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Agriculture Afforestation for Carbon Sequestration Under Carbon Markets in the United States: Leakage Behavior from Regional Allowance Programs

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Abstract *This study quantifies how leakage behavior from afforesting agricultural land affects the intensification of agricultural production. In particular, we examine the leakage percentage from carbon offset allowance at specific southern regions in the United States as a part of a carbon market. We use the Forest and Agriculture Sector Optimization Model-Greenhouse Gases model to examine responses between sectors as part of the regional afforestation policy analysis. Regional characteristics and a policy's time frame are found to play important roles in achieving net gains, in terms of greenhouse gases stored, from such regional policies. In some cases, however, leakage greater than 100% is evident.*

Key words: Agricultural afforestation, carbon markets, economics, leakage.

JEL codes: Q23, Q54, R14.

In recent years there has been an ongoing discussion on the potential of the agricultural and forest sectors to serve as carbon offset providers (Baker et al. 2010; Johansson et al. 2012). Indeed, recent high-profile bills for cap-and-trade legislation have aimed to limit greenhouse gases (GHG) from U.S. energy sectors. For example, the American Clean Energy and Security Act (H.R. 2454 2009) provided mechanisms to incorporate the sale of forest and agriculture sector carbon sequestration offsets to the capped sectors. In addition, it has been suggested that including these two sectors in a carbon trading system creates incentives to both control land use emissions and increase land use sinks (Reilly and Asadoorian 2007).

Currently, two regional collaborative efforts to control greenhouse gas emissions from the state governmental level are operating in the United States. These two market-based programs that focus on the energy sectors are the Regional Greenhouse Gas Initiative (RGGI) and the cap-and-trade program in California. Although the latter has maintained a steady carbon allowance price since its establishment in early 2013 ($11.50 per allowance as of May 16, 2014), the former has experienced a higher volatility in allowance prices with a minimum carbon allowance price of $1.86 (December 2010) and a maximum allowance price of $5.02 (as of June 2014).[1,2] Leakage of electricity production, and therefore of CO_2 emissions, to unregulated regions is suggested to be a significant concern in regional programs (Bushnell and Chen 2012). In addition, it is suggested that CO_2 leakage from regional programs are negatively related to carbon prices (Chen 2009). A projected increase in carbon price up to $80 per CO2-eq by 2030, with further increases by 2050, as suggested by the IPCC (IPCC 4th assessment 2007) should alleviate some of the CO_2 leakage from regional programs.

Although from an economic point of view, the more cost-efficient GHG reductions would be caused by an international or national reduction program, the two regional initiatives demonstrate the greater feasibility of a second-best solution under current political constraints. In the California program, regulated firms are expected to use forest offset credits to partially meet their reduction requirements for 2014. A similar approach may be adopted by the RGGI program as an attempt to elevate its low allowance prices ($3.21 per allowance as of June 5, 2013; Burtraw et al. 2013).

Afforestation of agricultural land has significant capacity to sequester carbon under potential carbon pricing programs (Alig et al. 2010a; Gorte 2009). Furthermore, some authors suggest that forest-based carbon sequestration is cost-effective in achieving reduction of about one-third of the U.S. target under the Kyoto Protocol (Lubowski et al. 2006; Richards and Stokes 2004). Other authors suggest an increase in net farm income due to afforestation of agricultural land, mainly through higher prices of commodities, increased demand for bioenergy feed-stocks, and additional revenues from offsets (Baker et al. 2010). However, despite the potential for significant offsets of emitted carbon through afforestation, a number of unknowns exist. These relate to sequestered carbon integrity, and in particular to how intensification of agricultural production on remaining agricultural land may reduce the projected magnitude of carbon sequestered through afforestation of agricultural land.

Several activities that mitigate GHG emissions have come under scrutiny for the net amount of damage avoided once both carbon emitted in production practices and indirect impacts are considered (e.g., Fissore et al. 2010). One reason is that market adjustments may reduce the net reductions provided by forest and agricultural GHG mitigation activities. Often, the focus of scrutiny is on the indirect land use changes that may occur as land owners adjust their behavior to increase their net returns given the new economic landscape with forest and agriculture offsets. This leakage occurring elsewhere (i.e., "distant") because of the sequestration action is difficult to quantify. Thus, most voluntary carbon sequestration programs only attempt to control for "internal" leakage within the acting land owner's operation (Sampson 2005). Using the Forest and Agriculture Sector Optimization

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[1] *For more details on the California Air Resource Board auctions, see http://www.arb.ca.gov/cc/capandtrade/auction/auction.htm.*

[2] *For more details on the Regional Greenhouse Gas Initiative auctions, see http://www.rggi.org/market/co2_auctions/results.*

Model-Greenhouse Gases (FASOM-GHG), Murray et al. (2004) projected that leakage (both "internal" and "distant") was between 20% and 40% for a 10 million acre afforestation program. The study, however, used a predefined temporal distribution of planting. In a later study, Murray et al. (2007) discussed the importance of accounting for leakage from conservation tillage and agriculture set aside programs, pointing out that internal leakage (land use change within the ownership) was relatively easy to control, but "distant" leakage may not be easily controlled and should be accounted for.

Within the United States, frequent land exchange takes place between the agricultural and forest sectors. Historically, compared with other regions, the southern region has experienced a relatively large amount of land-use change between the two sectors (Alig et al. 2010a). For the south, 1.5 and 3.2 million hectares on nonfederal lands transitioned from crop and pastureland uses, respectively, to forestland between 1982 and 1997. During the same period, approximately 0.6 and 1.3 million hectares shifted from forestland to crop and pastureland-uses, respectively (Alig et al. 2010b). In the north region, on the other hand, the dominant movement of land between 1982 and 1997 occurred within the agricultural sector, where about 4 million hectares were shifted from cropland to pastureland and 4.6 million hectares moved in the opposite direction (Alig et al. 2010a). Short timber rotations in the south (20 to 25 years) allow for more flexibility in land conversion between the two sectors, compared with other U.S. regions, as economic conditions changes.

Projected movement of land between agriculture and forest sectors in the south from 2002 to 2062 is even greater (a projected movement of 12.6 million hectares from agricultural to forest uses, and a movement of 7.7 million hectares from forest to agricultural uses). Moreover, competition for land in rural areas increases as rapid population growth occurs, and the area of land in urban-uses nearly doubles its size (Alig et al. 2010b). In the north, land movement within agricultural uses is projected to stay dominant, even though more land is projected to shift between the two sectors compared to the period of 1982 to 1997 (Alig et al. 2010b). This reflects the hesitancy of farmers and ranchers in the north to switch to forestland, probably owing to the longer timber rotations in the north compared to the south.

