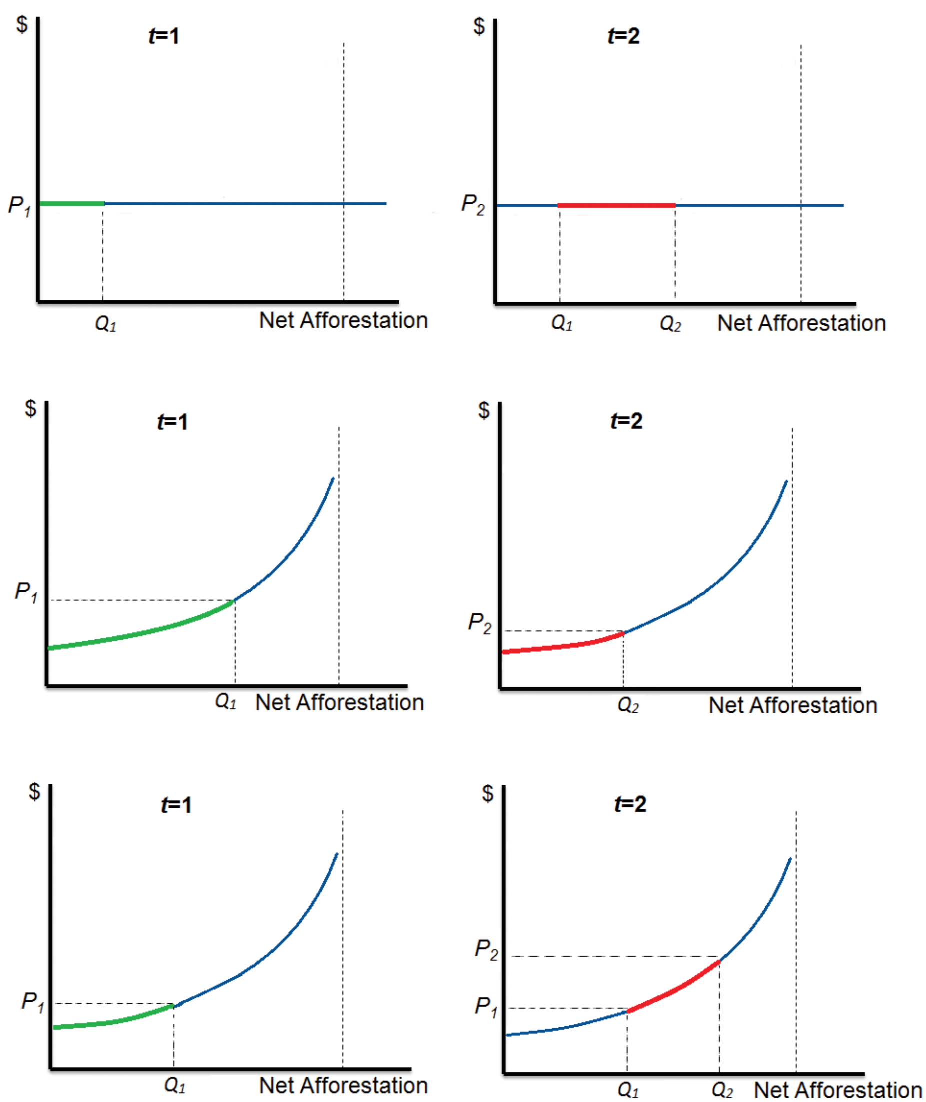
where *r, i, s* and *t* denote region, land type, step, and time periods in FASOMGHG, respectively. Regions in the FASOMGHG model include source regions into forestland, from cropland, range, and pastureland. Steps depict the number of linear steps included to represent the nonlinear function, ranging from 1 to several hundred, varying by region and land type.

$\widetilde{p_{r,i,s,t}}$ and $\widetilde{q_{r,i,s,t}}$ are the s^{th} grid point conversion price, in \$/acre, and number of acres, in million acres, from the land-use change supply curve that Figure 2 shows. $Q_{r,i,t}$ is the decision variable portraying the number of acres converted from land-use change. $\lambda_{r,i,s,t}$ is a weighting parameter between 0 and 1, allowing for linear combinations across s^{th} grid points to make up $Q_{r,i,t}$. This weighting parameter allows for the solution quantity to span across linearized steps, rather than constraining solution values to a single step. Total land-use change cost *Cost*, a component of the objective function, is the area under the supply curve, equaling to the sum of the multiplication of $\widetilde{p_{r,i,s,t}}$, $\widetilde{q_{r,i,s,t}}$ and $\lambda_{r,i,s,t}$.

