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Permanence of agricultural afforestation for carbon sequestration under stylized carbon markets in the U.S.

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ABSTRACT

This paper examines the permanence of agricultural land afforestation under stylized carbon markets at the regional level in the US. Attention is focused on Southern and Midwest regions which historically have experienced a relatively large amount of land-use change between the agriculture and forest sectors. The Forest and Agriculture Sector Optimization Model–Greenhouse Gases model is used to examine responses between sectors as part of the regional afforestation policy analysis. Main findings suggest that most of afforested area in the Midwest regions remains unharvested by mid-21th century but a significant percentage of afforested area in the Southern regions shifts back to agricultural uses by this time. We also simulated a policy where carbon sequestration credits paid for afforestation are reduced 40% relative to other mitigation actions. A permanence value reduction for afforestation further promotes the harvesting of afforested stands in the Southern regions. Also, it has an impact not only on grassland pasture but also on high productive cropland. Results of this analysis are robust to lower permanence value reduction rates for higher carbon prices and can serve as upper bound of impacts for lower carbon prices.

1. Introduction

Afforestation of agricultural land has significant capacity to sequester carbon under potential carbon pricing programs (Alig et al., 2010a Enkvist et al., 2007; Johnson et al., 2009). Moreover, it has been suggested that including the forest and agriculture sectors in a carbon trading system creates incentives to both control land use emissions and increase land use sinks (Reilly and Asadoorian, 2007). However, despite the potential for significant offsets of emitted carbon through afforestation, a number of unknowns related to sequestered carbon integrity, and in particular the issue of permanence of forest-based sequestration, make it difficult to determine the longevity of carbon sequestered through afforestation efforts on agriculture land.[1]

One concern is that afforested acres will revert to previous land uses over long timeframes or if market conditions change. Reversion to previous land use would cause at least some sequestered carbon to be lost back to the atmosphere. Harvesting of afforested stands to take advantage of increasing timber value is one way that sequestered carbon might be emitted (i.e., not meeting permanence considerations).[2] Despite this concern, there is at least some evidence that operators afforesting acres as part of government-assistance conservation programs tend to keep land in forest uses (Alig et al., 1980). The harvest option has generally received little attention in the terrestrial GHG mitigation literature. In previous studies examining projected GHG offsets in the agriculture sector, harvesting of afforested acres was not considered Enkvist et al. (2007); Murray et al. (2004) or was only considered implicitly (Lewandrowski et al., 2004[3]; Lee et al., 2007). This affects the expected values to the landowner from afforestation (because landowners do not have the possibility to harvest trees when they become commercially viable) and does not allow for examination of how harvesting behavior affects the permanence of afforested acres. Others have quantified the volume of carbon sequestered in afforested stands with and without harvesting activities (Birdsey, 1996), but have not projected the magnitude of harvests on afforested stands. The current study fills that broad gap both by considering the harvest option conceptually and by estimating the magnitude of associated impacts.

Buffers (additional carbon sequestered over and above compensated amounts) are suggested in response to concerns over the permanence

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[1] With respect to terrestrial carbon pools, sequestration occurs when plants extract CO_2 from the atmosphere and store C in biomass and soils. Emissions occur when C in soils and biomass is oxidized and returned to the atmosphere as CO_2. By international convention, C stocks and changes in C stocks (either as C sequestration or CO_2 emissions) are reported in CO_2 equivalents where 1 mt C = 3.67 mt CO_2.

[2] Aside from the anthropogenic factors there are many natural factors that could cause carbon release from trees into the atmosphere, such as forest fire and tree diseases.

[3] The Lewandrowski et al. (2004) study paid landowners the rental rate of carbon sequestered over a 15 year period and also factored in the landowner decision to enroll the value of 15 year-old standing timber. This framework is consistent with allowing landowners to harvest after 15 years.

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for forest carbon projects (Gorte and Ramseur, 2008). Such a buffer is typically implemented as requiring more carbon in the program that one receives credit for. That is, the total carbon in the forest program is discounted to serve as an insurance buffer. The discounts can be as high as 50% depending on how risky the project is (Gorte and Ramseur, 2008) and on the length of timber rotations, whether reforestation takes place, and whether credits for fuel offsets are applied (Kim et al., 2008). Yemshanov et al. (2012) estimate non-permanence conversion factors[4] with values ranging between 1 and 25 for different afforestation programs in Ontario, Canada. The authors find that these values depend on the reduction rate, future price expectations for temporary carbon offsets, geographic location, harvest rotation length, and plantation type. Others suggested a long term conservation easement or permanent timberland set aside programs (Sohngen and Brown, 2008 and Nepal et al., 2013) or a long enough commitment period (e.g., 100 years commitment period required by Climate Action Reserve (CAR, 2010)), to ensure permanence of forestry carbon offset program including afforestation.

The objective of this paper is to examine permanence issues of agricultural land afforestation under stylized carbon markets at the regional level in the US. We first quantify changes in projected afforestation levels and projected harvested afforestation hectares (hereinafter ha) under carbon pricing relative to a base case with no carbon price. We focus our attention on the Southern and Midwest regions which, historically, have experienced a relatively large amount of land-use change between the agriculture and forest sectors (Alig et al., 2010b). We then consider a simulated policy that reduces the value of carbon credits applied to carbon offsets from afforestation of agricultural land into our model. In particular, we explore changes in afforestation levels, harvested afforestation area, land use changes within the agriculture sector (pasture, conventional cropland, and energy crop) as well as land use movement between the agriculture and the forest sectors when afforestation carbon offsets are depreciated by 40% and when they are fully credited. To capture interactions between the agriculture and forest sectors, we employ the Forest and Agriculture Sector Optimization Model–Greenhouse Gases (FASOM–GHG), which projects changes in land uses involving forestry and agriculture and has an extensive carbon accounting system for the US 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 (no carbon price) and for the stylized national carbon market program. Then, we present changes due to carbon offsets reduction from agricultural afforestation. We describe changes in afforestation levels, harvest rates of afforestation stands, and land use. A sensitivity analysis for our main results closes the third section. The fourth section discusses the policy implications of our findings including changes in Greenhouse Gases (GHG) stored in both sectors due to the policy measures, and the fifth section concludes.

2. Simulation analysis

2.1. Model description

FASOM–GHG is a 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 (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 so as management strategy adoption, land use allocation between sectors, and resource use, among other variables. Commodity and factor prices are endogenous, determined by the supply and demand relationships in all markets included within 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.

FASOM–GHG includes all states in the contiguous U.S, broken into 11 market regions.[5] Afforestation of agriculture land is feasible in 8 regions (afforestation in the Great Plains, western Texas, and the western portion of the Pacific Northwest is currently not considered). Once tree planting occurs (either after timber harvest or after land conversion) timber harvest decisions are made based on market conditions and assumed minimum harvest ages. Minimum harvest age differs across regions. FASOM assumes longer timber rotations in the North, Midwest, and Pacific Northwest regions (about 40 to 50 years) compared with shorter timber rotations in the Southern regions (about 20 to 30 years). For carbon accounting associated with afforestation, FASOM–GHG adopts the FORCARB approach (Birdsey et al., 2000), which projects carbon budgets for privately owned forests in the US. The four major types of carbon pools included in FORCARB are trees, understory vegetation, forest floor, and soil. Other GHG accounting follows from Schneider (2000) and McCarl and Schneider (2001).