It has been suggested that GHG benefits from a particular afforestation program may be partially offset by converting forestland to agricultural uses in the other areas, implying a potential leakage from afforestation programs (Alig et al. 1997). Such emissions displacement in time and space outside of an afforestation program's boundaries should be quantified for proper accountability of GHG benefits generated by such a program. The objective of this paper is to examine the leakage behavior from afforesting agricultural land on the intensification[3] of agricultural production under carbon markets at the regional level in the United States. In particular, we quantify how tillage behavior and land use changes within the agricultural sector depend on whether afforestation offsets are allowed in two southern U.S. regions as part of a carbon market. To capture interactions between the

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[3] *Intensification of agricultural land includes changes in tillage practices, fertilization regimes, and irrigation patterns. Though our model incorporates all of the above in the analysis we only assess changes in tillage practices in this study due to space limitations.*

agriculture and forest sectors, we employ the FASOM-GHG, which projects changes in land uses involving forestry and agriculture and has an extensive carbon accounting system for the U.S. private forest and agricultural sectors, including final products and disposal.

The paper is organized as follows. In the next section we describe our policy simulation model and the methods used to examine alternative afforestation programs. Results are presented in the third section. We first present results for the base (zero carbon prices), and for the national carbon market program that disallows afforestation carbon offsets everywhere. We then present changes due to allowing afforestation carbon offsets only in specific regions relative to disallowing afforestation carbon offsets everywhere. Results include land area changes, agricultural production intensification (via changes in tillage behavior) and GHG stocks. The fourth section discusses the policy implications of our findings, while the fifth section concludes.

Simulation Analysis

Model Description. The FASOM-GHG is an equilibrium linked model of the agriculture and forest sectors that uses an inter-temporal dynamic optimization approach to simulate markets for numerous agriculture and forest products[4] (Adams et al. 1996; Lee et al. 2007). Because the model is linked across sectors, the agriculture and forest sectors can interact in the provision of substitutable products (e.g., biomass feedstock) and the use of lands that could produce either agriculture or forest products. Production, consumption, and export and import quantities in both sectors are endogenously determined in FASOM-GHG as management strategy adoption, land use allocation between sectors, and resource use, among other variables. Commodity and factor prices are endogenous, and determined by the supply and demand relationships in all markets included in the model. In addition to land conversion between the two sectors, FASOM-GHG also exogenously includes the conversion of land from the agriculture and forest sectors to developed land use. The FASOM-GHG includes all states in the contiguous United States, broken into 11 market regions.[5] Afforestation of agriculture land is feasible in only eight regions (afforestation in the Great Plains, western Texas, and the western portion of the Pacific Northwest is currently not considered).

For carbon accounting associated with afforestation, FASOM-GHG adopts the FORCARB approach (Birdsey et al. 2000). Other GHG accounting is from McCarl and Schneider (2001). The three primary agricultural GHGs, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are

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[4] *The FASOM-GHG combines component models of agricultural crop and livestock production, renewable fuels production, livestock feeding, agricultural processing, log production, forest processing, carbon sequestration, GHG emissions, wood product markets, agricultural markets, and GHG payments. For complete documentation of the FASOM-GHG model, see http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf or http://www.cof.orst.edu/cof/fr/research/tamm/FASOM_Documentation.htm.*

[5] *Though FASOM-GHG accounts for international trade in both forestry and agricultural products, we focus our attention on policy impacts within the United States.*

represented in the model. The FASOM-GHG accounts for and tracks a variety of agriculture and forest resource conditions and management actions. In addition to traditional agriculture and forest products, selected agricultural and forestry commodities can be used as feedstocks for biofuel production processes in FASOM-GHG. This, in turn, might affect fossil fuel usage and associated GHG emissions after accounting for emissions during hauling and processing of bioenergy feedstocks (hereafter referred to as offset fossil fuel emissions). A detailed description of GHG accounts by sector is found in appendix A. The FASOM-GHG is generally run for the timeframe 2010 to 2080, represented in 5-year time periods.

Simulating Baseline and National Carbon Market Program that both Disallows Afforestation Carbon Offsets Everywhere and Allows Afforestation Carbon Offsets only in Specific Regions. Within FASOM-GHG, a variety of practices and land use changes are available for agriculture and forestry producers to supply GHG offsets to a potential carbon market. In standard FASOM-GHG runs, all significant offset activities are available to their respective sectors and those activities are adopted as appropriate given optimal behavior. Land owners receive carbon payments for offsets but are penalized for carbon released to the atmosphere. There are no assumed contract lengths and management actions and land use changes can occur at any time based on market conditions.

Our initial run introduced an option in FASOM-GHG that does not allow carbon offsets to be provided by afforesting agriculture land. Agriculture operators were still able to afforest land to capture timber production values and supply bioenergy feedstocks (e.g., logging residues or short-rotation woody crops). We completed a zero carbon price (base case) as well as two standard FASOM-GHG carbon pricing runs at $30 and $50/tons CO_2, given national implementation of the policy.

In our second step, we compared each of the two runs with carbon prices with the base to quantify the magnitude of the importance of afforestation to the agriculture sector GHG offset provision in aggregate. In particular, we looked at area changes in land-uses, tillage practices, and changes in net GHG stored in agriculture, forests, and amount of avoided carbon emissions from bioelectricity production. Our third step included runs for which carbon offsets for the afforestation of agriculture land were allowed only within selected regions. Regional allowances were applied to the South Central (SC) region and the South East (SE) regions and were conducted for the same two carbon prices, and resulted in four additional runs. As before, changes in examined variables relative to the base (zero carbon price) were computed. Finally, changes at each one of the regional allowances for each carbon price relative to the base were compared with changes from runs disallowing carbon offsets for afforestation at the national level, relative to the base.

Using the abovementioned process, the additionality of each one of the regional programs was ensured. This is because any net gain or loss in GHG that would have occurred anyway under the base (disallowing carbon offsets from afforestation of agricultural land in all regions) was net out from our calculations. This procedure allowed us to explore how important each of the southern regions is to agriculture sector offsets. In addition, we were able to quantify the overall leakage (both internal and "distant") associated with the afforestation of agricultural land in individual regions. For clarity, only area changes that were greater than 0.2 million hectares and changes in GHG emissions of greater than 50 million tons in the regional allowance programs, relative to the national program, were considered. Moreover, we focus our attention on the first 45 years of the projection, which we believe to be the policy-relevant period. In this period the impact of-terminal conditions on the results is minimal.

Projected national and regional land areas were aggregated into four categories: energy crops, conventional crops, pasture,[6] and forest. Energy crops are plants grown as low-cost and low-maintenance harvest used to make biofuels or combusted for their energy content to generate electricity or heat. The FASOM-GHG currently includes three energy crops: switchgrass, willow, and hybrid poplar.[7] We distinguished between energy and conventional crops to capture different land area trends in these two categories as resulting from the introduction of carbon markets.