$\widetilde{p_{r,i,s,t}}$ and $\widetilde{q_{r,i,s,t}}$ are constant at all steps in the constant average cost case but differ by step in the static and dynamic rising marginal cost specifications. Furthermore, an additional constraint exists for the dynamic cost specification, where sum of $\lambda_{r,i,s,t}$ would be less than 1:

$$\Sigma_t \lambda_{r,i,s,t} \leq 1.$$

Figure 3. Graphical representation of land-use change cost specifications



Notes: (1) constant average cost, (2) static rising marginal cost, and (3) dynamic rising marginal cost.

As land with cheapest cost would be converted first and at earlier periods, this constraint would ensure that land conversion at period 2 starts at the highest cost ended at period 1 and then moves upward along the land-supply curve.

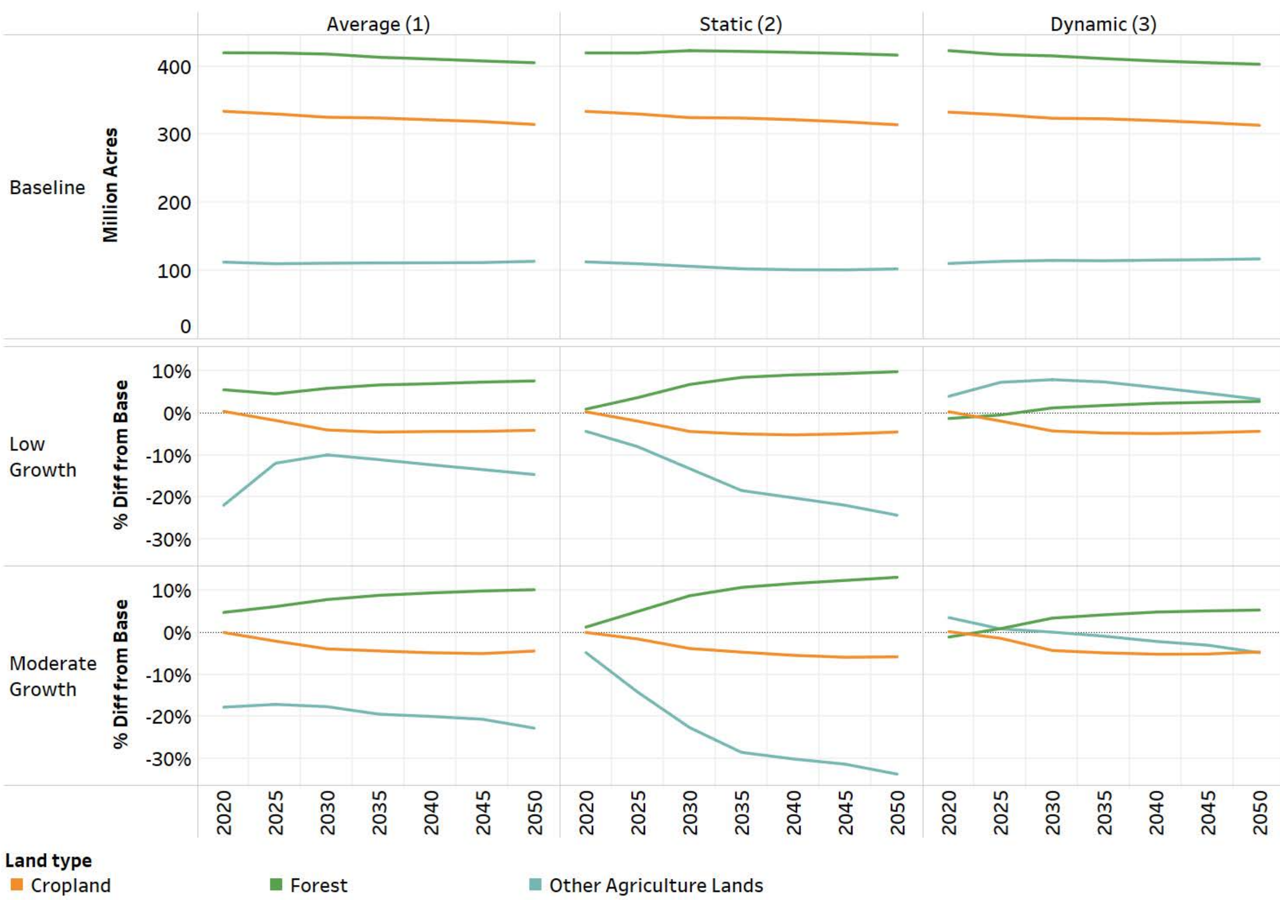
We applied each of the three afforestation cost-specification scenarios to three policy scenarios, including a baseline scenario with no additional policy incentives and two hypothetical mitigation policy cases. Each mitigation scenario starts with a mitigation price that incentivizes both increased carbon sequestration in the agriculture and forest sectors and reduced emissions from crop, livestock, and forestry production activities. The mitigation scenarios include initial price incentives of \$20 per ton of CO_2, rising annually at 1 percent for the low-growth scenario and 3 percent for the moderate-growth scenario.