FASOM–GHG accounts for and tracks a variety of agriculture and forestry resource conditions and management actions. In addition to traditional agriculture and forest products, selected agricultural and forestry commodities can be used as feedstocks for bioenergy production processes in FASOM–GHG, possibly affecting fossil fuel usage and associated GHG emissions after accounting for emissions during hauling and processing of bioenergy feedstocks (referred to here as offset fossil fuel emissions). For example, CO2 emissions from energy use can be reduced through renewable fuels, such as switchgrass and short-rotation tree species, which can be grown and used instead of fossil fuels to generate electricity or transportation fuels. Detailed description of GHG accounts by sector is found in Appendix A. FASOM–GHG is run here for the timeframe 2010 to 2080 represented in 5-year time periods with a discount rate set to 4%. A condensed mathematical description of the FASOM–GHG structure is available in Latta et al. (2011) and complete documentation is available in Beach et al. (2010).

2.2. Simulating baseline and stylized national carbon market program

Within FASOM–GHG, a variety of practices and land use changes are available for agriculture and forestry producers to supply GHG offsets to a simulated carbon market. In standard FASOM–GHG runs, all significant mitigation activities are available to their respective sectors and those activities are adopted as appropriate given optimal economic behavior. Landowners 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 included a zero carbon price (base) and two standard FASOM–GHG carbon pricing runs at $30 and $50/ton CO2e (hereinafter the unmodified scenarios), as presented in Fig. 1. We used a minimum $30/ton price based on results from Alig et al. (2010a), who found that little afforestation is projected for prices lower than $30/ton CO2e. We also simulated a scenario with $50/ton to investigate effects of a higher CO_2 price.

In our second step, we compared each of the two carbon-price runs with the base to quantify the longevity of afforested stands and, consequently, impacts on land use allocation within the agricultural sector. In particular, we looked at changes in afforestation levels, harvested

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[4] By converting carbon sequestration costs to a permanent offset equivalent. The authors define a non-permanence conversion factor as "*factor by which permanent offset credit prices would need to exceed the temporary offset price for the latter to be of interest to potential buyers who are interested in offset credits*"

[5] See Beach et al. (2010) for more details on region descriptions

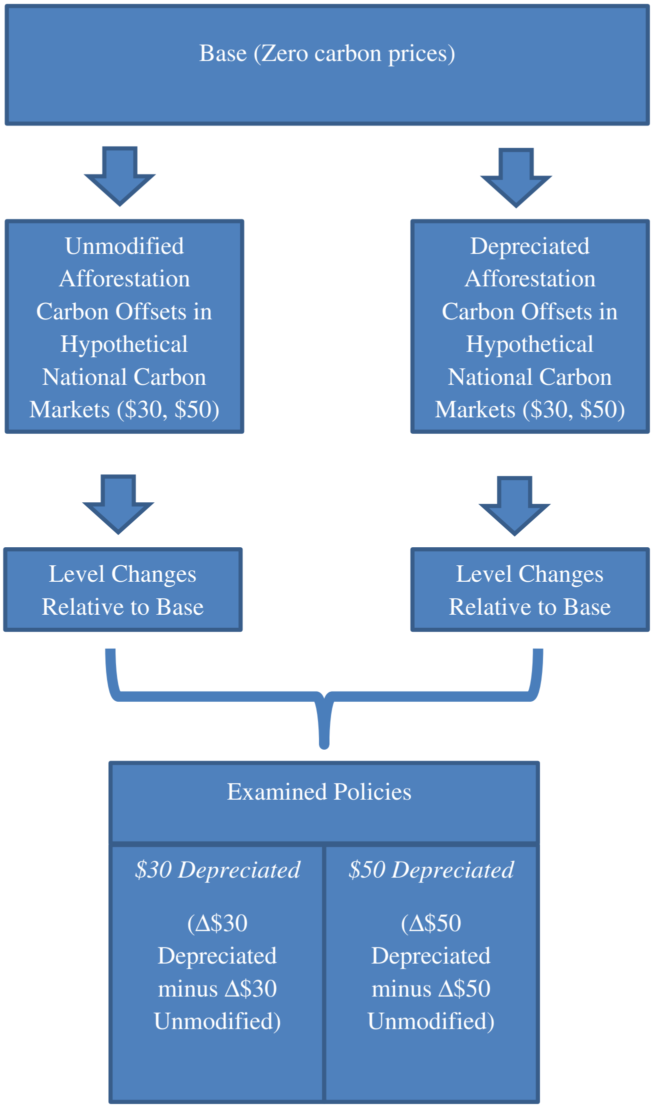

Fig. 1. Flow diagram of simulation runs and examined policies.

afforestation area, and land-uses areas in response to the presence of an unmodified stylized carbon market. Our third step included runs for which carbon offsets for afforestation of agriculture land were allowed but prices for that activity were depreciated by 40% relative to other mitigation practices[6] (hereinafter the depreciated scenarios). The 40% depreciation rate is consistent with the suggestions of Kim et al. (2008).[7] As before, changes in examined variables, relative to the base (zero carbon price), were computed.

Finally, the two policy measures, presented in the last row of Fig. 1, were examined. Both compare changes in afforested land, harvested afforestation land, and land use allocation in the agricultural sector, under stylized carbon markets, when carbon offset values from afforestation are reduced and when they are unmodified. We refer to these two policies as *$30 depreciated* and *$50 depreciated* from hereinafter. These two policies aim for examining the importance of permanence of afforested stands at different carbon prices. For clarity, only areas changes greater than 0.2 million ha were considered. Moreover, we focus our attention on the first 45 years of the projection which we believe to be the policy relevant period.

Projected national and regional land uses were aggregated into four categories; energy crop use, conventional crops, pasture,[8] and timberland. Energy crops are plants grown to make bioenergy feedstocks. FASOM–GHG currently includes three energy crops: switchgrass, willow, and hybrid poplar.[9] We distinguished between energy and conventional crops to capture different land area trends in these two categories as resulted from the introduction of stylized carbon markets.

3. Results

3.1. Base (zero carbon price) and unmodified stylized carbon markets

3.1.1. Afforestation

Projected cumulative afforested area and net afforested area (afforestation minus harvested afforestation land) at the national level under the base (zero carbon price) and stylized carbon markets of $30 and $50 carbon prices per ton for the period 2010–2055 are presented in Fig. 2. For the base, limited levels of afforestation occur between 2010 and 2030 (hereinafter the short term), accumulating to almost 10.0 million ha.[10] No additional land is shifted from agriculture to timberland use between 2035 and 2055 (hereinafter the long term). Afforested area greatly increases under simulated carbon markets, reaching 34.0 and 38.6 million ha in 2055 under a $30 and a $50 carbon price, respectively. Positive carbon prices change landowner profitability on the margins, creating incentives to reallocate some of their land to more profitable uses. Similar to the base, much of the afforestation activity under stylized carbon markets occurs in the short term. In part, this behavior is a reflection of the perfect foresight required for the modeling framework employed in this study. Contrary to the base, under stylized carbon markets, small increments in afforestation levels are further evident in the long term.

