Welfare changes associated with forest carbon offset credits in the United States

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Abstract

This paper analyzes forest carbon offset credits arising under a possible cap-and-trade system in the United States and its effect on net revenue and commodity prices. A real option model determines the optimal switching from agriculture to forestry under uncertainty in both activities. The key aspects of the model are uncertainty, endogenously determined commodity prices, and spatially explicit modeling in a real option framework. The model is calibrated to counties in the contiguous United States and includes nine major crops and pasture. We show that the highest increase in net revenue occurs in the Southeast and the Northwest with small increases in the Corn Belt. Switching from agriculture to forestry starts occurring early in counties with low crop yields but does not manifests itself immediately in the crop price which results in smaller impacts on commodity prices than previously estimated.

Keywords: Land-use change, cap and trade, real options, welfare

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1. Introduction

In the United States, the American Clean Energy and Security (ACES) Act of 2009 and the American Power Act (APA) of 2010 have been presented to mitigate climate change. A cap-and-trade system is established under both acts and includes the possibility for the agricultural sector to provide offset credits from carbon mitigating and sequestering practices such as afforestation. The forest offset credits are intended to compensate farmers and landowners for the potential increase in energy prices. In order to analyze the impact on net revenue, we build a real option model with endogenously determined commodity prices and modeling U.S. agriculture at the county level.

Given uncertainty and costly reversibility, it might be optimal for a landowner to delay afforestation in order to gain more information about future prices and revenues (Dixit and Pindyck, 1994; McDonald and Siegel, 1986; Schatzki, 2003). The article by Song et al. (2011) analyzes the farmer's decision to switch from food to energy crops under stochastic prices for both crops. In our

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analysis, we include an endogenous revenue process and calibration to counties in the contiguous United States.

The majority of real options literature analyzes investment decision under the assumption that the number of market participants does not change. The seminal paper by Leahy (1993) shows that for a real option model, the investment threshold is unaffected by the presence of entry and exit, i.e., endogenous commodity prices. The intuition behind the result is that competition reduces the value of the option to wait and the value of the investment proportionally with the consequence that the myopic landowner behaves optimally. Note that the landowner is myopic about the number of industry participants but behaves rationally by forming expectations about the future evolution of prices. These results allow us to simulate the switching decision of individual landowners at the county level using the real option model and by taking the aggregate production level as given. The entry and exit decisions of other landowners is taken into account and aggregate production (which is determined by the number of landowners), and thus net revenue, are updated in every period.

Our results show that landowners find it optimal to delay afforestation in order to gain more information concerning the carbon price and the evolution of revenue from agriculture. Afforestation starts occurring early in counties characterized by low agricultural productivity. The loss of cropland in those areas is compensated by an increase in production elsewhere and hence, the increase in crop prices is steady over the projection period. Afforestation is observed in parts of the country with low net revenues from agriculture, i.e., the Southeast and the Northeast. Almost no land conversion takes place in the Corn Belt, which is contrary to previous studies. Counties that have low agricultural net revenue profit the most from switching whereas counties that have high agricultural net revenue only profit form the increase in commodity prices.

The remainder of the paper is organized as follows. Section 2 presents the theoretical model used in our analysis. Section 3 introduces the data in terms of agricultural production (e.g., yield potential, demand function calibration, etc.) and forest characteristics (e.g., carbon sequestration rates, conversion cost, etc.), outlines assumptions concerning the CO_2 price, and details the numeric simulation. Section 4 presents the results and section 5 concludes and highlights the implications for future policies.

2. Model

The basic setup of the model involves a fixed number of landowners, i.e., one representative landowner for each county i. At time t, the landowner of county i can be in either of two regimes k: agriculture (A) or forestry (F). At each point in time, the landowner observes the net revenue from agriculture (π_A) and forestry (π_F). In addition to the net revenue observations, the landowner knows the stochastic processes governing the net revenue disturbance and the CO_2 price. Based on this information, the landowner can form rational expectations about the evolution of future revenues in both regimes. The landowner then decides whether to stay in the current regime or switch to the other. The key decision variables in the model are the regime $k \in \{A, F\}$ and, if a landowner decides to stay in agriculture, the land allocation among the crops. The crop prices adjust according to the production in agriculture. Switching costs are incurred if the landowner changes from agriculture to forestry.

2.1. Net Revenue in Agriculture and Forestry

The landowner faces commodity demand functions $Q_{jt} = D(\mathbf{p}_t)$ for crop j at time t which are functions of the price vector $\mathbf{p}_t$. The net revenue function for county i when in agriculture is written as (subscripts i and t are dropped for notational convenience):

$$\pi_A(\mathbf{a}_A, \epsilon_A) = \max_{\mathbf{a}_A} \sum_{j=1}^{J} \left[p_j a_j y_j - K_j(a_j) \right] \epsilon_A \tag{1}$$

where a_j and y_j are the crop yield and area allocated to crop j, respectively. The cost function is $K_j(a_j)$ with increasing marginal cost and $\mathbf{a}_A = [a_1, \ldots, a_J]$. The uncertainty in the net revenue is introduced by ϵ_A which follows a stochastic process and is the same for all spatial units. We justify this assumption by the fact that all landowners face the same output prices, which are correlated with yield disturbances. Idiosyncratic shocks in the competitive equilibrium framework are possible as shown by Zhao (2003) but would increase the computational time significantly by requiring simulation of a covariance matrix for 3070 counties at each time step. The disturbance term ϵ_A can be thought of as summarizing all uncertainties due to yield, output price, and cost fluctuations. The maximization problem with respect to crop area allocation of the individual landowner i while in agriculture in its most general form is written as

$$\max_{a_{ij}} \sum_{j=1}^{J} p_j a_{ij} y_{ij} - K(a_{ij}) \qquad \text{s.t.} \sum_{j=1}^{N} a_{ij} = \bar{a}_i$$