Results

The results show that afforestation cost specifications play a vital role in simulated land-use decisions in sectoral modeling. In this section, we focus on how the land-use cost specifications can provide substantially different estimates of land-use change, carbon storage in forestland, and agricultural and forestry commodity production under common policy assumptions.

In our baseline policy scenario, forestland and agricultural land decline slightly over time, driven by development encroaching on these lands as well as intensive practices of both crops (through assumed increased yields) and forestry (through replacement of naturally regenerated stands with plantation-style management systems). Once an incentive is put into place aimed at decreasing carbon emissions/increasing carbon sequestration, forestland expands. Figure 4 presents the baseline scenario results for land use across sectors, and the difference from baseline for the low and moderate mitigation scenarios. These results are then compared across all three afforestation cost scenarios, average (1), static (2), and dynamic (3). Expectedly, the average cost specification (1) results in afforestation rates that fall between the other scenarios. Next, the static marginal cost specification (2) leads to the highest rates of afforestation due to the constant availability of low-cost forestland. On the other hand, the dynamic marginal cost specification (3) had the lowest amount of afforestation, as land conversion costs were continuously increasing over the simulation horizon. The availability of lower cost land for conversion under the static specification (below the average cost threshold) resulted in greater near-term afforestation

Figure 4. Change in land use for forestry, cropland and other agriculture lands



Notes: Baseline land-use projections for forestry, cropland and other agriculture lands (top); difference from baseline of total land area for low growth scenario (middle); difference from baseline of total land area for moderate growth scenario (bottom).

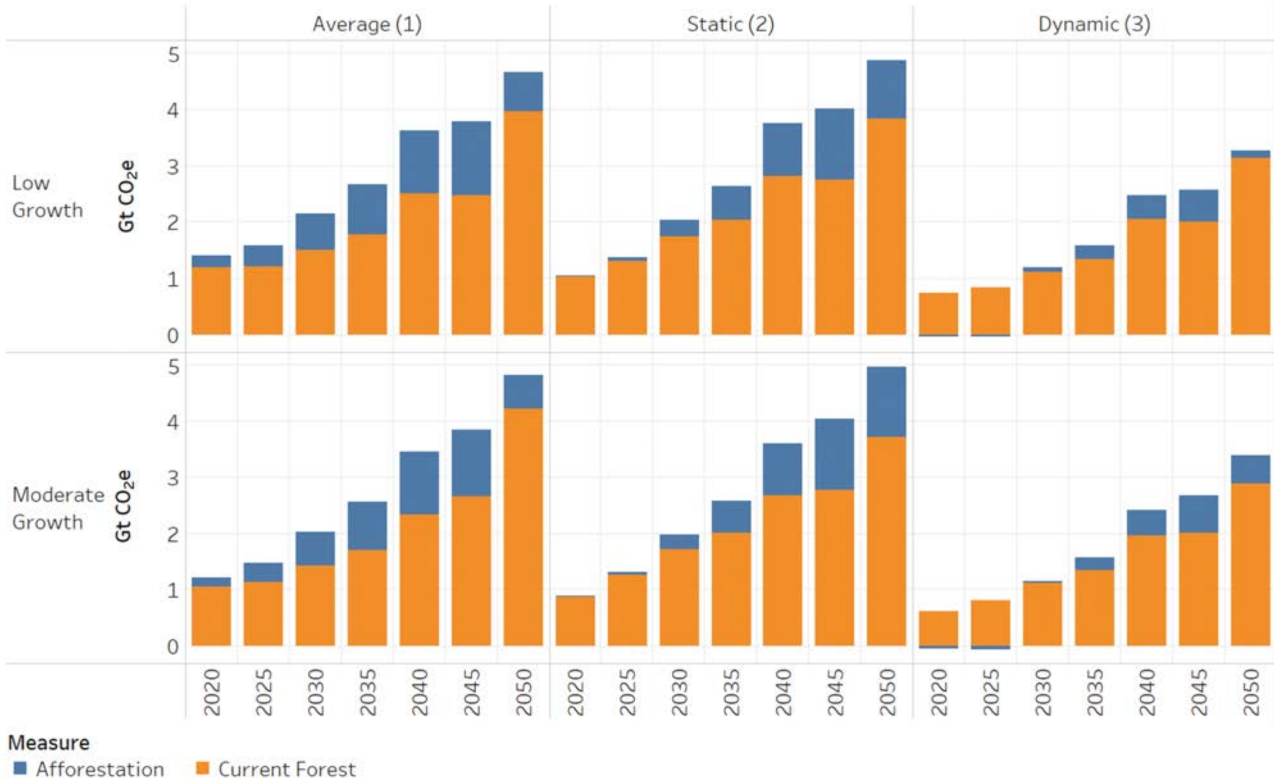
levels relative to the other cost specifications. By mid-century, in the moderate growth mitigation scenario, privately managed forestland increased approximately 13 percent (~55 million acres) under the static specification (2), 10 percent (~41 million acres) under average costs (1), and 5 percent (~21 million acres) under the dynamic cost specification (3). Cropland was relatively constant across all three costs specifications. In the moderate growth scenario, at the mid-century there was between 4 percent (14 million acres) and 6 percent (18 million acres) less cropland area compared with the baseline. Conversely, other agricultural lands showed a large variation in total area across the three cost specifications. Large declines in other agricultural lands occurred in both the average cost specification (23 percent difference from base in the moderate growth scenario), and the static cost specification (34 percent difference from base in the moderate growth scenario). When dynamic rising marginal costs of afforestation are considered, about a 5 percent decline occurs in other agricultural land area. This difference is driven by the increased price of afforestation, which allows alternative mitigation activities on other agriculture lands to be at a lower relative cost compared with afforestation. This difference in price exists for a shorter period of time in the moderate growth scenario which is why there is not a large increase in other agricultural lands in this scenario. This discrepancy between cost scenarios could significantly alter mitigation potential from the land-use sectors.