We assume that newly afforested stands of timber could not be harvested until they are at least 20 years old and, therefore, no harvesting of afforested stands occurs prior to 2020 (20 years after the simulation start) (Fig. 2). For the base, harvesting of afforested stands gradually increases over time, leaving only 22% of afforested land unharvested by 2055. Despite considerably higher afforestation levels under stylized carbon markets, smaller relative harvest levels are evident until 2030 for $30 and $50 carbon prices. In the long term, however, net afforestation gradually declines (largely due to landowner's behavior in the Southern regions as we further discuss below), leaving only 54 and 62% of afforested land unharvested for the $30 and $50 carbon prices, respectively, by 2055.[11]

Large variations in afforestation and net afforestation levels are evident at the regional level (Fig. 3). For the Corn Belt (CB) region, all afforestation occurs by 2020 and 2025 under the base and when a carbon markets are present (Fig. 3, Panel 3A). Moreover, for this region, carbon prices above $30 initiate limited levels of additional afforestation and only a slight effect on the rates that afforested stands are harvested (less harvesting under higher carbon prices). Furthermore, due to FASOM's minimum harvest age assumption,[12] harvesting of afforested stands begins only at 2040 in the CB region. Small amounts of afforestation are evident in the Lake States (LS) region under the base, most of

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[6] One could argue that offsets from agricultural activities are also temporary in nature and therefore should be deprecated. However, in this study we focus our attention on impacts associated with afforestation activities only as those represent the major potential for increasing GHG stored due to land-use shifts between the two sectors.

[7] Kim et al. (2008) analyzed different cases of forest-based offset. They found a permanence discount range of 23 and 52% resulted from a 20 year rotation forestry under constant carbon prices depending on whether harvest is followed by reforestation or not.

[8] Pasture-land includes cropland pasture, private rangeland, public rangeland, private grazed forest, and public grazed forest. For further details see Beach et al. (2010).

[9] For further details on energy crops in FASOMGHG see Subsection 5.1.2 in Beach et al. (2010).

[10] Note that at the same period of time total forestland declines by 2 million ha under the base.

[11] Afforestation levels are still much higher at 2055 under stylized carbon markets, relative to the base.

[12] Assumed rotation lengths vary across regions in FASOM. In the SC and SE, harvest may occur as early as after 20 years whereas rotation lengths in the CB and LS are typically 40 to 50 years.

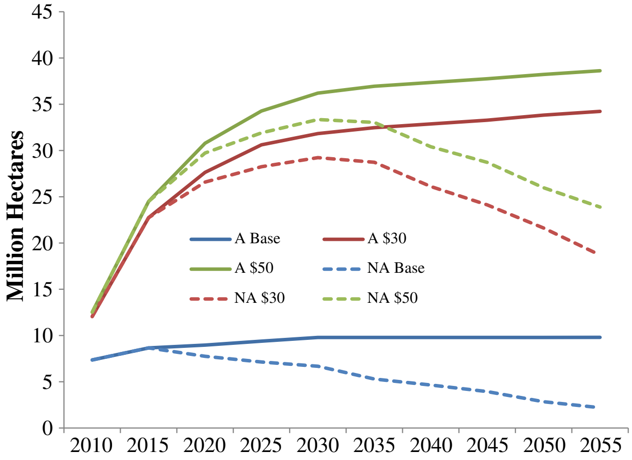

Fig. 2. Projected cumulative national afforestation (A) levels and net afforestation (NA) levels (afforestation minus harvested levels of afforestation stands) under the base and under hypothetical carbon markets for $30 and $50 carbon prices per ton for the period 2010–2055 in million ha.

which occurs at 2010 (Fig. 3, Panel 3B). Afforested area considerably increases under stylized carbon markets in this region with further increases with higher carbon prices. As in the CB region, harvesting of afforested ha begins only at 2040. In the absence of a carbon market, no afforested area is left by 2055. However, in the presence of carbon prices of $30 and $50, only 14% and 8% of afforested acres have been harvested by 2055, respectively, reflecting the much higher profitability from afforestation under carbon market in this region.

Afforestation levels under the base in the South Central (SC) region reach a peak of 4.2 million ha in 2030 (Fig. 3, Panel 3C). This region is projected to undergo the highest afforestation levels of all regions under stylized carbon markets, accounting for 35% and 38% of nationwide afforested area in 2055 under the $30 and the $50 carbon prices, respectively. Afforestation rates reach their maximum levels in 2025 and 2030 for the $30 and the $50 carbon prices, respectively. We assume that southern pine stands can be harvested at relatively young ages (20 years) and model results indicate that many afforested area are harvested once timber becomes merchantable. In the absence of a carbon market, harvesting of afforested area increases over the period 2020 to 2035. No further harvesting takes place in the long term and net afforestation reaches 0.4 million ha in the base case. In the presence of carbon market, harvesting of afforested area begins in 2020 but net afforestation accumulates to 2030. This is followed by a considerable decline in net afforestation rates in the long term under stylized carbon market. Finally, afforested area in 2055 is only 2.2 and 4.8 million ha for the $30 and the $50 carbon prices, respectively. Patterns of afforestation and net afforestation levels in the Southeast region (SE) are similar to that found for the SC region (Fig. 3, Panel 3D). However, for the SE

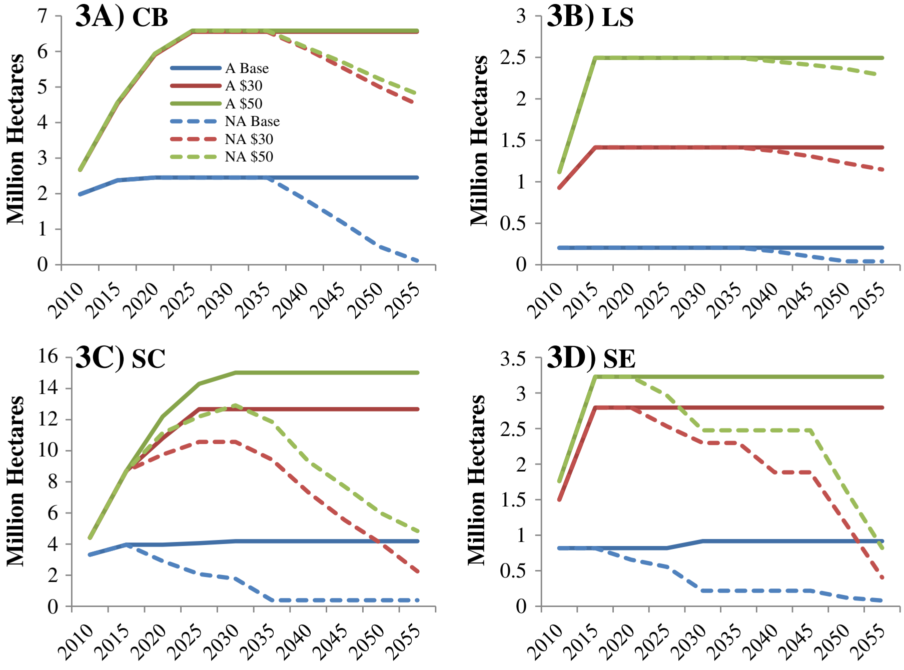

Fig. 3. Projected cumulative regional afforestation (A) levels and net afforestation (NA) levels (afforestation minus harvested levels of afforestation stands) under the base and under hypothetical carbon markets for $30 and $50 carbon prices per ton for the period 2000–2055 in million ha.