The farmers allocates land such that the marginal product between any two crops is equal, i.e.;

$$\frac{p_j y_j}{p_k y_k} = \frac{dK(a_{ik})/da_{ik}}{dK(a_{ij})/da_{ij}}, \quad j \neq k \tag{2}$$

Agriculture is a perfectly competitive market and hence, all agents are price takers and do not take the effect of their acreage decision on output prices into account. In aggregate however, the dynamics of the net revenue are endogenous to the model. If landowners decide to move from agriculture to forestry, less cropland is available for production, thus increasing the net revenue and vice versa.

There are two sources of revenue while in forestry. First, the standing forest represents a value in terms of wood (stumpage), which can be harvested at the end of the rotation period. Second, carbon credits can be earned for the carbon sequestered in trees. The net revenue from forestry is written as:

$$\pi_F(a_{iF}, \epsilon_F) = R_F(p_F, a_{iF}, y_{iF},) + a_{iF} \cdot h_i \cdot \epsilon_F \tag{3}$$

where R_F is the non-carbon net revenue function, p_F is the stumpage price, a_F is the area in forestry, and y_F is the yield in terms of timber growth per years. The county specific sequestration rate is h and ϵ_F represents the stochastic carbon price. We do not explicitly model the harvest decision or the rotation of forest. The function $R(\cdot)$ in equation (3) incorporates this information implicitly by representing the land rent for a spatial unit per year.

2.2. Maximization and Regime Switching Problem

The most general problem of the landowner is characterized by the possibility of switching from a regime which yields one stochastic return to a new regime which results in a flow of profits with different stochastic properties. We denote the disturbance terms as ϵ_A and ϵ_F for agriculture and forestry, respectively. Given the initial values of the state variables at $t = 0$ as ϵ_A and ϵ_F, the maximization problem is written as (Brekke and Øksendal, 1994; Vath and Pham, 2007):

$$J^k(\epsilon_A(t), \epsilon_F(t), \alpha) = E\left[\int_0^\infty e^{-rt}\pi_k(\epsilon_A(t), \epsilon_F(t))dt - \sum_{n=1}^{\infty} e^{-r\tau_n} H(\kappa_{n-1}, \kappa_n)\right] \tag{4}$$

where r represents the discount rate, k denotes the regime, and $H(\cdot)$ is the cost of switching. In what follows, $H(A, F) \equiv C_{AF}$ and $H(F, A) \equiv \infty$, i.e, switching back to agriculture once a forest is established is not possible. The last assumption does not alter our analysis because the carbon price is increasing whereas the revenue from agriculture is mean reverting and thus, it would never be optimal to switch back to agriculture. The dynamic problem of the land owner can be thought of as finding a sequence α of N stopping times (τ_n) and new regimes (κ_n), i.e., $\alpha = (\tau_1, \tau_2, \ldots, \tau_N, \kappa_1, \kappa_2, \ldots, \kappa_N)$, in order to maximize the payoff from a unit of land. The stopping times and new regimes cannot be found explicitly but are determined by the impulses ϵ_A and ϵ_F received by the land owner. The following stochastic processes for agriculture and forestry are assumed throughout the paper:

$$d\epsilon_A = \eta(\bar{\epsilon}_A - \epsilon_A)dt + \sigma_A \epsilon_A dz_A \tag{5}$$

$$d\epsilon_F = \mu\epsilon_F dt + \sigma_F \epsilon_F dz_F \tag{6}$$

where $\bar{\epsilon}_A = 1$ and the correlation between the processes is $E(dz_A, dz_F) = 0$. In the model, it is assumed that the shocks influencing the carbon price are independent of the disturbances influencing the net revenue. Odening et al. (2007) argue that a mean reverting process is more consistent with economic theory in the presence of competitive markets independent of whether the price process passes a unit-root test or not. Hence, we chose to model the agricultural revenue disturbance ϵ_A to be mean reverting. The stochastic variable ϵ_F represents directly the emission allowance price. Let the infinitesimal generator of state process be written as follows (Balikcioglu et al., 2011):

$$\mathcal{L} = \eta_A(\bar{\epsilon}_A - \epsilon_A)\frac{\partial}{\partial\epsilon_A} + \mu_F\epsilon_F\frac{\partial}{\partial\epsilon_F} + \frac{1}{2}\sigma_A^2\epsilon_A^2\frac{\partial^2}{\partial\epsilon_A^2} + \frac{1}{2}\sigma_F^2\epsilon_F^2\frac{\partial^2}{\partial\epsilon_F^2}$$