With all cost specifications, most of the projected afforestation occurs in the southeast due to the high productivity and prevalence of plantation-style forests in this region. These forests are relatively quick growing, and a forward-looking model such as FASOMGHG balances the expected future benefits from increased future yields with the additional costs that intensive management incurs in the current period. Afforestation is slightly delayed in the dynamic marginal cost specification to lessen the effect of higher relative conversion costs by waiting until carbon prices have increased. Furthermore, for all cost specifications, afforestation occurs mostly on other agricultural lands, including pasture in the southeast, which have lower conversion costs and net opportunity costs relative to cropland.

Figure 5 presents cumulative GHG mitigation potential from the forest sector under the low- and moderate-growth mitigation scenarios. These estimated values represent projected cumulative forest carbon stock changes, disaggregated between changes in carbon storage in existing forests and carbon stock changes driven by afforestation. Such results are driven by management changes (including forest rotation extension and pre-harvest thinnings) and reduced land conversion. Potential mitigation on afforested lands represents aboveground forest carbon changes on new forestlands that have been converted from alternative land uses.

Across the low- and moderate-growth mitigation scenarios, cumulative mitigation potential in the forest sector between the years 2020 and 2050 ranges between 3.3 and 4.9 $GtCO_2$, representing an average annual sequestration increase of more than 200 million tCO_2e/year. These projected carbon stock changes are attributed mostly to existing forests in the near term, but over time in the average (1) and static cost specifications (2), more mitigation is met through afforestation. Between 2030 and 2050, afforestation accounts for approximately 26 percent of the cumulative carbon gains for the average and static conversion cost specifications, whereas only 10 percent of cumulative carbon gains are from afforestation between 2020 and 2030. The dynamic cost specification (3) shows the lowest potential mitigation overall and the lowest relative contribution from afforestation (only 16 percent of cumulative carbon gains is from afforestation between 2030 through 2050). Furthermore, there is a delay in afforestation investments for the dynamic cost specification relative to the average and static cost specifications, which see early extensive margin investments in new forestry for both the low and moderate growth mitigation scenarios. This result illustrates the importance of temporal considerations for conversion costs for projections and policy analysis.

Figure 5. Cumulative mitigation of forest sector in Gt CO_2e across alternative cost specifications and mitigation scenarios



Furthermore, mitigation potential from existing forests is lower overall for the dynamic marginal cost specification (3) relative to the average (1) and static (2) cases. This result suggests that mitigation from extensive margin shifts (afforestation) are complementary to mitigation at the intensive margin on existing forestlands. Lower afforestation levels resulting from the dynamic cost specification reduce forest inventories overall, resulting in less systematic flexibility to extend rotations or increase carbon sequestration through other management interventions on existing forests. Delayed investments in new plantation systems reduces net mitigation potential from other forest management activities on existing forests. Thus, the magnitude, timing, and relative portfolio of mitigation contributions from afforestation and existing forests are all affected by land conversion cost assumptions.

In addition to forestry land-use and carbon stock changes, the alternative cost specifications can affect simulated agricultural production and crop area variables. The agriculture sector faces higher opportunity costs of production when forest mitigation incentives are in place, leading to a decline in agricultural production in both the low- and moderate-growth scenarios when compared with the baseline (selected baseline results, and percent changes from baseline are shown in Tables 1a-d and Tables 2a-d, respectively).

Early in the simulation horizon and across all three cost assumptions, cropland moves into forestry under the influence of the mitigation price incentives. Under the moderate growth scenario, a second decline in cropland and other agricultural lands occurs toward mid-century in both the dynamic and static cost specifications due to the relatively higher mitigation price incentives realized in later simulation periods. Projected land-use change for cropland and other agricultural lands use are lower under the average afforestation cost specification, in which more land moves out of agricultural production early in the moderate-growth scenario simulation horizon.