Table 1
Projected average areas in timberland, conventional cropland, energy crop, and pastureland for the base (zero carbon prices) as well as projected changes relative to the base for $30 and $50 carbon prices per ton for the period 2010–2030 (short term) and the period 2030–2055 (long term).

		Timberland (MM hectares)					Conventional Cropland (MM hectares)					Energy Crops (MM hectares)					Pasture (MM hectares)				
			Unmod$^{\tau}$		Dep$^{\gamma}$			Unmod		Dep			Unmod		Dep			Unmod		Dep	
			Change		Change			Change		Change			Change		Change			Change		Change	
		0	30	50	30	50	0	30	50	30	50	0	30	50	30	50	0	30	50	30	50
Total	Short	139.2	16.4	18.8	12.5	15.5	118.8	(10.4)	(15.0)	(9.8)	(13.6)	1.5	6.4	11.8	6.8	12.0	287.5	(6.5)	(9.8)	(4.1)	(7.4)
	Long	129.7	23.6	27.4	16.4	20.7	117.9	(12.4)	(17.9)	(9.4)	(13.4)	2.2	8.5	11.1	9.0	12.1	287.1	(11.2)	(14.2)	(7.3)	(10.3)
CB	Short	11.5	2.8	2.8	2.3	2.8	33.9	(2.7)	(4.3)	(2.9)	(4.3)	0.0	2.6	4.2	7.2	2.9	4.2	0.9	1.3	0.4	1.2
	Long	9.8	4.4	4.6	4.0	4.4	33.9	(3.9)	(4.0)	(3.8)	(4.0)	0.3	3.9	3.9	3.9	3.9	4.4	1.3	1.3	0.8	1.3
LS	Short	10.3	1.7	2.5	1.6	1.7	15.2	(2.0)	(3.0)	(2.0)	(2.3)	0.0	1.5	1.8	1.5	1.8	0.6	(0.2)	(0.4)	(0.0)	(0.3)
	Long	9.1	1.7	3.1	1.8	2.0	15.3	(2.2)	(3.2)	(2.3)	(2.5)	0.0	1.8	1.7	1.8	1.8	0.6	(0.3)	(0.5)	(0.2)	(0.4)
NE	Short	27.8	2.2	2.2	1.8	1.9	2.1	(0.2)	(0.0)	(0.0)	(0.0)	0.1	0.2	0.2	0.2	0.2	3.4	(0.7)	(0.9)	(0.0)	(0.0)
	Long	27.0	3.6	2.4	2.0	2.0	0.4	0.2	(0.0)	0.9	1.1	0.0	0.2	0.0	0.0	0.2	3.4	(2.0)	(2.2)	(0.2)	(0.8)
RM	Short	7.4	1.3	1.3	1.3	1.3	8.9	0.0	(0.6)	0.0	(0.6)	0.0	0.0	1.0	0.0	1.0	142.0	(1.3)	(1.7)	(1.3)	(1.7)
	Long	7.4	3.2	3.2	2.7	3.0	9.0	(0.7)	(0.9)	(0.0)	(1.2)	0.0	0.0	0.3	0.0	0.8	141.8	(2.6)	(2.6)	(2.6)	(2.6)
SC	Short	43.2	6.0	6.8	3.8	5.2	11.0	(3.7)	(3.9)	(3.1)	(3.5)	0.5	0.6	0.5	0.6	0.6	17.7	(2.8)	(3.4)	(1.3)	(2.3)
	Long	39.1	7.9	10.5	4.2	6.4	13.4	(5.4)	(6.5)	(2.9)	(4.6)	0.6	0.6	0.4	1.0	0.7	16.9	(2.7)	(4.1)	(1.9)	(3.9)
SE	Short	29.4	1.9	2.2	1.2	2.1	5.4	(1.2)	(1.2)	(0.8)	(0.9)	0.1	0.5	0.5	0.5	0.5	9.5	(1.3)	(2.0)	(0.9)	(1.8)
	Long	27.8	2.0	2.7	1.3	2.3	5.1	(0.8)	(1.5)	(0.3)	(0.7)	0.5	0.2	0.2	0.3	0.2	9.5	(1.8)	(2.3)	(1.4)	(2.1)
REST	Short	9.7	0.7	0.8	0.5	0.5	42.3	(0.7)	(1.9)	(0.8)	(1.8)	0.8	1.0	3.6	1.0	3.6	110.5	(1.1)	(2.6)	(0.9)	(2.4)
	Long	9.4	0.7	0.9	0.5	0.6	40.8	0.4	(1.7)	(0.8)	(1.7)	0.8	1.8	4.3	1.9	4.4	110.1	(3.1)	(3.8)	(1.8)	(3.6)

Note: CB—Corn Belt, LS—Lake States, NE—Northeast, RM—Rocky Mountains, SC—South Central, SE—Southeast, and the REST region is constructed of the Great Plains, Pacific Southwest, Pacific Northwest West, Pacific Northwest East, and Southwest. MM—million, τ—unmodified runs and γ—depreciated runs.

region, all of the projected afforestation in response to stylized carbon markets occurs in the first years of the simulation.

3.1.2. Areas changes

Projected average areas in forest, conventional cropland, energy crops, and pastureland for the base (zero carbon prices) for the short and long terms are reported in Table 1. Although forest area nationally declines by about 7% (mostly to satisfy that assumed levels of demand for developed land uses) between the short and long terms, only small decreases are evident in the areas 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.[13]

The national trend masks a considerable movement of land between the two sectors in the regional level between the two periods. Contrary to the national trend, the area of conventional cropland in the SC region expends by about 2.4 million ha (a 22% increase), whereas timberland in this regions declines by 4 million ha (a 9.5% decrease) between the two periods. The former compensate for the considerable decline in conventional cropland in the NE region (from 2.0 million ha to 0.3 million ha) and the latter is largely a result of urban land expansion in this region. In addition, an increase of 0.7 million ha (a 18% increase) in pastureland is evident in the CB region. In this region, timberland shifts towards energy crops and pastureland.

Area changes under the unmodified stylized national carbon markets for the $30 and the $50 carbon prices per ton, relative to the base (no carbon prices) for the short and long terms are also presented in Table 1. Increases of 12.0 (13.5) and 18.2% (21.0%) in national timberland are evident in the short and long terms for the $30 ($50) carbon price, respectively, relative to the base. At the national-level, the area in conventional cropland and pasture decline considerably whereas the area in energy crops tremendously increases under both carbon prices for both periods, relative to the base.