If currently in agriculture, Brekke and Øksendal (1994) show that the Hamilton-Jacobi-Bellman equation for (4) results in:

$$rV^A(\epsilon) \geq \sup_{a_A} \left\{ \pi_A(a_A) + \mathcal{L}V^A \right\} \tag{7}$$

and

$$V^A(\epsilon) \geq V^F(\epsilon) - C_{AF} \tag{8}$$

To determine whether to switch or not, one of the equations must hold with equality. Both equations holding with equality defines the border of the switching region. If equation (7) holds with equality, then the landowner stays in agriculture because the rate of return from regime agriculture is equal to the sum of the current return and the expected capital appreciation. The expected capital appreciation plays an important role in the option valuation because it determines the expected future evolution of the current use. In addition to the first equation holding with equality, equation (8) holding with inequality means that the value from staying in agriculture is bigger than the value from the forestry minus the switching cost. A switch of the regime is triggered when the current return plus the expected rate of capital appreciation is smaller than the rate of return from staying and if the value function from regime k is equal to the value function from the other regime minus the switching cost (Fackler, 2004). The solution to equation (7) and (8) subdivide the π_A-π_F space into two regions corresponding to "staying in current use" or "switching to forestry" (Nøstbakken, 2006; Song et al., 2011; Balikcioglu et al., 2011).

No explicit solution exists and we rely on the collocation method discussed and implemented in Miranda and Fackler (2002) and Fackler (2004) to solve for equations (7) and (8) numerically. In our case, we solve the problem on the interval [0,8] for agriculture (i.e., we assume that the maximum net revenue from agriculture is 800 dollars) and [0,5] for the carbon price. The number of nodes is 40 and 25, respectively.

3. Empirical Model

The model covers the 3070 counties in the contiguous United States and nine commodities (barley, corn, cotton, hay, oats, rice, soybeans, sorghum, and wheat) plus pasture. The model is calibrated to 2010 as the base year because this represents the year the policy change would have taken place. Legislation would distribute carbon credits based on additional forest and not on existing forest and hence, we include only counties that have recently been in agricultural production. We restrict afforestation to areas with more than 700 millimeters of average annual precipitation and had previous forest coverage (Figure 1). Time as a state variable in our model would increase the computational time exponentially. Neither the demand functions nor the yield in the next section include a time trend. Implicit in those assumptions is that any yield increase is offset by an increase in demand leaving the crop area unchanged in the long-run. If yield increases at a faster pace than the crop demand, more cropland becomes available for forest because the increase in supply leads to lower commodity prices. Landowners would then have the incentive to switch away from agriculture leading to potential afforestation and stable commodity prices.

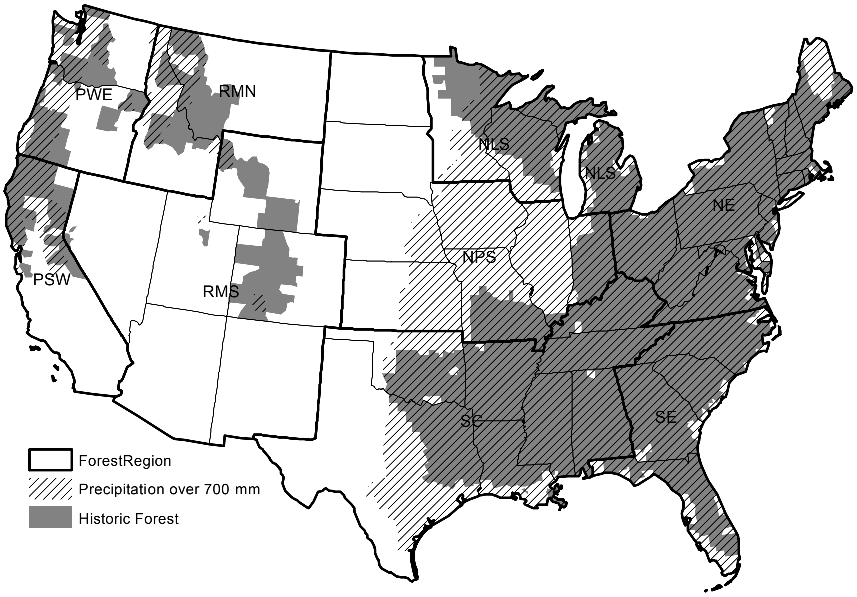

Figure 1: Geographic coverage with historic forest coverage and precipitation over 700 millimeters: The average annual precipitation between 1960 and 2008 for the United States was obtained from the PRISM Climate Group at Oregon State University. Historic forest cover was obtained from "Global Forest Watch" and the forest regions correspond to Smith et al. (2006).