Results

Base (Zero Carbon Prices) and a National Carbon Market Program that Disallows Afforestation Carbon Offsets Everywhere

Area Changes. Projected average areas of land covered by forest, conventional cropland, energy crops, and pasture for the base (zero carbon prices) for 2010–2030 (short-term), and 2030–2055 (long-term) are reported in table 1. Although forest area nationally declines by about 7% between the short- and long-terms, only small decreases are evident in hectares of conventional crops and pasture between the two periods. Furthermore, area devoted to energy crops expands by about 30% due to the Renewable Fuel Standard (RFS2) requirements incorporated in FASOM-GHG.[8]

The national trend masks a considerable movement of land between the agriculture and the forest sectors in the regional level between the two periods. Contrary to the national trend, the area covered by conventional cropland in the SC region expands by about 2.4 million hectares (a 22% increase). About half of the national decrease in forestland occurs in the SC region, where forest area declines by 4 million hectares (a 9.5% decrease). The southwest (SW) region is responsible for about 75% of the decline in area of conventional cropland in the REST region (a bit more than 1.2 million hectares), which includes the Great Plains, Pacific Southwest, Pacific Northwest Westside, Pacific Northwest Eastside, and SW (GP, PSW, PNWW, and PNWE, respectively).

Also presented in table 1 are areas changes in land uses under the national carbon market program without carbon offsets from afforestation ("disallowing everywhere") for both carbon prices for the short-term and the long-term, relative to the base (zero carbon prices). Using longer timber rotations to capture carbon gains and to delay deforestation carbon payments result in area increases of 1.5% and 4.5% in national forestland in the short- and long-terms, respectively, with further moderate increases with a

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[6] *Pastureland includes cropland pasture, private rangeland, public rangeland, private grazed forest, and public grazed forest. For further details see http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf.*

[7] *For further details on energy crops in FASOMGHG, see subsection 5.1.2 in http://www.cof.orst.edu/cof/fr/research/tamm/FASOMGHG_Model_Documentation_Aug2010.pdf.*

[8] *Area in urban land expands by 31 and 58 million acres in the short- and long-term, respectively.*

Table 1 Projected Average Areas in Forestland, Conventional Cropland, Energy Crop, and Pastureland for the Base (Zero Carbon Prices), as well as Projected Changes Relative to the Base under Disallowing Everywhere Scenario for $30 and $50 Carbon Prices per Tonne for the Period 2010–2030 (short-term) and the period 2030–2055 (long-term)

		Forestland (MM hectares)			**Conventional Cropland (MM hectares)**			**Energy Crops (MM hectares)**			**Pasture (MM hectares)**		
			Change			*Change*			*Change*			*Change*	
		0	**30**	**50**	**0**	**30**	**50**	**0**	**30**	**50**	**0**	**30**	**50**
National	Short	139.22	2.04	2.80	118.84	(7.56)	(10.87)	1.54	7.76	12.38	287.46	(2.44)	(4.73)
	Long	129.66	5.83	7.26	117.87	(6.58)	(9.13)	2.18	9.40	13.03	287.13	(3.82)	(10.83)
CB	Short	11.47	(0.75)	(0.76)	33.89	(3.49)	(4.30)	0.00	3.44	4.22	3.72	0.00	0.00
	Long	9.79	0.00	0.22	33.89	(4.18)	(4.25)	0.34	3.91	3.90	4.41	1.67	1.84
LS	Short	10.33	0.58	0.58	15.24	(2.04)	(2.35)	0.00	1.55	1.84	0.57	(0.00)	(0.00)
	Long	9.11	1.36	1.47	15.29	(2.42)	(2.53)	0.00	1.81	1.79	0.64	(0.00)	(0.00)
NE	Short	27.75	(0.51)	(0.53)	2.06	0.81	0.87	0.00	0.28	0.29	3.38	0.00	0.00
	Long	27.02	0.76	0.86	0.35	1.72	1.78	0.00	0.26	0.27	3.88	(0.00)	(0.45)
RM	Short	7.38	0.78	0.78	8.90	0.00	(0.61)	0.00	0.00	1.03	141.98	(0.78)	(1.20)
	Long	7.39	1.95	2.01	9.00	0.00	(0.93)	0.00	0.00	1.15	141.79	(2.08)	(2.23)
SC	Short	43.22	1.20	1.56	11.02	(1.56)	(2.02)	0.49	0.87	0.80	17.74	(0.45)	(0.26)
	Long	39.14	0.31	0.57	13.44	(1.02)	(1.34)	0.55	1.22	1.17	16.89	(0.00)	(0.00)
SE	Short	29.35	0.68	1.03	5.44	(0.53)	(0.62)	0.00	0.57	0.59	9.51	(0.71)	(1.10)
	Long	27.77	1.21	1.90	5.13	(0.00)	(0.22)	0.45	0.29	0.29	9.45	(1.49)	(2.12)
REST	Short	9.72	0.00	0.00	42.30	(0.74)	(1.84)	0.80	1.05	3.60	110.53	(0.63)	(2.12)
	Long	9.44	0.00	0.23	40.77	(0.73)	(1.63)	0.77	1.83	4.46	110.07	(1.49)	(7.71)

Note: Values in parentheses contain negative values.

higher carbon price relative to the base. Consequently, less conversion of land from forest to agricultural uses occurs under the disallowing everywhere scenario, relative to the base. In addition, with the introduction of carbon markets the profitability of energy crops increases relative to conventional cropland and pasture, so farmers shift more land in the agricultural sector towards energy crops. For these reasons the area covered by conventional cropland and pasture decline considerably, whereas the area covered by energy crops tremendously increases under both carbon prices for both periods, relative to the base.

At the regional level, the Corn Belt (CB) and the NE regions experience a constant decline in forest area in the short-term across the two carbon prices, relative to the base, which is opposite to the national trend. However, in the long-term no region shows a decline in forest area, relative to the base, for the two carbon prices. Furthermore, conventional cropland expands by about 40% and 500% in the NE region in the short- and long-terms for both carbon prices, respectively, relative to the base. The longer timber rotations in the NE, compared with other regions, together with increases in prices of agricultural commodities due to hectare decline in conventional crops in other regions incentivize land owners in the NE to enter idle land into crop production. Moreover, farmers in the CB (LS) region shift between 10.0% and 12.5% (13.5% and 16.5%) of their conventional cropland to energy crops (to both energy crops and forestland) to realize monetary gains from positive carbon prices.

Projected average afforested area under the base (zero carbon price) and changes in afforested area under the disallowing everywhere scenario for \$30 and \$50 carbon prices per ton, relative to the base, for 2010–2055 are presented in figure 1, case 1A. For the base, around 4.8 million hectares are being afforested in the period 2010–2055. The SC region is responsible for 40% and the CB and NE regions individually account for 22% of afforested hectares.[9] After the introduction of carbon markets, national afforested area increases by 150% and 172% for carbon prices at \$30 and \$50, respectively, relative to the base.