Following the national trend, area in timberland and energy crops expands in all regions whereas, conventional cropland decreases in all regions with the exception of the REST region in the long term for the $30 carbon price, relative to the base. Values placed on carbon stored incent landowners to maintain timberland area and convert agriculture land to timberland. New demand for bioenergy feedstocks promotes expansion of the land devoted to energy crop production. Conventional cropland in the CB region shrinks by 11.5% in the long term for both carbon prices and by 23% and 37% in the short term for the $30 and the $50 carbon prices, respectively, relative to the base. The CB region also experiences a substantial expansion in hectares of energy crops. For a $30 carbon price, about 40% to 45% of the increase in energy crop acreage comes from the CB in the short and long terms, respectively. However, as carbon price increases to $50 per ton, the national share of energy crops grown in the CB region decreases to only 35% at both periods, relative to the base. Regional patterns of pastureland follow the national one with the exception of the CB region at both periods and for both carbon prices.

Stylized national carbon markets with depreciated offsets from afforestation activities result in smaller movements of land between the two sectors. In particular, national area in timberland declines by 24 and 18%, in the short term and compared to the unmodified market, when carbon prices are $30 and the $50 for mitigation activities other than afforestation. Further decreases in timberland area are found in the long term. These declines are mirrored by land expansion in both conventional crops and pasture and minor increases in area devoted to energy crops. Most of the changes in land-use allocation between the two sectors in the depreciated scenarios, relative to the unmodified ones, occur in the Southern regions (SC and SE) where timber rotations are relatively short and landowners are more flexible in reallocating their land between the agricultural and the forest sectors.

3.2. Changes due to reduction of afforestation carbon offset value

3.2.1. Afforestation

Other research has suggested that credits applied to afforestation might be reduced in value, relative to other sequestration actions, because of permanence issues for afforestation (Gorte and Ramseur, 2008). When the credit applied to afforestation is depreciated, relative to other mitigation activities, the area undergoing afforestation is reduced considerably in the short term (Fig. 4). By 2025 (2030), afforested area shrinks by 25 (20%) in the *$30 depreciated* (the *$50 depreciated* scenario). Further small declines in afforested area are evident in these two

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[13] In FASOM–GHG, bioenergy and so the related production of energy crops, contribute net GHG mitigation. Therefore, mitigation due to additional afforestation is not partially offset by activities in bioenergy production. Furthermore, CO_2 payments associated with bioenergy (i.e. welfare gains) accrue outside the farm sector whereas agriculture benefits from higher commodity prices.

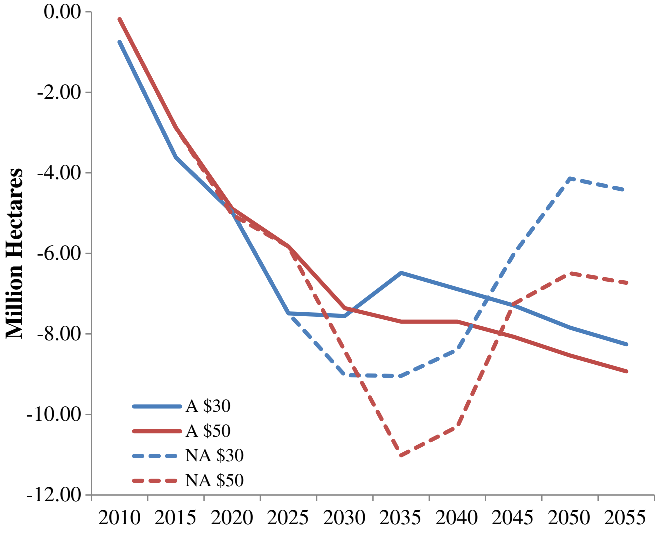

Fig. 4. Projected changes in cumulative national afforestation (A) levels and national net afforestation (NA) levels (afforestation minus harvested levels of afforestation stands) for the two examined scenarios: *$30 depreciated* and *$50 depreciated* for the period 2010 to 2055 in million ha, from the unmodified scenarios.

scenarios in the long term, reaching an overall reduction of 8.2 and 9.0 million ha in the *$30 depreciated* and the *$50 depreciated* policies, respectively, by 2055, relative to the relevant unmodified scenarios.

Timber takes time to reach minimum levels of economic maturity and no harvesting of afforested acres is projected before 2025. From 2025 to 2035, higher levels of afforested stand harvesting are projected in both scenarios to reduce net afforestation in both scenarios for that period. Post 2040 and to the end of the policy period, net afforestation increases as harvesting pressure on afforested stands declines and some afforestation continues. In 2055, net afforestation under the *$30 depreciated* and the *$50 depreciated* scenarios are 4.6 and 4.0 million ha less than that found in the *no reduction $30* and *$50* carbon price scenarios, respectively.

Projected changes in cumulative afforestation levels and net afforestation levels for the three scenarios for the period 2010 to 2055 at the regional level in million ha are presented in Fig. 5. For the CB region, changes in afforestation levels are evident only in the *$30 depreciated* scenario, as depicted in Panel 5A. For this scenario, afforestation levels decline by 1.4 million ha between 2020 and 2030 and then increase by the same amount in 2035. In addition, net afforestation in this region slightly declines under both scenarios owing to increases in harvesting levels of afforested stands. In the LS region, on the other hand, no changes in afforestation and harvesting levels are evident under the *$30 depreciated* over time (Fig. 5, Panel 5B). In the *$50 depreciated* scenario, however, 1.1 million afforested ha are being harvested between 2010 and 2015.

Adoption of policies to depreciate carbon sequestered through afforestation result in more significant changes in afforestation and harvesting behavior in the two southern regions. Similar to the national trend, afforested area in the SC region considerably declines under the *$30 depreciated* and the *$50 depreciated* scenarios in the short term and shows no further changes in the long term (Fig. 5, Panel 5C), as no further afforestation takes place in that period under the unmodified and the depreciated scenarios. By 2055, declines of 3.6 and 3.9 million ha are evident in the *$30 depreciated*, the *$50 depreciated*, respectively. Smaller harvesting levels in the long term increase net afforestation levels under both scenarios. At 2055, net afforestation under the *$30 depreciated* and the *$50 depreciated* is 1.4 and 3.1 million ha short, relative to the relevant unmodified scenarios. In the SE region, a similar pattern of changes in afforested area and net afforested area with a smaller magnitude compared with the SC region is evident under the *$30 depreciated* and the *$50 depreciated* scenarios (Fig. 5, Panel 5D). However, declines in afforested area occur only in 2010 and 2015 and net afforestation increases only during the last 10 years of the program (2045 to 2055). Contrary to the SC region, by 2055, net afforestation under the *$50 depreciated* scenario is the highest, representing an increase of 0.5 million ha, relative to the *$50 unmodified* scenario.