Changes in regional land use, forest product output, and agricultural commodity production, as well as

Table 1a. Baseline results for key regional output variables in 2050 for each Afforestation Cost Assumption: total land area (million acres)

Region	Forest			Cropland			Other agriculture		
	Average	Dynamic	Static	Average	Dynamic	Static	Average	Dynamic	Static
CB	30.40	32.45	30.92	89.63	89.63	89.63	22.55	20.50	22.03
GP	6.62	6.62	6.62	78.00	78.00	78.00	9.17	9.17	9.17
LS	46.89	49.43	48.51	39.46	39.46	39.46	11.67	9.12	10.04
NE	76.51	77.62	82.12	14.56	14.41	14.11	9.99	9.03	4.84
PNWE	24.89	24.89	24.88	9.48	9.48	9.48	1.12	1.12	1.13
PNWW	26.13	26.13	26.13						
PSW	31.47	31.94	31.94	9.22	9.22	9.22	1.48	1.01	1.01
RM	148.58	154.95	151.81	27.35	27.35	27.35	10.82	4.44	7.58
SC	118.59	104.85	118.47	43.88	43.90	43.86	6.36	20.11	6.36
SE	85.70	84.64	85.57	22.72	21.23	22.59	2.71	5.34	2.71
SW	52.44	52.44	52.44	40.12	40.12	40.12	37.93	37.51	37.80
Total	**648.22**	**645.98**	**659.42**	**374.43**	**372.80**	**373.82**	**113.80**	**117.36**	**102.68**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

Table 1b. Baseline results for key regional output variables in 2050 for each Afforestation Cost Assumption: forest products (million m^3)

Region	Sawlogs			Pulplogs		
	Average	Dynamic	Static	Average	Dynamic	Static
CB	1.74	1.50	2.11	0.60	0.89	0.70
GP	0.68	0.73	0.11	0.95	0.93	0.04
LS	5.94	6.29	5.19	6.19	7.05	5.14
NE	31.83	32.97	35.46	21.86	22.00	23.15
PNWE	11.36	11.70	13.15	3.11	2.65	3.39
PNWW	48.84	38.19	41.14	13.45	9.84	11.97
PSW	5.10	20.30	12.14	0.38	0.37	0.30
RM	15.11	13.43	15.59	7.65	5.65	7.33
SC	86.11	74.14	80.13	53.18	49.12	48.97
SE	76.00	79.90	79.25	41.93	52.57	48.09
SW	0.09	0.09	0.10	0.05	0.12	0.05
Total	**282.79**	**279.23**	**284.35**	**149.35**	**151.18**	**149.15**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

Table 1c. Baseline results for key regional output variables in 2050 for each Afforestation Cost Assumption: cumulative emissions (MMT CO_2e)

Region	Ag CO_2			Ag non-CO_2			Soils CO_2			Forest biomass CO_2		
	Average	Dynamic	Static	Average	Dynamic	Static	Average	Dynamic	Static	Average	Dynamic	Static
CB	8.71	8.71	8.71	3.02	3.02	3.02	-3.82	-3.82	-3.82	-7.65	-7.82	-7.69
GP	5.24	5.24	5.24	1.72	1.72	1.72	-0.27	-0.27	-0.27	-0.86	-0.87	-0.85
LS	3.36	3.36	3.36	1.24	1.24	1.24	-4.25	-4.25	-4.25	-7.06	-7.27	-7.09
NE	0.85	0.85	0.85	0.34	0.35	0.34	-1.62	-1.65	-1.53	-20.87	-20.93	-21.25
PNWE	0.46	0.46	0.46	0.18	0.18	0.18	-0.37	-0.37	-0.37	-2.03	-2.07	-2.04
PNWW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-3.96	-3.96	-3.89
PSW	1.35	1.35	1.35	0.37	0.37	0.37	-0.45	-0.45	-0.45	-3.87	-4.03	-3.83
RM	2.20	2.20	2.20	0.50	0.50	0.50	-0.54	-0.54	-0.54	-6.19	-6.81	-6.44
SC	3.35	3.36	3.35	2.32	2.32	2.32	-6.58	-6.58	-6.58	-20.83	-18.86	-20.50
SE	1.15	1.06	1.15	0.52	0.48	0.52	-3.01	-3.00	-2.98	-13.02	-13.08	-13.02
SW	1.95	2.01	1.95	0.83	0.85	0.83	0.20	0.12	0.16	-4.83	-4.83	-4.83
Total	**28.62**	**28.59**	**28.61**	**11.04**	**11.02**	**11.03**	**-20.71**	**-20.80**	**-20.63**	**-91.16**	**-90.52**	**-91.43**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