3.1. Commodity Demand

There are up to four demand sectors for each commodity: food/domestic, feed, exports, and biofuel. We assume a constant elasticity demand function which is of the general form:

$$q_{jm} = \alpha_0 \prod_{j=1}^{N} p_j^{\alpha_{jm}}$$

where j represents the crop and m denotes the crop demand sector. The total demand for crop j is the sum of the demand from the different sectors, i.e., $q_j = \sum_{j=1}^{M} q_{jm}$. The elasticities are presented in table 1. The demand elasticities for cotton are obtained from the POLYSYS model[1] and are set to -0.05 for mill demand and -1 for export demand. The inclusion of cross-price elasticities allows for domestic cross-commodity effects as well as spatial aspects of crop production, e.g., the conversion of land used for corn and soybean production will have an effect on wheat prices and vice versa. We assume that the elasticities remain unchanged over the projection period. For corn, we assume a constant ethanol production over the projection period which is set

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[1] The POLYSYS Modeling Framework: A Documentation, www.agpolicy.org/tools/doccom.pdf, accessed December 14th, 2011

Table 1: Food, feed, and export demand elasticities

	p_{BA}	p_{CO}	p_{HY}	p_{OA}	p_{RI}	p_{SB}	p_{SG}	p_{WH}
Food Demand								
Barley	-0.117^{3}	-	-	-	-	-	-	-
Corn	-	-0.389^{1}	-	-	0.001^{4}	0.002^{4}	-	0.003^{4}
Rice	0.208^{1}	0.016^{4}	-	-	-0.380^{3}	-	-	0.003^{4}
Oats	0.081^{1}	-	-	-0.789^{1}	-	-	-	-
Soy. Oil	-	-	-	-	-	-0.604^{1}	-	-
Sorghum	-	-	-	-	-	-	-0.827^{1}	-
Wheat	-	0.004^{4}	-	-	-	0.001^{4}	-	-0.137^{1}
Feed Demand								
Barley	-2.167^{1}	1.080^{2}	-	-	-	-	-	-
Corn	0.094^{1}	-0.883^{1}	-	-	-	0.090^{3}	-	-
Hay	-	0.070^{3}	-0.491^{1}	-	-	-	-	-
Oats	0.410^{1}	0.790^{2}	-	-0.620^{3}	-	-	-	-
Soy. Meal	-	0.081^{4}	-	-		-0.513^{1}	-	-
Sorghum	-	3.401^{1}	-	0.074^{1}	-	1.204^{1}	-3.611^{1}	-
Exports	-0.500^{2}	-0.420^{2}	-	-0.35^{2}	-0.480^{2}	-0.570^{2}	-0.500^{2}	-0.380^{2}

Notes. The price of soybeans (SB) refers to soybean meal in the case of feed and to soybean oil in the case of food. The elasticities for food and feed demand are calculated using the Linear Approximation Almost Ideal Demand System (1). Some elasticities were adjusted because the estimates from the LA/AIDS were inconsistent with economic theory. The elasticities are corrected using the POLYSYS model (2), the Food and Agricultural Policy Research Institute (FARPI) model (3), and the Economic Research Service/Pennsylvania State trade model (4).

at 4.8 billion bushels or 13.11 billion gallons of ethanol. Hence, the demand for corn (in million bushels) is appended by the consumption for biofuels: $q_{corn} = \tilde{q}_{corn} + 4,800$ where $\tilde{q}_{corn}$ represents the corn demand for food, feed, and exports. An increase in ethanol production would lead to an increase in the demand for corn making it more likely to stay in agriculture because of increased returns.

The constant α_0 is determined by matching the price level in $t = 0$ which is assumed to be the long-run equilibrium from the 2011 USDA outlook[2] with the resulting production from the yield and area by county when all counties considered in our model are in agriculture.

There is no demand function for pasture and the net revenue from an acre of pasture is linked to the price of hay (Lubowski et al., 2006). Iowa State University's extension service[3] recommends

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[2] USDA Long-term Projections, February 2011, accessed January 15th, 2012

[3] http://www.extension.iastate.edu/agdm/wholefarm/pdf/c2-23.pdf

multiplying the estimated forage production from an acre of pasture by 35% of the hay price. We do not have forage production from pasture per county but have the 2010 cash rent collected from USDA's NASS which we use as a proxy for pasture quality and forage production. The net revenue from pasture is calibrated such that the county cash rent in 2008 matches the 35% of the price of hay and a quality index associated (and constant over time) for each county. Thus, an increase in the price of hay translates into a rising net revenue from pasture. The amount of pasture available is based on the 2007 Agricultural Census from the U.S. Department of Agriculture.

3.2. County Specific Agricultural Production and Net Revenue

We include counties that were in crop production for at least five years after 2000. The base area in each county is calculated as the average crop area harvested between 2000 and 2010. In a second step, we use 1975-2010 yield data from the National Agricultural Statistical Service to fit a linear trend for each county and each commodity to determine the expected yield by crop and county in 2010.

Cost and return data are obtained from the USDA's Economic Research Service[4]. The total cost in our model is represented as $K_i(a_{ij}) = \alpha_{1i}a_{ij} + (1/2)\alpha_{2i}a_{ij}^2$ where $K_i(a_{ij})$ represents the operating cost. The increasing marginal cost captures either the decrease of yields because marginal land with lower average yields is brought into production if cropland is expanded or the requirement of more fertilizer use for the same reason. The increasing marginal cost is also necessary to obtain a solution to the profit maximization problem of the landowner. County specific cost data are not available and hence the direct estimation of the county specific parameters α_{1i} and α_{2i} is not possible. To obtain county specific parameters, we proceed in two steps. First, we obtain data from the USDA/ERS cost and return database on operating cost by crop and farm resource region between 2005 and 2010 and set the parameter α_{1i} equal to the total of operating cost but exclude fertilizer and chemical costs. We assume that all counties in a particular farm resource region have the same α_{1i}. The values are represented in table 2. Second, assuming profit maximizing but price taking behavior allows the calculation of the county specific parameters α_{2i} because the landowner sets marginal revenue equal to marginal cost, i.e., $p_j \cdot y_{ij} = \alpha_{1i} + \alpha_{2i}a_{ij}$. Given p_j, y_{ij}, α_{1i}, and a_{ij} enables us to obtain α_{2i} for the base year.