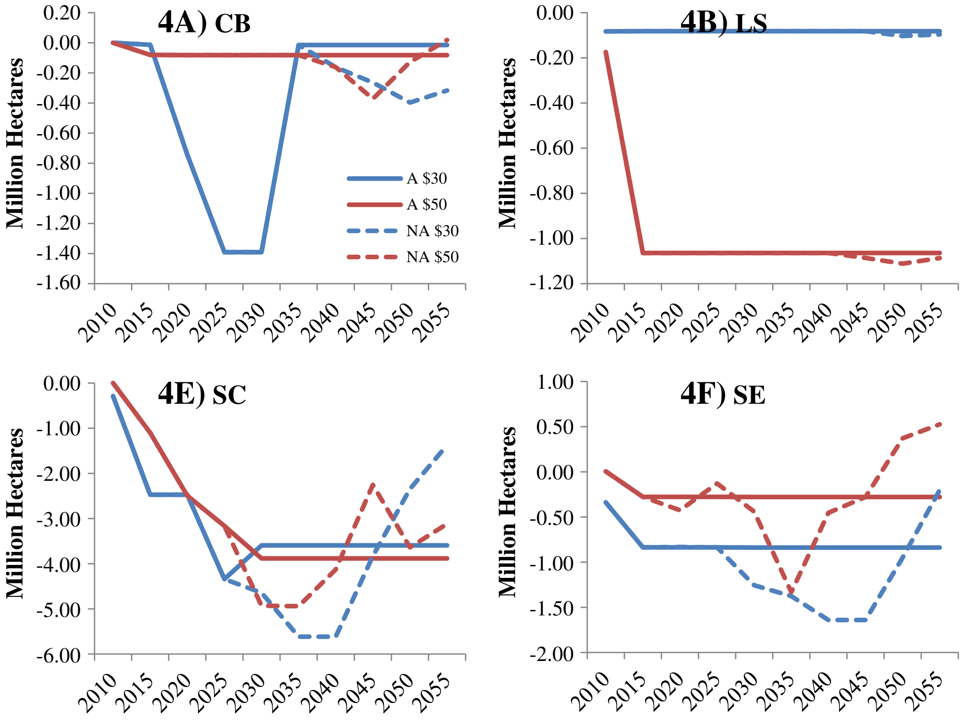

Fig. 5. Projected changes in cumulative afforestation (A) levels and net afforestation (NA) levels (afforestation minus harvested levels of afforestation stands) for the two examined scenarios: *$30 depreciated* and *$50 depreciated* for the period 2010 to 2055 at the regional level in million ha, from the unmodified scenarios.

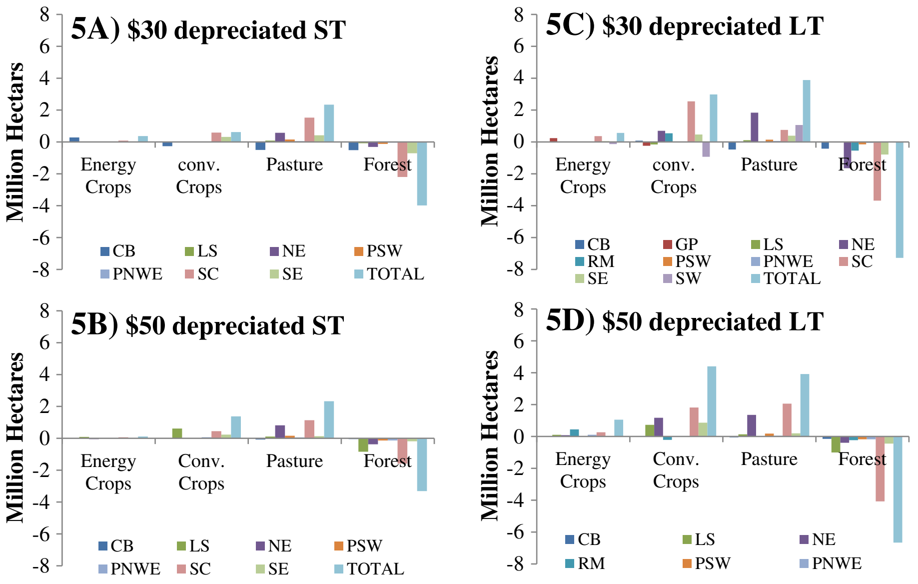

Fig. 6. Projected major changes in averages of land use areas in timberland, conventional cropland, energy crops, and pasture-land in the short term (2010–2030) for 5A) *$30 depreciated*, and 5B) *$50 depreciated* and in the long term (2030–2055) for 5C) *$30 depreciated* and 5D) *$50 depreciated*, from the unmodified scenarios.

3.2.2. Areas changes

Projected major[14] average area changes of energy crops, conventional crops, pasture, and timberland for the *$30 depreciated*, the *$50 depreciated* scenarios in the short and long terms, relative to the relevant unmodified scenarios, are presented in Fig. 6. Large land movements between the two sectors occur in the *$30 depreciated* and the *$50 depreciated* scenarios in both periods. At the national level, timberland declines by 3.9 and 3.3 million ha for the *$30 depreciated* and the *$50 depreciated* scenarios, respectively, in the short term, as depicted in Fig. 6A and B. Further decreases of about 3.3 million ha in timberland are evident in the long term in both scenarios (Fig. 6 panels C and D) for the *$30 depreciated* and the *$50 depreciated* scenarios, respectively. These large decreases are mirrored by area expansion in pasture and conventional crops in both periods. Nationally, pastureland (conventional cropland) increases by 2.3 (3.0) and 4.0 (4.4) million ha in the *$30 depreciated* and the *$50 depreciated* scenarios in both periods (the long term), respectively. Smaller rates of expansion are evident in conventional cropland in the short term however (0.6 and 1.4 million ha in the *$30 depreciated* and the *$50 depreciated* sectors in both periods, respectively).

At the regional level, the SC region is responsible for at least half to 61% of the decline in timberland in the *$30 depreciated* and the *$50 depreciated* scenarios in both periods, relative to the unmodified scenarios. Other noticeable decreases in timberland area include a decline of 1.6 (0.5) million ha in the NE (CB) in the *$30 depreciated* scenario in the long (short) term and a decrease of 1 (0.8) million ha in the LS region in the *$50 depreciated* scenario in the long (short) term. Consistent with the national trend, decreases in timberland in the SC region are translated to increases in pastureland and conventional cropland in this region in both scenarios and in both periods. The SC region is responsible for 65% of increase in national pastureland in the *$30 depreciated* scenario in the short term but to only 19% in the long one. For the *$50 depreciated* scenario however, the SC region is responsible for around 50% of increase in national timberland in both periods. Increases in area of conventional cropland in this region are greater in the long term than in the short one in both scenarios. For the long term, increases in the SC region reflect 85% of the total increase in conventional cropland in the *$30 depreciated* scenario but only 41% of total increase in conventional cropland in the *$50 depreciated* scenario.