Table 1d. Baseline results for key regional output variables in 2050 for each Afforestation Cost Assumption: agriculture products (MMT)

Region	Corn			Rice			Soybeans			Wheat		
	Average	Dynamic	Static	Average	Dynamic	Static	Average	Dynamic	Static	Average	Dynamic	Static
CB	182.38	182.59	183.76	0.00	0.00	0.00	0.00	0.00	0.00	18.55	18.55	18.55
GP	102.89	102.72	102.81	0.00	0.00	0.00	0.00	0.00	0.00	38.28	38.36	38.30
LS	70.77	70.77	70.80	0.00	0.00	0.00	0.00	0.00	0.00	10.85	10.85	10.85
NE	47.60	46.50	46.04	0.00	0.00	0.00	0.00	0.00	0.00	0.79	1.27	0.92
PNWE	1.03	1.03	1.03	0.00	0.00	0.00	0.00	0.00	0.00	13.69	13.46	13.61
PNWW	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PSW	1.57	1.57	1.57	2.53	2.53	2.53	1.52	1.52	1.52	2.03	2.03	2.03
RM	7.93	8.05	7.98	0.00	0.00	0.00	0.00	0.00	0.00	15.73	15.73	15.73
SC	26.33	26.33	26.33	12.15	12.15	12.15	7.29	7.29	7.29	4.14	4.14	4.14
SE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.61	6.20	6.61
SW	10.32	10.80	10.42	1.04	1.08	1.05	0.63	0.65	0.63	8.22	8.53	8.30
Total	**450.81**	**450.34**	**450.73**	**15.73**	**15.76**	**15.74**	**9.44**	**9.46**	**9.44**	**118.88**	**119.12**	**119.04**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

national totals, are displayed in Tables 2a-d, which show cumulative (or total) percent changes in key output variables in 2050 relative to the baseline for the moderate-growth mitigation scenario. National changes are relatively small for most land-use and commodity production categories. Net national land-use change is minimal for croplands and forestlands; the former declines slightly overall, whereas the latter increases. The largest land-use changes occur in other agriculture lands in the average and static cost specifications. Sawtimber production decreases nationally as harvest levels for hardwood sawtimber stands slow. Pulpwood production increases commensurate with the shift to faster-growing plantation systems induced by the mitigation price incentive. Corn production decreases slightly (less than 3 percent), whereas relatively less profitable crops (soy and wheat) decline approximately 5 percent. Rice production also decreases under the influence of the mitigation price, as reductions in methane from rice cultivation are directly incentivized.

The Southeast (SE) region shows the greatest net changes and variability in regional land use and product output across all cost specifications and mitigation scenarios. Land is highly fungible in this region, both at the intensive and extensive margin, so changes to land conversion cost specifications have a dramatic impact on land-use and management projections. Intensive margin changes include more

Table 2a. Cumulative (or total) percent changes in key regional output variables in 2050 relative to the baseline for the moderate growth mitigation scenario: total land area

	Forest			Cropland			Other agriculture		
Region	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**
CB	0.0%	6.7%	44.2%	0.0%	0.0%	0.0%	0.0%	-10.3%	-61.3%
GP	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
LS	23.1%	3.5%	17.9%	-3.6%	-3.6%	-3.6%	-82.2%	-4.0%	-71.8%
NE	12.7%	6.8%	5.2%	-9.0%	-41.1%	-23.2%	-80.3%	0.4%	-12.4%
PNWE	-1.5%	-2.1%	-0.8%	-11.0%	-10.7%	-14.4%	113.5%	133.9%	132.1%
PNWW	0.0%	0.0%	0.0%						
PSW	0.0%	-1.5%	0.8%	0.0%	0.0%	-8.7%	-0.2%	46.5%	46.4%
RM	0.0%	-3.5%	-0.5%	0.0%	-3.1%	-8.0%	0.0%	126.5%	32.7%
SC	0.4%	-0.8%	-0.6%	-0.3%	-0.3%	-0.2%	-4.0%	4.8%	8.6%
SE	14.1%	12.8%	14.2%	-62.8%	-60.9%	-62.7%	-8.6%	-5.0%	-8.2%
SW	0.0%	0.0%	0.0%	23.7%	38.7%	41.0%	-13.7%	-22.7%	-23.7%
Total	**5.2%**	**2.1%**	**5.7%**	**-3.5%**	**-3.5%**	**-3.8%**	**-19.3%**	**-0.9%**	**-23.2%**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

Table 2b. Cumulative (or total) percent changes in key regional output variables in 2050 relative to the baseline for the moderate growth mitigation scenario: forest products