Not all commodities compete for the available land in a particular county at the same time. The cropland allocation in agriculture is rational in the sense that it is consistent with the resulting price level (equation 2). Once crop prices adjust and the crop area is allocated, the net revenue can be calculated based on equation (1). Before switching to forestry, landowners left in agriculture have the flexibility to expand the area planted and thus increase net revenue. In the absence of any switching to forestry, net revenue from agriculture will fluctuate around a mean in the long-run. The quantity Q is the total production based on the yield parameter, landowner's area allocation, and the number of landowners in the regime "agriculture", which is determined by the real options switching model. Although we model the net revenue from agriculture for the individual landowner

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[4] www.ers.usda.gov/Data/CostsAndReturns accessed January 15th, 2012

Table 2: Average operating cost except fertilizer and chemicals

Region	Barley	Corn	Cotton	Oats	Rice	Sorghum	Soybeans	Wheat
Basin and Range	64							55
Eastern Uplands		100					78	
Fruitful Rim	101		467		316	64		100
Heartland	53	109	327	59		51	76	52
Mississippi Portal			320		243		107	
Northern Crescent	65	121		60			84	64
Northern Great Plains	48	118		39		34	80	53
Prairie Gateway		168	227	34		83	103	53
Southern Seaboard		110	264				72	
United States	63	119	273	53	272	77	83	52

Notes. The ERS subdivides the United States into 9 regions to capture differences in cropping systems and farm sizes for a better determination of costs and returns.

i as mean reverting, the mean itself is influenced by the total production in the regime "agriculture" which is endogenous to the model. At each time step t, a number of producers might switch from agriculture to forest thereby decreasing the supply of agricultural commodities. The individual landowner's decision real option decision threshold is unaffected by this switching but, at each time step, the mean has to be recalculated to reflect the current crop production based on the number of counties in agriculture. The landowner takes the new long-run net revenue for her or his plot of land to form rational expectations about the future stream of revenue. We assume that each spatial unit has an upper maximum $\bar{a}_i$ of land area which can be in forestry or agriculture.

3.3. Forestry Model

The landowner switching to forestry receives two streams of revenue. The annualized value from timber and the carbon sequestration credits. For computational ease, we assume the timber value to be non-stochastic and fixed over time. In addition, the benefits from planting a forest today are received several decades into the future when harvesting and selling the timber. We do not model the harvest decision but include the stumpage value, i.e., the value of the standing timber. The value from wood is modeled as the net present value times the interest rate which is an approach consistent with Sohngen et al. (2009). In addition, the type of forest planted in a county is exogenously determined.

The net revenue function for forest $R_F(p_F, a_{iF}, y_{iF},)$ is calibrated using yield data from the U.S. Forest Service (Smith et al., 2006). Stumpage prices were obtained from various public and private institutions. Forest yield and growth data as well as the forest regions (figure 1) were taken from Smith et al. (2006). We assume that the forest growth rate, the stumpage price, and the forest sequestration rate remain constant over the projection period. The assumption of a constant sequestration rate simplifies the computations in the empirical section of the paper because the dependency on t is avoided. To determine the optimal rotation period and thus the final period

Table 3: Forest rent and sequestration

Region	Forest type	Wood	\$/t	Rent	NPV	CO_2-e/year
NE	Oak-hickory	H	45	53.87	673.42	3.39
NLS	Oak-hickory	H	25	34.41	430.17	2.13
NPS	Elm-ash-cottonwood	H	15	21.72	271.56	2.06
PSW	Fir-spruce-mountain hemlock	S	15	22.19	277.39	1.85
PWE	Douglas-fir	S	15	18.89	236.13	4.47
RMN	Douglas-fir	S	35	47.04	588.01	2.52
RMS	Douglas-fir	S	35	47.04	587.95	2.25
SC	Loblolly-shortleaf pine	S	30	34.27	428.32	3.25
SE	Loblolly-shortleaf pine	S	30	34.27	428.32	3.19