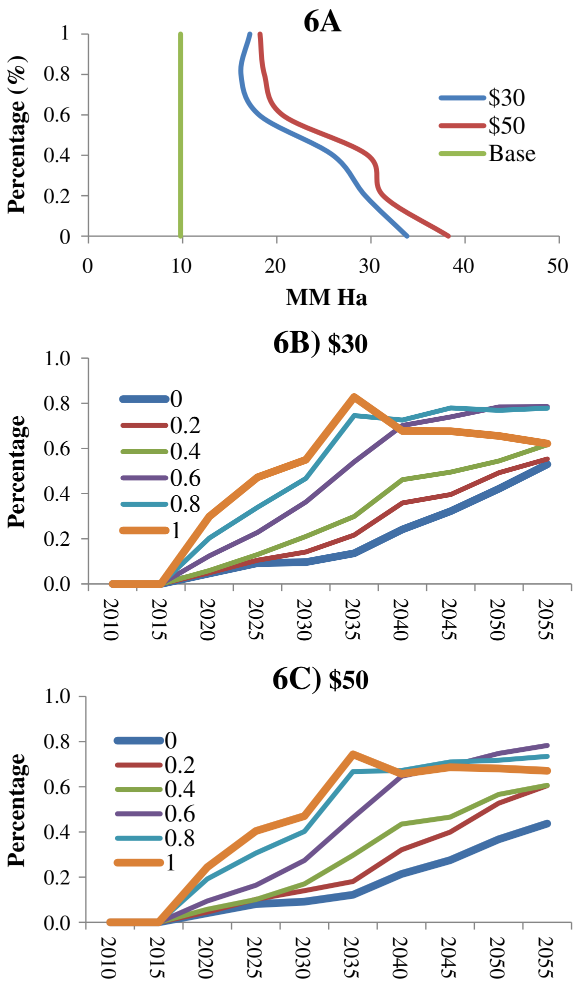

Fig. 7. Projected levels of afforestation (6A) under hypothetical carbon markets in million ha and cumulative percentage of harvested afforested stands out of total afforestation for $30 (6B) and for $50 (6C) as a function of the depreciation rate of afforestation carbon offsets for the period 2010 to 2055.

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[14] As defined above to changes greater than 0.2 million ha.

The NE region experiences an increase of 0.6 (0.8) million ha of pastureland in the *$30 depreciated* (*$50 depreciated*) scenario in the short term and 1.8 (1.3) million ha of pastureland in the *$30 depreciated* (*$50 depreciated*) scenario in the long term. Furthermore, in the short term, pastureland decreases by 0.5 million ha in the CB region in the *$30 depreciated* scenario and conventional cropland increases by 0.6 million ha in the LS region in the *$50 depreciated* scenario. Larger changes are evident in the long term. For the *$30 depreciated* scenario, 1.0 million ha move from conventional cropland to pastureland in the SW region, conventional cropland increases by 0.5 (0.7) million ha in the SE and RM (NE) regions, and pastureland decreases by 0.5 million ha in the CB region. For the *$50 depreciated* scenario, area in conventional cropland expands by 0.8, 1.1, and 0.7 million ha in the SE, NE, and LS regions, respectively.

3.3. Sensitivity analysis

The above analysis was conducted under the assumption of 40% reduction of carbon offset values from agricultural land afforestation activities. However, alternate depreciation rates might be considered in the policy. Afforestation levels shrink from 34.0 (38.0) million ha when no depreciation is applied on carbon offsets from afforestation to about 17.0 (18.0) million ha when carbon offsets from afforestation are 100% depreciated for the $30 ($50) carbon price (Fig. 7, panel A). At 100% value reduction, afforestation is effectively not an allowed sequestration strategy, but all other mitigation activities in both sectors are allowed. With 100% value reduction, afforestation is a bit less than twice the level of afforestation under the base (zero carbon prices). Longer rotations of other forestry activities (e.g. reforestation[15]), due to carbon payments, are compensated with higher afforestation levels, relative to the base, to keep timber prices from a sharp incline. For the $30 carbon price, afforestation levels are more sensitive to depreciation rates up to 60%. For the $50 carbon price, the greatest changes in afforestation levels are evident at 20% and 60% depreciation rates. Our adopted assumption of 40% depreciation captures the range of carbon prices where results are most responsive.

Harvesting percentages of afforestation area are smaller under no reduction of carbon offsets from afforestation than under any rate of reduction all along the examined period for both carbon prices, as depicted in Fig. 7B and C respectively. By 2055, 53 and 44% of total afforested land is harvested under no reduction of afforestation carbon offsets for the $30 and the $50 carbon prices, respectively. Generally, percentage of harvested afforested area increases with greater depreciation levels. The greatest difference in harvest percentage, 70 and 60% more in the $30 and the $50 carbon prices, respectively, appears between no reduction and full depreciation of afforestation carbon offsets in 2035. Also, reduction rates greater than 50% lead to higher harvest percentages in the short term but to lower percentages in the long term, compared with reduction rates smaller than 50%.

4. Discussion

Projections for the base (zero carbon prices) point to a mild increase in afforested area, mostly in the Southern and in the Midwest regions in the next half century. Far greater levels of afforestation are projected when stylized carbon markets are introduced. Even though harvesting levels of afforested stands under stylized carbon markets are about 1.5 times the afforested area in the base in 2055, net afforestation greatly rises in the presence of carbon markets, with further increases with higher carbon prices. For $30 and $50 carbon prices, 45% and 38% of total afforested area is harvested by 2055 (15.5 and 14.8 million ha), respectively. In the absence of a carbon market, 77% of afforested area is harvested by 2055.

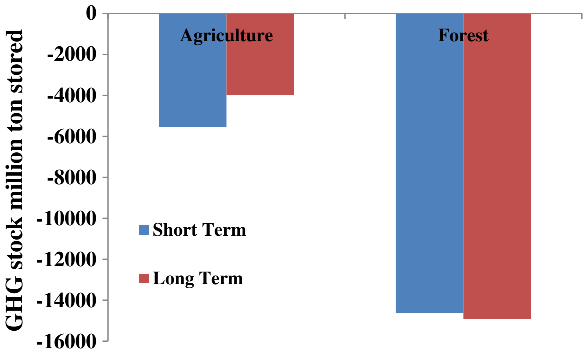

Fig. 8. Projected annual average GHG level stocks from forest and agriculture in million ton stored for the base in the short and long terms at the national level.

Large variation in afforestation amounts and net afforestation levels is evident across regions and across different periods. First, harvesting of afforested stands begins as early as 2020 in the Southern regions but only at 2040 in the Midwest regions, reflecting differing timber types and assumed minimum timber rotation lengths. Second, the timing of afforestation appears to differ, with some regions, such as the LS and SE regions completing all afforestation early in the simulation while other regions, such as the CB and SC regions, spreading afforestation out over longer time periods. This result has to do with regional differences in the capacity of the land to support timberland and agriculture to timberland conversions as well as regional differences in the relative markets for agriculture and forest sector products. Third, the responsiveness of afforestation behavior to increasing carbon prices differs by region, with some regions more responsive (e.g., the LS) and others less responsive (e.g., the CB) to higher carbon prices and there are likely region-specific tipping points where afforestation becomes more attractive. That is, for this range of carbon prices, the opportunity cost to agricultural operators for shifting their operations to timberland, on the margin, differs between regions. Fourth, harvesting levels are much smaller in the Midwest regions, compared with the Southern regions, in the long term. For the former, percentage of harvested afforested stands, out of total afforested area, ranges between 8 and 32% in 2055. However, for the latter, percentage of harvested afforested stands ranges between 67 and 84% of total afforested area in 2055, with lower harvesting levels for higher carbon prices.