Agricultural Production Intensification. Projected averages of area covered by conventional, conservation, and zero tillage in both periods under the base are reported in table 2.[10] Average national hectares covered by both conventional and conservative tillage decline by 2% and 13%, respectively, whereas zero tillage area increases by 18% between the two periods. Consistent with the expansion in conventional cropland in the SC region and unlike the national trend, this region experiences an increase of 32% in conventional tillage (about 2.4 million hectares).

Table 2 also reports average area changes in tillage practices under the disallowing everywhere scenario for \$30 and \$50 carbon prices per ton, relative to the base, for the short- and long-terms. At the national level and consistent with the great expansion in energy crops, hectares of zero tillage almost doubled (tripled) for \$30 (\$50) carbon price in the short-term, relative to the base. This tremendous increase mirrors decreases of 7.5 million (a

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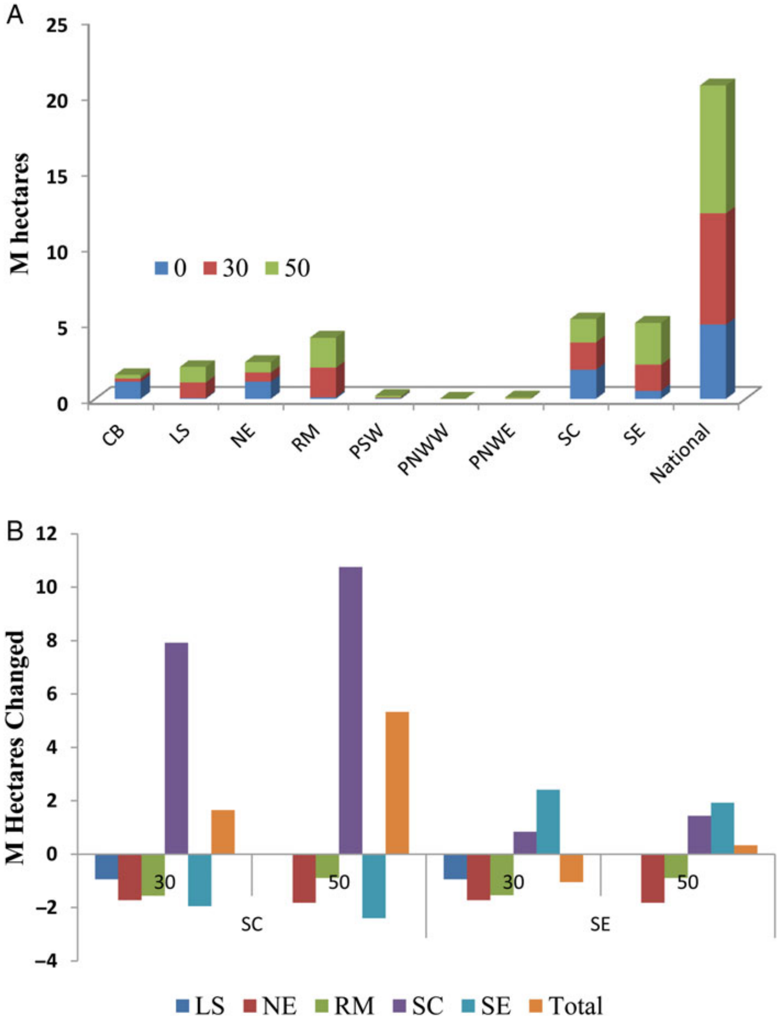
[9] *Due to space constraints, deforestation trends are excluded from this paper. For the base however, the projected national area of deforestation is greater than the area of afforestation for the period 2010 to 2055. This, in turn, results in a decline in total forestland area at the national level under the base.*

[10] *Zero tillage refers to growing agricultural crops from year to year without disturbing the soil through tillage (also known as direct planting).*

Figure 1 Projected average afforested areas for the base (zero carbon prices), changes in afforested area under the disallowing everywhere scenario for $30 and $50 carbon prices per ton, relative to the base, for the period 2010–2055 (Panel 1A), and changes in afforested area under the two regional allowance programs for $30 and $50 carbon prices per ton for the same period, relative to the disallowing everywhere scenario (panel 1B)



61.5% decrease) and 8.8 million hectares (a 62.5% decrease) in conventional tillage for the $30 ($50) carbon price for the short- and long-terms, respectively, relative to the base. This result is largely due to the declines in conventional cropland under carbon markets. Moving away from conventional tillage, farmers reduce their GHG emissions (and therefore payments) and increase their GHG storage (and therefore gains) by adopting zero tillage through higher levels of carbon sequestrated in the soil. And, as carbon prices increase, it becomes profitable to move hectares from conservation tillage to zero tillage. This is indicated by the decline of 70% in conservation tillage hectares for the $50 carbon price in both periods, relative to the base.

A farmer's opportunity cost for switching among the tillage practices varies across regions. For example, in the SC region most of the land shifts from conventional to zero tillage in the short-term. On the contrary, major

Table 2 Projected Average Areas in Conventional, Conservation, and Zero Tillage for the Base (Zero Carbon Prices), as well as Projected Changes Relative to the Base under the Disallowing Everywhere Scenario for $30 and $50 Carbon Prices per Ton for the Period 2010–2030 (short-term) and the period 2030–2055 (long-term)

		Conventional Tillage (MM hectares)			**Conservation Tillage (MM hectares)**			**Zero Tillage (MM hectares)**		
			Change			*Change*			*Change*	
		0	**30**	**50**	**0**	**30**	**50**	**0**	**30**	**50**
National	Short	75.93	(14.18)	(46.63)	22.80	(4.25)	(15.90)	21.63	18.64	64.04
	Long	74.56	(16.41)	(46.77)	19.89	(13.06)	(14.43)	25.57	32.33	65.13
CB	Short	18.37	(0.00)	(14.92)	6.55	0.00	(6.41)	8.97	0.00	21.26
	Long	18.68	(0.96)	(15.17)	6.55	(6.41)	(6.41)	8.97	7.11	21.26
LS	Short	10.91	(5.95)	(8.16)	2.91	0.00	0.00	1.42	5.46	7.65
	Long	11.00	(6.07)	(8.39)	2.91	0.00	0.00	1.42	5.46	7.65
NE	Short	0.97	0.53	0.59	0.00	0.54	0.54	1.06	0.00	0.00
	Long	0.00	0.85	0.94	0.00	1.02	0.21	0.19	0.90	0.90
RM	Short	5.80	(0.00)	(1.19)	2.45	(1.42)	(2.10)	0.66	1.59	3.70
	Long	5.72	(1.23)	(2.15)	1.20	(1.00)	(1.00)	2.08	2.36	3.36
SC	Short	7.75	(5.08)	(5.32)	1.15	(0.49)	(1.15)	2.59	4.88	5.26
	Long	10.25	(6.52)	(6.36)	1.15	(1.12)	(1.15)	2.60	7.85	7.34
SE	Short	4.12	(0.29)	(2.49)	0.24	(0.24)	(0.24)	1.20	0.57	2.71
	Long	3.52	(1.28)	(2.04)	0.00	0.00	0.00	2.06	1.51	2.10
REST	Short	28.01	(3.16)	(15.14)	9.37	(1.20)	(13.61)	5.71	6.11	23.44
	Long	25.22	(2.64)	(6.54)	8.07	(4.76)	(6.08)	8.26	7.14	22.52