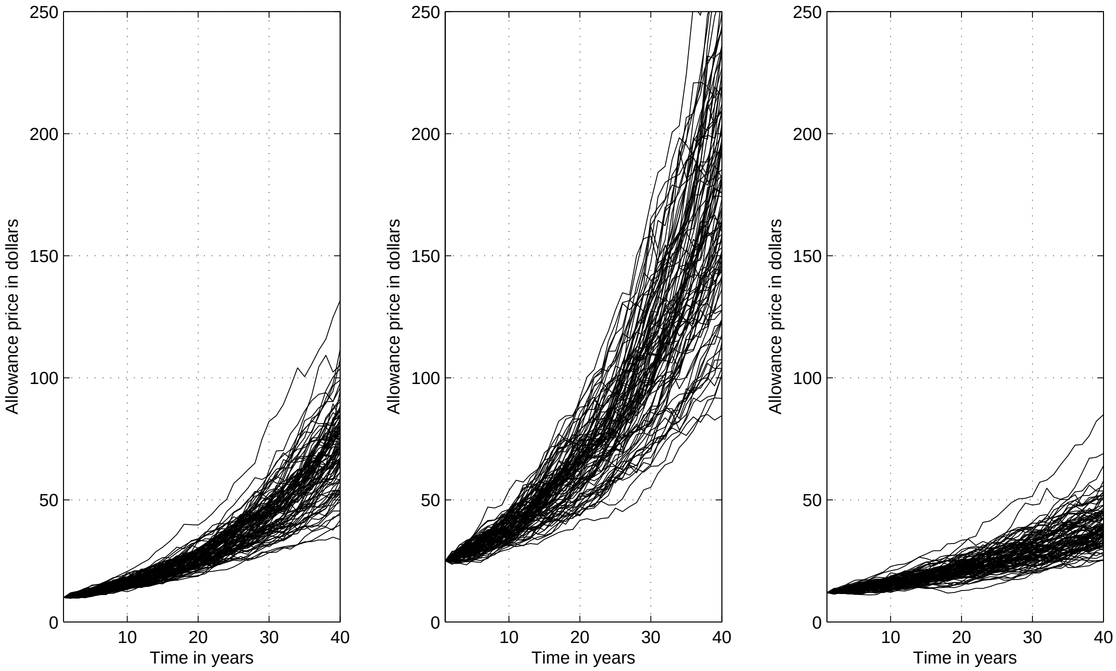
Notes. "Wood" refers to hardwood (H) or softwood (S). "\$/t" is the stumpage price per ton, i.e., the value of the standing forest. "Rent" and "NPV" are annualized rent and the net present value, respectively. "Cost" is the per acre switching cost.

for the net present value analysis, we use the Faustmann formula to determine the optimal harvest time. Our choice of forests in a particular county is based on the type that is most likely to be planted given historic presence. For example, in the Southeast, the loblolly-shortleaf pine is the most predominant type of tree and hence, we chose that particular type of tree in the Southeast and South Central part of country. Table 3 summarizes the results in terms of growth per year, tons of CO_2-e sequestered per year, price, cash flow (CF), net present value (NPV), and annual non-carbon rent for all potential tree species by region.

We contacted the National Resources Conservation Service (NRCS) in 48 states and obtained typical afforestation costs. For the regions outlines in Smith et al. (2006), we calculated the average afforestation cost based on the responses (35) from the NRCS offices.

3.4. CO_2 Price Dynamics

The lack of data concerning the CO_2 price makes the analysis more difficult. USDA bases its analysis on a CO_2 price starting at \$10 per ton in 2010 increasing at 5% per year. This results in a CO_2 price of US-\$ 70.40 by 2050. The ACES Act and APA include a price collar to limit compliance costs. For the APA, the inflation-adjusted price floor starts at \$12 per t CO_2 and increases at 3% per year and the price ceiling starts at \$25 per t CO_2 and increases at 5% per year. We run three scenarios in line with the previous literature and price collar assumptions. Scenario 1 ("Base Case") starts at a allowance price of \$10 with an increase of 5% and is consistent with the scenario analyzed by USDA (2009). Scenario 2 ("Price Floor") replicates the price floor in terms of expected prices starting at \$12 and increasing at 3%. Scenario 3 ("Price Ceiling") starts at \$25 and increases at 5%. We assume a volatility parameter of $\sigma = 4$. The three carbon price paths in figure 2 depict 100 possible price evolutions for the scenarios.



(a) Base Case (b) Price Floor (c) Price Ceiling

Figure 2: Allowance price simulations (n=100)

3.5. Numerical Simulation

Although the model presented here is in continuous time and the adjustments in terms of crop production happen instantaneously, the simulation of the model will be conducted in discrete time following Song et al. (2011) and Chladná (2007). Between time steps, the net revenue disturbances for both regimes are realized and the decision process continues for the next period. The revenue disturbance parameters for the regime "agriculture" are set to $\eta_A = 0.6$ and $\sigma_A = 0.25$. Those values are consistent when estimating η_A and σ_A individually for the net revenue of the commodities included in this model which range between 0.13 and 0.81 for η_A and 0.21 and 0.53 for σ_A. The discount rate for the model is set to 0.08.