To further explore land owners incentives to afforest land, we apply a permanence value reduction on afforestation carbon offsets. We find that depreciated carbon offsets promote harvesting of afforested land, with further harvesting with higher carbon prices. Moreover, substantial declines in afforestation levels are evident in the *$30 depreciated* and the *$50 depreciated* scenarios. Landowners do not only afforest less of their land but also shift afforested land back to agricultural uses earlier than when afforestation offsets are not reduced. Moreover, according to our model, permanence value reduction of afforestation carbon offsets has an impact not only on grassland pasture but also on high productive cropland. For example, in the SC region under the *$30 depreciated* scenario for the long term, soybeans area expands by about 1.4 million ha, hay area rises by 0.4 million ha, and cotton and corn area increase by 0.2 million ha each.

So far we analyzed the permanence of agricultural land afforestation in terms of land-use allocation within the agricultural sector, afforestation levels, and harvest schedules. We now turn to discuss how the changes in the above factors impact afforestation capacity of producing GHG mitigation. Projected annual average GHG level stocks from forest and agriculture in million ton stored for the base in the short and long terms are presented in Fig. 8. The forest sector is a net sink of GHG emissions with a minor stock increase between the two periods. On the other

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[15] Note the difference between reforestation and afforestation. Reforestation occurs on forest land whereas afforestation occurs on agricultural land.

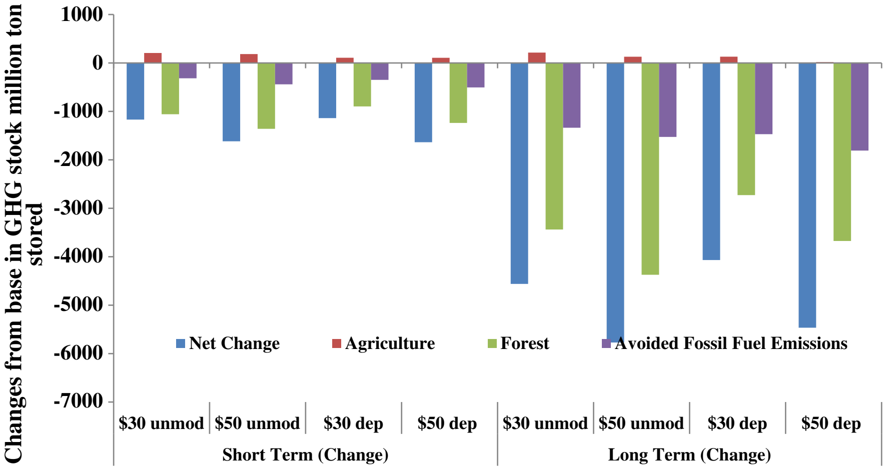

Fig. 9. Projected annual average changes from base in GHG level stocks from forest, agriculture, avoided fossil fuel emissions and net change in million ton stored for the unmodified and deprecated scenarios for $30 and $50 carbon prices in the short and long terms at the national level.

hand, the agricultural sector is a net source of GHG emissions with a reduced stock of 28% between the two periods.[16]

Projected annual average changes from the base in GHG level stocks from forest, agriculture, avoided fossil fuel emissions and net change in million ton stored for the unmodified and deprecated scenarios for $30 and $50 carbon prices in the short and long terms are presented in Fig. 9. The net change column is the summation of changes in GHG level stocks stored in agriculture, forest, and avoided fossil fuel emissions. Several observations are worth noting. First, GHG mitigation in the agriculture and forest sectors is much more cost effective at $30/ton CO_2e than at $50/ton CO_2e. That is, the marginal benefits of raising CO_2 price from $30 to $50/ton CO2e are relatively small. Second, GHG benefits are heavily skewed to the long term (post 2030). This reflects the higher flexibility of land owners in the long term to adjust their land use in response to positive carbon prices, relative to the short term. Third, energy offsets (i.e. avoided fossil fuel emissions) appear to be between third to half those of forestry offsets. This result has to do with RFS2 requirements incorporated in FASOM–GHG and with energy crops being an allowable offset. Fourth, GHG stock reductions in the agriculture sector are always greater under the unmodified and depreciated scenarios, relative to base (i.e. agriculture is always a net source of emissions). This result is largely due to the intensification of remaining agricultural production land. Fifth, only minor changes in net improvement of GHG stocks from stylized carbon markets are evident between the unmodified and depreciated scenarios, relative to the base, in the short term. Lastly, it takes time for the large gains in GHG stock associated with afforested lands or changes in forest sector management to accrue. More considerable changes are evident in the long term. In particular, the depreciated scenarios experience a decline of 300 and 500 million tons annual-average in net change GHG stored in the $30 and $50 carbon price, respectively, relative to the unmodified ones, which is equal to approximately 4.5 and 7.5% of U.S. GHG emissions in 2010 (EPA, 2013).

Results of our analysis are robust to lower permanence value reduction rates for the higher carbon price and can serve as upper bound of impacts for the lower carbon price. However, the combination of greater declines in afforestation area alongside much higher harvest percentages of afforested area which are projected with higher value reduction rates of afforestation carbon offsets implies even more movement of land between the two sectors with greater effects on land use in different agricultural uses.

5. Conclusion

We examine the permanence of agricultural land afforestation under stylized carbon markets at the regional levels in the United States by employing a cross sectoral nonlinear optimization model. Our main findings suggest that carbon markets significantly increase afforestation levels initially in all regions, relative to base. However, although most afforested area in the Midwest regions remain unharvested in the long term, significant percentages of afforested area in the Southern regions shift back to agricultural uses over time. A permanence value reduction on afforestation carbon offsets has a large negative impact on afforested area in the Southern regions of the U.S. but only a minor negative effect in the Midwest regions. Furthermore we find that such a permanence value reduction promotes the harvesting of afforested stands in the effected regions. This is an unintended consequence of the policy. The lower value of afforestation compared with other mitigation offsets from agricultural activities, incentivizes land owners to shift their land back to agricultural uses earlier than without the value reduction. This trend is particularly evident in the Southern regions which are characterized by shorter assumed timber rotations, relative to Midwest regions, and therefore have greater opportunities for land conversion between the two sectors.

Another policy concern has to do with carbon price levels. In the SC and LS regions, the smaller carbon price entails moderate reductions in net afforestation in 2055, compared with the higher carbon price. In the SE region, on the contrary, while the smaller carbon price results in humble declines in net afforestation in the same period, modest expansion in net afforested area is evident under the higher carbon price. That is, regional characteristics, even in similar geographic areas, are important in applying a national permanence value reduction program. Such characteristics include the capacity and flexibility of land movement between the two sectors as well as land shifts within the agricultural sector at each region.

Lastly, FASOM–GHG projects future conditions based on optimal economic behavior in a world with perfect information and foresight. Therefore, projections of the magnitude of carbon sequestration through afforestation will represent what is possible given the assumptions and inputs but not necessarily the ultimate outcome.

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[16] GHG level stocks from avoided fossil fuel emissions are very minor under the base and are thus omitted from Fig. 8.

Appendix A. GHG 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 form 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.

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