	Sawlogs			Pulplogs		
Region	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**
CB	105.7%	118.5%	71.0%	99.2%	20.2%	94.7%
GP	-39.6%	-40.7%	-44.3%	-83.4%	-83.4%	-66.5%
LS	-21.8%	-15.8%	-17.3%	29.8%	44.6%	38.4%
NE	-23.9%	-29.7%	-27.4%	-29.0%	-21.0%	-30.2%
PNWE	-17.4%	-16.6%	-19.0%	-35.2%	-30.5%	-37.5%
PNWW	-9.2%	-2.0%	-5.7%	-21.7%	5.9%	-21.3%
PSW	-33.8%	-26.1%	-17.1%	-16.8%	-13.3%	4.1%
RM	-26.3%	-7.7%	-18.6%	-37.2%	-37.8%	-27.0%
SC	8.2%	-5.3%	0.1%	19.7%	6.2%	17.3%
SE	-7.9%	-6.3%	-9.0%	-2.2%	6.1%	0.6%
SW	24.2%	8.7%	17.9%	-5.8%	18.1%	91.0%
Total	**-7.4%**	**-8.5%**	**-8.5%**	**2.1%**	**2.8%**	**2.9%**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

Table 2c. Cumulative (or total) percent changes in key regional output variables in 2050 relative to the baseline for the moderate growth mitigation scenario: emissions

	Ag CO_2			Ag non-CO_2			Soils CO_2			Forest biomass CO_2		
Region	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**
CB	-1.7%	-1.4%	-1.4%	-0.1%	0.0%	-0.1%	-0.8%	-3.5%	-21.5%	-1.4%	-4.3%	-13.9%
GP	-1.1%	-1.0%	-1.2%	0.1%	0.2%	0.1%	0.0%	0.0%	0.0%	3.8%	4.2%	2.6%
LS	-3.8%	-3.7%	-3.7%	-2.7%	-2.7%	-2.7%	-10.1%	-1.6%	-8.5%	-7.5%	-0.3%	-6.1%
NE	-7.0%	-36.1%	-19.9%	-6.7%	-34.2%	-18.7%	-4.4%	-3.3%	-1.4%	-4.2%	-2.4%	-0.2%
PNWE	-6.4%	-7.5%	-9.0%	-6.7%	-8.2%	-9.8%	0.8%	0.9%	0.6%	0.7%	0.2%	0.1%
PNWW							0.0%	0.0%	0.0%	-2.1%	-2.1%	-2.1%
PSW	-0.4%	-0.4%	-4.5%	-0.7%	-0.6%	-4.2%	-0.2%	0.7%	-1.1%	-7.2%	-6.3%	-7.7%
RM	-0.2%	-1.7%	-3.2%	0.1%	-1.9%	-4.1%	0.0%	1.0%	0.2%	-0.1%	1.3%	0.0%
SC	0.7%	0.6%	0.7%	-2.4%	-2.3%	-2.2%	-6.7%	-6.6%	-6.2%	-9.6%	-9.7%	-7.4%
SE	-45.0%	-43.5%	-45.0%	-48.2%	-46.9%	-48.1%	-9.5%	-8.7%	-9.2%	-13.7%	-9.4%	-13.0%
SW	10.3%	17.8%	19.1%	4.8%	10.5%	11.2%	1.0%	1.8%	1.9%	0.3%	0.4%	0.3%
Total	**-2.5%**	**-2.7%**	**-2.7%**	**-4.3%**	**-4.3%**	**-4.1%**	**-3.2%**	**-1.9%**	**-3.7%**	**-4.8%**	**-3.3%**	**-4.4%**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

Table 2d. Cumulative (or total) percent changes in key regional output variables in 2050 relative to the baseline for the moderate growth mitigation scenario: agriculture products

	Corn			Rice			Soybeans			Wheat		
Region	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**	**Average**	**Dynamic**	**Static**
CB	-2.0%	0.7%	0.5%				3.4%	3.4%	3.5%	-20.1%	-21.9%	-21.1%
GP	-0.6%	0.5%	-1.6%				0.0%	3.6%	-3.8%	-0.1%	-0.7%	0.5%
LS	-4.1%	-3.6%	-3.9%				-3.6%	-3.6%	-3.6%	-3.4%	-3.4%	-3.4%
NE	-14.7%	-45.5%	-28.7%				-14.5%	-45.3%	-28.5%			
PNWE	-0.7%	2.7%	-1.8%							-9.6%	-7.8%	-12.6%
PNWW												
PSW	-0.2%	-0.6%	-1.7%	-2.1%	-1.5%	-0.9%				-0.6%	0.3%	0.5%
RM	1.7%	-1.6%	-8.1%							1.0%	-2.3%	-10.5%
SC	4.5%	4.9%	5.7%	-5.8%	-5.0%	-4.8%	-4.7%	-3.8%	-3.7%		0.0%	-48.9%
SE							-60.3%	-58.2%	-60.2%			-100.0%
SW	7.4%	9.8%	9.9%	-12.1%	-11.8%	-11.4%	8.5%	9.9%	10.7%	-2.1%	-0.2%	-0.4%
Total	**-2.5%**	**-2.3%**	**-2.2%**	**-5.7%**	**-5.0%**	**-4.7%**	**-4.7%**	**-5.0%**	**-5.1%**	**-4.7%**	**-5.3%**	**-6.1%**