The numerical analysis for this model is computationally intensive thus we impose certain restrictions. First, we limit our Monte Carlo simulation to 100 runs simulating agriculture and forestry over a period of 40 years. Second, the net revenue from agriculture per period and county is rounded to the next integer which allows us to calculate the decision threshold for a relatively small set of values and reuse those values at each step. The county long-run net revenue changes every period and would require solving a partial differential equation for each county, each year, and for all 100 Monte Carlo simulations. Because this is numerically very intensive, we use the integer values for the mean value when calculating the decision threshold. The model initialization takes place for the year 2010. The two key components of the algorithm are a vector of regimes

$$s_t = \begin{bmatrix} s_{1,t} & s_{2,t} & \cdots & s_{3070,t} \end{bmatrix}^\top$$

and a vector of commodity prices

$$p_t = \begin{bmatrix} p_{BA,t} & s_{CO,t} & \cdots & p_{WH,t} \end{bmatrix}^\top .$$

The vector **s** is of size 3070 × 1 where i and t represent the county and year respectively. Each $s_{i,t}$ can take three values: 0 if neither in agriculture nor forestry, 1 if in agriculture, and 2 if in forestry. At the beginning of the simulation period, all the potential forestland is assumed to be in agriculture and hence, s_{it} is only composed of zeros and ones. The vector **p** represents the nine commodity prices in our model. In addition, we have a matrix of crop area allocations

$$A = \begin{pmatrix} a_{1,BA} & a_{1,CO} & \cdots & a_{1,WH} \\ a_{2,BA} & a_{2,CO} & \cdots & a_{2,WH} \\ \vdots & \vdots & \ddots & \vdots \\ a_{N,BA} & a_{N,CO} & \cdots & a_{N,WH} \end{pmatrix}$$

where N represents the number of counties. The generic algorithm for our model is as follows:

Model initialization ($t = 0$)
All counties considered for agriculture or forestry are in the regime "agriculture". The allowance price is $C_0 = \$10$, $C_0 = \$10$, or $C_0 = \$25$ depending on the scenario. Commodity prices and production are at their baseline level p_0 and Q_0 and the long-run net revenue for county i is $\bar{\pi}_{i,0}(Q_0)$. In $t = 0$, we also assume $\pi_{i,0} = \bar{\pi}_{i,0}$.

Step 1 (for $t \geq 0$**):**
Moving from period t to period $t+1$, we draw an allowance price disturbance and net revenue disturbance based on equations (3.9) and (3.10). The parameters for the carbon price disturbance was previously specified whereas the net revenue disturbance for agriculture ($\epsilon_{A,t}$) is parameterized with $\eta_A = 0.6$ and $\sigma_A = 0.25$. So $\pi_{i,t+1} = \pi_{i,t}\epsilon_{A,t}$

Step 2:
Given $\pi_{i,t+1}$, a landowner in spatial unit i decides whether to stay in agriculture or switch to forestry. After all landowners choose a regime to be in, a new vector s_{t+1} is created.

Step 3:
Given the new vector s_{t+1}, two regimes can emerge for each county:

Table 4: Key scenario assumptions and parameters

	Scenario 1	Scenario 2	Scenario 3
Initial CO_2 price	\$10	\$12	\$25
CO_2 price growth rate	5%	3%	5%
Expected CO_2 price in 2050	\$73.89	\$39.84	\$184.73
Stochastic process: Agriculture	Mean reversion		
Stochastic process: Carbon	Geometric Brownian motion		
Standard deviation	0.04	0.04	0.04

1. Forestry: For the counties which switched to forestry, all potential land is in forestry and no switching back occurs. For all future periods, the net revenue from forestry evolves according to

$$\pi_F(a_F, \epsilon_F) = R_F(a_F, y_F, p_F) + a_F \cdot h \cdot \epsilon_F$$

2. Agriculture: Based on the vector of regimes **s**, landowners in agriculture update their expectations about the long-run net revenue in their county. The algorithm to search for the new long-run net revenues is implemented as follows:
   - An initial guess for price vector p_t is passed into the search algorithm, the counties remaining in agriculture allocate their area according to equation 2 resulting in an area allocation matrix A.
   - The area allocation matrix A times the yield matrix will result in an aggregate production level Q for all commodities.
   - If the aggregate production level is consistent with the previously passed price vector, the program exits or otherwise continues.
   - Given the correct price vector, the long-run net revenue can be calculated.

4. Results

A summary of the key assumptions and parameters for all three scenarios is provided in table 4. A key premiss of our model is that agricultural markets in the United States are in the long-run equilibrium at the beginning of the simulation period. Hence, any reference to the baseline refers to the prices and quantities in the year 2010. In addition, we focus on scenario 1 and 2 because scenario 3 represents a very unlikely case.

4.1. *Price and Production Impacts*

The scenarios are simulated 100 times and the results reported are the average across those runs. The option to delay afforestation and wait for more information about the CO_2 price and the net revenue leads to a waiting period at the beginning of the simulation where no afforestation takes place. The allowance price and the revenue earned from carbon sequestration are relatively low compared to the net revenue from agriculture during this period.

The price and quantity effects from counties switching to forestry can be offset by an expansion of cropland into pasture in counties which stay in agriculture. Counties which have a high yield usually have a low amount of pasture and hence, the net revenue in those counties does not decrease much and neither does the threshold to switch to forestry. However, those high yield counties can slightly increase their production (with a high impact because of the higher yield) by expanding into pasture when other counties pull out of crop production. This leads to a lower effect on prices because the second effect of crop expansion into pasture outweighs the effect of more counties switching. From a political and economic perspective, the finding of overall lower price impacts on crops is key in evaluating the impacts of a cap-and-trade policy on agriculture.