Note: Values in parentheses contain negative values.

land movement from conventional to zero tillage happens in the REST and the CB regions only for the $50 carbon price. The NE is the only region to experience an increase in conventional tillage under carbon markets, relative to the base. This is in agreement with the projected increase in conventional cropland in this region.

GHG Stocks. Table 3 presents stocks of regional GHG emissions in million tons GHG emitted from agriculture, forestry, and offset fossil fuel emissions for the base (zero carbon prices) in the short- and long-terms. Net GHG stock in the agriculture sector declines by 28% between the two periods. This decline is mainly due to higher carbon emissions from the use of fossil fuel, grain drying, water pumping, and fertilizer production, and from increased methane emissions from enteric fermentation and manure management in the long-term. No major changes appear in net GHG stock from offset fossil fuel emissions and forestry between the two periods, despite the considerable decline in forestland between them. This is mainly due to increased GHG stock from afforestation activities, which reaches its maximum at 2040. The agricultural sector in all regions remains a GHG sink with the exception of the SE region in the long-term (due to increased emissions from fertilizer production, methane enteric fermentation, and manure management).

Changes in stocks of GHG emissions in million tons of GHG emitted from agriculture, forestry, and offset fossil fuel emissions under the

Table 3 Projected Average Stock of Regional GHG Emissions in Million Tons GHG Emitted for the Base (Zero Carbon Prices), as well as Changes in Stock of GHG Relative to the Base under the Disallowing Everywhere Scenario for $30 and $50 Carbon Prices per Ton for the period 2010–2030 (Short-term) and the Period 2030–2055 (Long-term)

		Offsets Fossil Fuel Emissions			**Agriculture**			**Forest**		
		Stock	***Change in Stock***		***Stock***	***Change in Stock***		***Stock***	***Change in Stock***	
		0	**30**	**50**	**0**	**30**	**50**	**0**	**30**	**50**
National	Short	0	(1,934)	(2,589)	(27,743)	(450)	(818)	(73,182)	(2,308)	(3,509)
	Long	0	(7,850)	(9,448)	(19,971)	(408)	(1,048)	(74,539)	(7,146)	(10,028)
CB	Short	0	(682)	(913)	(4,819)	(154)	(372)	(5,991)	(280)	(233)
	Long	0	(2,866)	(3,113)	(3,212)	(68)	(436)	(5,684)	(96)	0
LS	Short	0	(159)	(200)	(1,281)	(107)	(150)	(6,949)	(675)	(673)
	Long	0	(804)	(889)	(587)	(162)	(248)	(6,391)	(1,501)	(1,580)
NE	Short	0	(87)	(86)	(532)	0	0	(20,440)	(220)	(621)
	Long	0	(228)	(246)	(326)	(187)	(184)	(20,486)	(1,059)	(1,550)
RM	Short	0	0	(150)	(8.109)	(51)	(63)	(2,995)	(340)	(427)
	Long	0	(210)	(552)	(7,361)	(110)	(113)	(2,976)	(1,391)	(1,636)
SC	Short	0	(384)	(365)	(2,889)	(206)	(249)	(17,070)	(838)	(1,280)
	Long	0	(1,501)	(1,352)	(1,965)	(411)	(464)	(17,994)	(1,316)	(2,262)
SE	Short	0	(203)	(201)	0	0	0	(13,274)	(192)	(341)
	Long	0	(696)	(640)	377	0	0	(13,778)	(1,005)	(1,754)
REST	Short	0	(373)	(674)	(10,082)	(69)	(128)	(6,463)	(323)	(400)
	Long	0	(1,546)	(2,657)	(6,897)	(69)	(228)	(7,231)	(971)	(1,279)

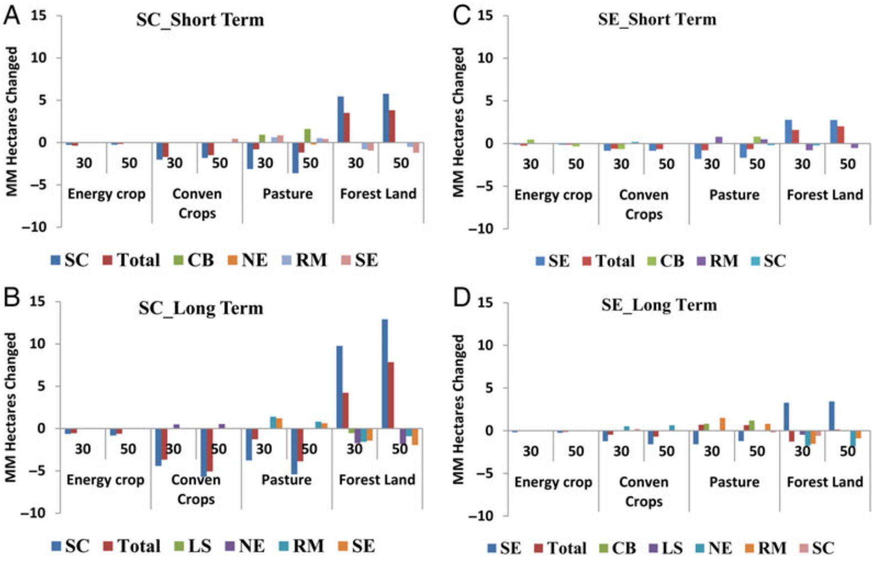
Note: Values in parentheses contain negative values.

disallowing everywhere scenario for $30 and $50 carbon prices per ton for the short- and long-terms are also presented in table 3. The introduction of positive carbon prices results in tremendous increases in net GHG stock from offset fossil fuel emissions in both periods, relative to the base. Net GHG stock in forestry increases by only 3.0% and 4.8% in the short-term, but by 9.6% and 13.5% in the long-term for the $30 and $50 carbon prices, respectively, relative to base. Following the national trend, all regions experience an increase in net GHG stock for both carbon prices in both periods with the exception of agriculture in the SE region (due to the small changes in agricultural production in this region).