Notes: Regional abbreviations are CB: Corn Belt, GP: Great Plains, LS: Lake States, NE: Northeast, PNWE: Pacific Northwest-East, PNWW: Pacific Northwest-West, PSW: Pacific Southwest, SC: South Central, SE: Southeast, SW: Southwest.

forest-planting and crop-mix changes, whereas total agricultural land declines significantly in the SE as more land is afforested and crop production shifts to other regions. Agricultural production and associated emissions increase in the Southwest (SW) region as corn and soybean production expands in this region to compensate for lost production elsewhere in the system (hence, leakage from afforestation in more productive crop producing regions). Crop mix changes occur in other regions, and these crop mix changes are also sensitive to cost specifications (e.g., the South Central [SC]).

The regional effects are more variable with dynamic afforestation cost specification (3), suggesting that interregional allocation of land-use and management changes in response to carbon policies are more sensitive to land conversion cost specifications than national-level results.

Discussion and Conclusions

This analysis compares alternative afforestation cost specifications using a detailed intertemporal economic model of US forestry and agriculture. Although previous literature has evaluated afforestation potential under different policy drivers or has provided comparisons of mitigation outputs across multiple models (van Meijl et al., 2018), few studies have focused on the implications of alternative land conversion cost specifications within a single modeling framework. We seek to fill this gap by differentiating two commonly used frameworks (average and static rising marginal costs), plus a newly developed dynamic marginal conversion cost specification. To provide a direct comparison of conversion cost representations, we develop projections of afforestation and other relevant variables on a regional scale across a baseline and two hypothetical GHG mitigation policy scenarios.

Projecting afforestation potential under alternative policy assumptions remains important given the current state of voluntary carbon markets in the United States and elsewhere, in which markets are incentivizing conversion of marginal agricultural lands to forestry (Van Winkle et al., 2017). Incorporating spatial heterogeneity in conversion cost assumptions can aid in planning for public or private entities interested in offset market development or investment. Furthermore, recent literature has emphasized the potential contributions of land-based mitigation strategies for achieving long-term climate stabilization goals (Tian et al., 2018; Rose et al., 2012). Recent integrated assessment modeling literature discusses the critical role of the global land-use sectors in supporting negative emissions technologies such as bioenergy with carbon capture and sequestration, plus traditional carbon sequestration pathways through afforestation (Havlík et al., 2014; Doelman et al., 2018). Furthermore, a recent US government report suggested that significant investments in new forests will be required if the United States pursues a mid-century climate action pathway consistent with the long-term ambitions of the Paris Agreement (The White House, 2016). Thus, increased attention to afforestation as a key mitigation strategy supports the need to improve land conversion cost assumptions to more accurately assess large-scale land-use change potential and associated economic costs, especially over long time frames.

If policy efforts include afforestation in mitigation, more robust estimates of conversion costs can improve methodologies designed to evaluate the potential spatial extent and costs of afforestation, which in turn can help improve policy design. Even in the absence of GHG policy goals, improving afforestation cost specifications in projections-modeling frameworks is important in regions such as the United States, where changes in forest-product market demand (e.g., increased demand for wood pellets) can increase investment in forests at the intensive and extensive margins (Tian et al., 2018; Galik & Abt, 2016).

Results of our analysis indicate the potential sensitivity of land-use change, carbon sequestration, and commodity production projections to alternative afforestation cost specifications, especially in light of a meaningful GHG mitigation price incentive. Models that rely on regional average conversion cost assumptions may overstate afforestation potential in response to a policy or market incentive by not accounting for the diminishing returns associated with varying land qualities. That is, developing upward sloping marginal cost functions based on heterogenous land quality and conversion costs can improve land-use change projections for market models that are represented by regional aggregates. (Example modeling frameworks include FASOMGHG and most partial-equilibrium, computable general equilibrium, and integrated assessment models.)

Furthermore, relying on upward-sloping marginal cost functions that are not dynamic in nature can also bias simulation results, as relatively inexpensive land is available to convert to forestry in all simulation periods. To address this potential bias, we develop new marginal cost functions based on county-level estimates adapted from (Nielsen et al., 2014) and a dynamic conversion cost specification that aligned to the intertemporal modeling framework applied in this framework. These dynamic marginal cost estimates better reflect trade-offs that landowners face, which leads to more robust projections of mitigation potential. Our results show substantial differences in the magnitude, timing, and portfolio of GHG-mitigation contributions from afforestation and existing forests and other regional outputs under the dynamic marginal cost specification. Thus, simplified average land conversion cost assumptions can result in both temporal and spatial bias.

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