Changes Due to Allowing Afforestation Carbon Offsets only in Specific Regions Relative to Disallowing Afforestation Carbon Offsets Everywhere

Area Changes. Projected major average area changes of energy crops, conventional crops, pasture, and forestland for the two regional allowance programs for $30 and $50 carbon prices in the short-and long-terms, relative to the disallowing everywhere scenario, are presented in figure 2. Large land movements between the two sectors occur in the SC region, when allowing for carbon accounting from afforestation activities in only this region, as land owners in the SC region respond to profitability changes in afforestation. As expected, considerable increases in forestland are projected in the SC region for both carbon prices and in both periods relative to disallowing everywhere. In the short-term, an increase of about 5.6 million hectares for both carbon prices is projected and for the long-term, increases of 9.7 and 13 million hectares for $30 and $50 carbon prices are projected, respectively, as depicted in figure 2, cases 2A.SC_Short-term and 2B.SC_Long-term for the short- and long-terms, respectively. These large increases are mirrored by area declines in conventional crops and pasture in this region. Land owners in other regions are also affected by the SC regional policy due to

Figure 2 Projected major average changes in areas of forestland, conventional cropland, energy crop, and pastureland for the two regional programs for $30 and $50 carbon prices per ton and for the short- and long-terms, relative to the disallowing everywhere scenario



changes in the supply of agricultural and forestry commodities in the SC region (induced by price changes in agricultural and forestry communities in the SC region). Movements from forestland to pasture (cropland) are evident mainly in the SE and the RM (CB) regions in both periods (long-term).

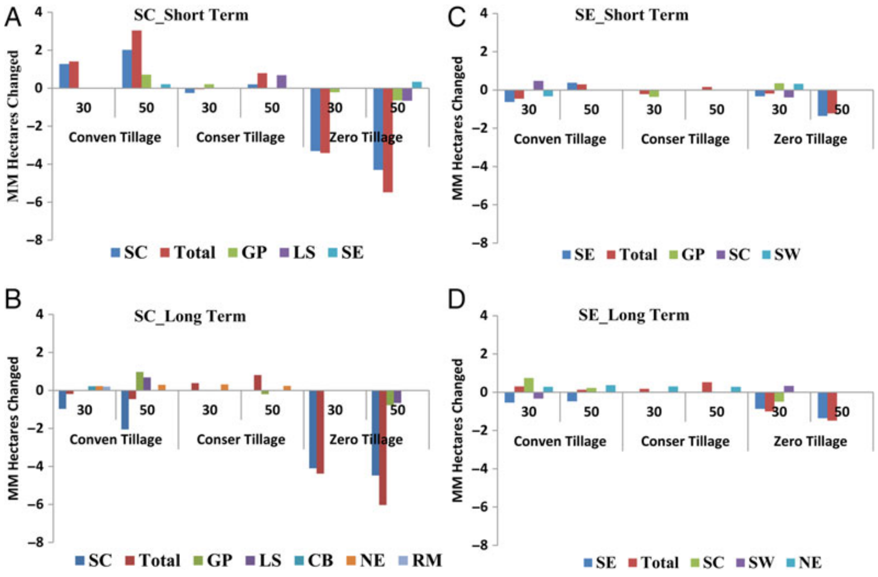
On the other hand, only modest area changes are evident when allowing for carbon accounting from afforestation activities in only the SE region. For the short-term (figure 2, case 2C.SE_Short-term), national forestland increases by 1.6 and 2 million hectares for $30 and $50 carbon prices, respectively, relative to the disallowing everywhere scenario. These increases represent 57% and 74% of increases in forestland for $30 and $50 carbon prices, respectively, in the SE region. Despite declines of 1.7 and 1.6 million hectares in pastureland in the SE region for $30 and $50 carbon prices, respectively, national area in pasture decreases by only 0.8 and 0.65 million hectares for $30 and $50 carbon prices for this period.

A different pattern is noticeable in the long-term (figure 2, case 2D.SE_Short-term). First, even though forestland in the SE region expands by 3.25 and 3.45 million hectares for $30 and $50 carbon prices, respectively, forest area nationally declines by more than 1.2 million hectares for the $30 carbon price and does not change for the $50 carbon price. This is due to decreases of about 1.75, 1.6, and 0.6 (1.8 and 0.9) million hectares in forestland in the NE, RM, and SC regions (NE and RM regions), for a $30 ($50) carbon price. Second, national area in pastureland slightly increases for both carbon prices despite a decline of 1.2 and 1.6 million hectares of pastureland in the SE region for $30 and $50 carbon prices, respectively. This is mainly due to increases in pastureland in the CB and RM regions. Lastly, a decline in area in conventional crops in the SE region is partially compensated by increases in the NE region at both carbon prices.

Projected changes of average afforested land for the two regional allowance programs for $30 and $50 carbon prices for 2010–2055, relative to the disallowing everywhere scenario, are presented in figure 1, case B. An expansion of 8.1 and 10.5 million hectares of afforested land is evident in the SC region for a $30 and $50 carbon price, respectively, when allowing carbon offsets for afforestation only in this region. However, the national afforested area increases by only 1.6 and 5.25 million hectares for a $30 and $50 carbon price, respectively, due to declines in afforested area in the LS, NE, RM, and SE (LS, NE, and RM) regions for $30 ($50) carbon price. On the other hand, allowing for carbon offsets from afforestation in only the SE region results in a decline of 1 million hectares in national afforested land for a $30 carbon price and a slight increase (less than 0.4 million hectares) in national afforested land for a $50 carbon price. This is despite increases of 2.4 (0.8) and 1.9 (1.4) million hectares in afforested land in the SE (SC) region for $30 and $50 carbon prices, respectively, and due to declines in the LS, NE, and RM regions (NE and RM) for a $30 ($50) carbon price.

Agricultural Production Intensification. Projected major changes in average areas of conventional, conservation, and zero tillage for the two regional allowance programs for both carbon prices in both periods, relative to disallowing everywhere scenario, are reported in figure 3. As can be seen in figure 3, cases 3A.SC_Short-term and 3B.SC_long-term, allotment of carbon accounting from afforestation activities in only the SC region has a reverse effect on national hectares in conventional tillage in the short and long-terms, respectively. For the former, acreage expansion in conventional

Figure 3 Projected major average changes in areas of conventional, conservation, and zero tillage for the two regional allowance programs for $30 and $50 carbon prices per ton and for the short- and long-terms, relative to the disallowing everywhere scenario



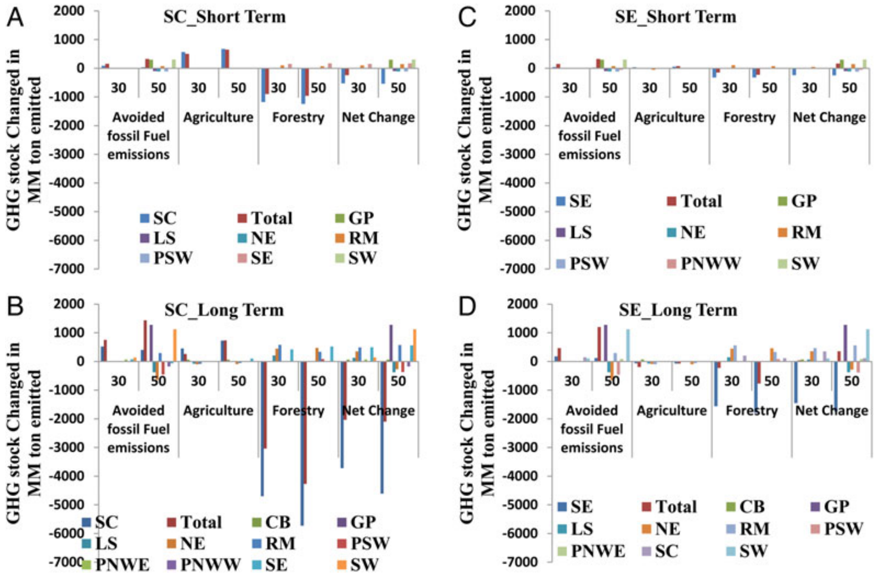
tillage on the national level is evident, mostly due to increases in the SC region (1.2 and 2 million hectares for $30 and $50 carbon prices, respectively) and smaller increases in the GP and SE regions for $50 carbon price. The overall reduction in area of conventional cropland results in a price increase of agricultural commodities. This in turn induces farmers to adopt higher-cost practices that increase productivity but are not profitable at lower commodity prices. For the latter, on the other hand, despite a contraction of 1 and 2 million hectares in conventional tillage in the SC region, only minor declines in conventional tillage are evident at the national level. This is due to area increases in conventional tillage in other regions (increases in conventional tillage in the CB, NE, and RM regions (GP, LS, and NE) for a $30 ($50) carbon price). Hectares in zero tillage fall dramatically in the SC region for both prices in both periods.

Major changes in average acres of land covered by conventional, conservation, and zero tillage, when allowing for carbon accounting from afforestation activities in only the SE region for both prices, in the short and long-terms, relative to the disallowing everywhere scenario, are reported in figure 3, cases 3C.SE_Short-term and 3D.SE_Long-term, respectively. A decline of about 0.6 million hectares of conventional tillage in the SE region for a $30 carbon price in either period leads to a reduction of 0.4 million hectares of conventional tillage at the national level in the short-term, but a small increase in the long-term. The former occurs despite an increase of about 0.4 million hectares in the SC region, whereas the latter is due to an expansion of around 0.8 million hectares in the SC region. For a $50 carbon price, the area covered by conventional tillage nationwide slightly increases. National acreage of zero tillage declines by 1 million hectares due to decreases in SE and SC regions for a $30 carbon price in the long-term. For a $50 carbon price, major reductions in zero tillage occur only in the SE region, resulting in declines of 1.2 and 1.4 million hectares on the national level in the short- and long-terms, respectively.

GHG Stocks. Projected major average changes in net GHG stock for the two regional allowance programs for $30 and $50 carbon prices in both periods, relative to the disallowing everywhere scenario, are presented in figure 4. In the short-term, allowing for carbon accounting from afforestation activities in only the SC region results in an increase of about 530 million tons five-year average GHG stored in the SC region for both carbon prices. These increases, however, are translated to only 240 million tons five-year average more of GHG stored on the national level for $30 carbon price and no actual impact at the national level for the $50 carbon price, relative to the disallowing everywhere scenario, as depicted in figure 4, case 4A.SC_Short-term. The leakage from the program for $30 and $50 carbon prices in the short-term in national net GHG stored are therefore about 54% and 102%, respectively. Greater gains in national GHG stored for this regional allowance program are achieved in the long-term. As shown in figure 4, case 4B.SC_Long-term, increases of about 3.7 and 4.6 billion tons five year average GHG stored are attained in the SC region for $30 and $50 carbon prices, respectively. These large increases are accompanied by increases in GHG emissions in the GP, SW, RM, and SE regions which, in turn, lead to only 2 billion tons five-year average GHG stored on the national level. Therefore, in the long-term, the leakage from the program in terms of national net GHG stored is 45% and 54% for $30 and $50 carbon prices, respectively.

Allowing for carbon accounting from afforestation activities in only the SE region has no actual impact on net GHG stored for the $30 carbon price but a net increase of 165 million tons five-year average emitted for the $50 carbon price on the national level in the short period, relative to base, as depicted in figure 4, case 4C.SE_Short-term. This is despite increases of 250 million tons five-year average GHG stored in forests in the SE region for both carbon prices in this period. Leakage from the SE regional allowance program for $30 and $50 carbon prices in the short-term national net GHG

Figure 4 Projected major average changes in net GHG emissions for the two regional allowance programs for $30 and $50 carbon prices per ton and for the short- and long-terms, relative to the disallowing everywhere scenario



stored are about 105% and 166%, respectively. A similar but stronger trend is visible in the long-term. As depicted in figure 4, case 4D.SE_Long-term, at the national level there are no net changes in GHG stored for the $30 carbon price and an increase of about 350 million tons GHG emitted for the $50 carbon price. Large increases in net GHG stored from forestry occur in the SE region for both carbon prices. Leakage from the SE regional allowance program for $30 and $50 carbon prices in the long-term in national net GHG stored is about 102% and 120%, respectively. These results are further discussed below.

Discussion

Projections for the base (zero carbon prices) point to a substantial decline in forestland, mostly in the South and in the Midwest in the next half century, which is largely alleviated by the introduction of carbon markets. On the contrary, the introduction of carbon markets aggravates slight area decreases in conventional crops and pasture under the base. Furthermore, positive carbon prices tremendously expend the area covered by energy crops in both the short- and the long-terms. These land-use changes within the agricultural sector and between the two sectors represent the changes in land owners' opportunity cost initiated by carbon markets. Both sectors are net sinks of GHG emissions under the base with a potential to further absorb more GHG emissions given positive carbon prices, especially through planting trees and expanding land in energy crops.

Results for the SC regional allowance program indicate a significant amount of land conversion between the two sectors within the region, with spillovers to other regions. The conversion of additional agricultural land in the SC region to forestland, which increases over time and with higher carbon prices, has an impact on commodity prices in both sectors and consequently on the optimal allocation of land outside the allotted region. For example, land shifts from forest to pasture are evident in the RM and SE regions, with an increasing rate over time. Also, area covered by conventional crops in the NE region is expanding (mainly hay, corn, silage, and willow) on the expanse of forestland in this region in the long-term. Tillage practices in other regions are also influenced by the SC regional allowance program. This is because price increases of agricultural commodities induce farmers to adopt higher-cost practices that increase productivity but are not profitable at lower commodity prices. For the $50 carbon price, untilled land shifts to conventional and conservation tillage in the GP and LS, respectively, in the short-term, but to conventional tillage in both these regions in the long-term. These changes in tillage behavior in the GP and LS regions occur despite no major land changes in agricultural uses in either region. The SE regional allowance program, on the other hand, triggers a much smaller increase in forestland in the allotted region but considerable spillovers to other regions. Similar to the SC regional allowance program, all projected afforested hectares under the base in the NE region (about 1.2 million hectares) are shifted to agricultural uses, mainly to conventional crops (hay, corn, silage, and willow). Furthermore, pastureland expands in the RM (and CB) region in both periods (in the long-term) for both carbon prices.

Our leakage estimates for the SC regional allowance program are in the ballpark of previous estimations (e.g., Murray et al. 2004), with the exception of $50 carbon price in the short-term. This is an interesting result, especially since Murray et al. (2004) considered a pre-determined 10 million-acre (about 4 million hectares) afforestation program in this region with no carbon prices. On the other hand, our endogenous approach, which incorporates positive carbon prices, resulted in a greater expansion of afforested land, that is, about 30 to 37 million acres (about 12 to 15 million hectares), in this region. In addition, our leakage estimates for the SE regional allowance program are significantly higher than those suggested by Murray et al. (2004). This is despite similar afforestation levels in this region in both studies. The two results together imply that, at least in the long-term, a large afforestation capacity is required in the allotted region in order to partially offset emission spillovers in the other regions, which result from the change in land owners' incentives due to the introduction of carbon markets.

Conclusions

We examine leakage behavior from afforesting agricultural land on the intensification of agricultural production under carbon markets at the regional level in the United States by employing a cross-sectoral nonlinear optimization model. Our main findings suggest that an afforestation program under carbon markets in only the SC region could result in considerable gains in net GHG stored. Such a regional program could result in as much as an additional 400 million tons, on average, per year of GHG stored, which is equal to approximately 6% of U.S. GHG emissions in 2010 (EPA 2013). In contrast, such a program executed only in the SE region will lead to losses in net GHG stored, relative to disallowing afforestation credits everywhere. For the former, net gains in GHG stored are much greater in the long-term, whereas for the latter, net losses in GHG stored are greater in the long-term for the $50 carbon price only.

Our analysis shows that regional characteristics are very important for applying regional-specific GHG mitigation policies. For example, we find that for a regional allowance program to have net gains in terms of GHG reduction, a large afforestation activity should be triggered in that region. Interactions between regions should be well understood so as to minimize policy impacts outside the allotted region's boundaries. A regional allowance program in the SC region, for example, intensifies agricultural production in the GP and LS regions in the short- and long-terms. Therefore, incentivizing farmers in these regions to keep their lands under zero tillage will result in even higher GHG net gains from the regional allowance program. On the contrary, under the SE regional allowance program, such an incentive mechanism is inefficient as intensification of agricultural land does not occur in the LS region, whereas in the GP region, land shifts to zero tillage from the other two tillage practices.

Carbon pricing is an additional policy issue to be considered. The two carbon prices used in this research are well placed within carbon price projections to 2030 by the IPCC (IPCC 2007) and are inside the bid price range of the last quarterly auction ($11.34 and $50 per allowance, May 16th, 2014) in the California cap-and-trade program (California air Resources Board 2013). Our results show that higher carbon prices trigger larger shifts in land uses and tillage practices both across and within sectors. However, according to our results and contrary to previous findings for regional projects in the energy sectors (Chen 2009), higher carbon prices do not necessarily lead to higher net gains in GHG reductions.

Results of this study demonstrate the importance of the leakage problem due to the implementation of regional reduction programs. With the constantly growing interest in regional control programs in the United States, local and regional policy makers should be aware that regional allowance programs do not necessarily lead to higher net gains in GHG reductions. A better understanding of regional characteristics of the two sectors would help to set correct incentives for landowners, and to promote higher net gains in GHG reduction while minimizing potential leakage.

Two caveats should be mentioned. First, in FASOM-GHG, landowners receive carbon payments for offsets but are penalized for carbon released to the atmosphere. Theoretically, revenues collected from carbon released in both sectors could be used to pay landowners for carbon sinks. In practice, agricultural and forest operators may be forced to pay for carbon emissions related to fossil fuels through the implementation of a national/regional carbon tax. Revenues from such a regulatory mechanism could then be redirected to compensate landowners for additional carbon sinks. Second, because GHGs are a classical global commons problem, an international or multi-national reduction program would result in a more cost-efficient GHG reduction and a smaller leakage potential compared with regional programs. The empirical results of our regional analysis represent a second-best solution. However, with the recent increased popularity of regional reduction programs and with the recent approval of forest-based carbon offsets in the California cap-and-trade program, it is important to quantify leakage behavior from afforestation activities at the regional level.

Future studies might cover other regions in the United States that are characterized by longer timber rotations, and where historically, the dominant movement of land occurred within the agricultural sector rather than between the agricultural and forest sectors (such as the Midwest and the Northeast) to produce a more accurate picture of leakage behavior associated with agricultural afforestation under carbon pricing. At a larger scale, future research efforts could focus on integrating land-based mitigation models such as FASOM-GHG, and energy-based mitigation models such as the World Induced Technical Change Hybrid model to further quantify short- and long-term tradeoffs related to mitigation options in these sectors.[11]

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[11] *The WITCH model was developed within the Fondazione Eni Enrico Mattei (FEEM) Sustainable Development research programme. For further details on the WITCH model, see http://www.witchmodel.org/.*

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Appendix A

Greenhouse gas accounts by sector

Forest GHG Accounts	Sequestration from carbon in standing (live and dead) trees, forest soils, the forest understory vegetation, forest floor including litter and large woody debris, and wood products both in use and in landfills. Emissions from fossil fuels used in forest production (including emission savings when wood products are combusted in place of fossil fuels (particularly when milling residues are burned to provide energy). Carbon content for products processed in and coming from Canada, imported from other countries, and exported to other countries.
Agricultural GHG Accounts	Amount of carbon sequestered in agricultural soils (due to choice of tillage and irrigation along with changes to crop mix choice. Emissions from crop and livestock production, including fossil fuel use, nitrogen fertilizer usage, other nitrogen inputs to crop production, agricultural residue burning, rice production, enteric fermentation, and manure management.
Bioenergy GHG Accounts	Emission savings from biofuel production (including biodiesel, bioelectricity, cellulosic ethanol, and starch or sugar-based ethanol) after accounting for emissions during producing, transporting, and processing of bioenergy feedstocks.
Developed Land GHG	Carbon sequestered on converted agriculture and forestry lands to developed uses.