4.2. Net Revenue Impacts

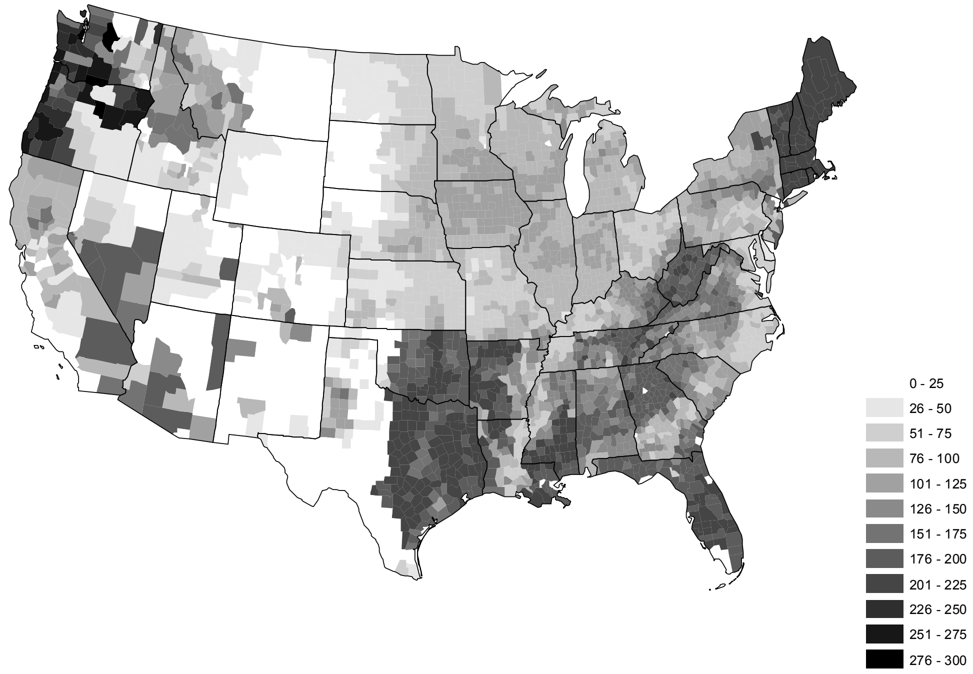
An important consideration for including forest offset credits in the legislation is to improve the welfare of landowners or farmers. Counties with a high probability of switching gain more from the afforestation program than counties that stay in agriculture although net revenue increases for both. Several issues can explain this phenomena: First, low agricultural productivity does not translate into low carbon sequestration rates for trees. For example, the Northeast has a low agricultural productivity but the the carbon sequestration rate of 3.39 t CO_2-e per acre for oak-hickories are only exceeded by tree species in the Pacific Northwest and the Pacific Southwest. Second, once counties switch from agriculture to forestry, the net revenue from forestry is increasing at an expected rate of 5% which is not necessarily true for counties which stay in agriculture (figures 3, 4 and 5.

4.3. Crop Area Impact

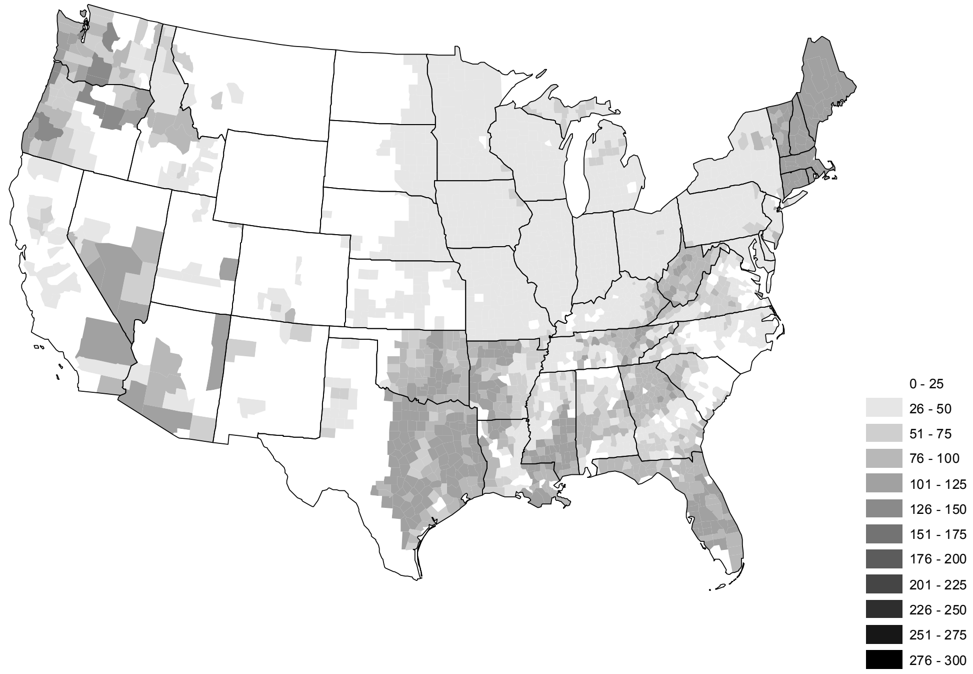
Figure 6 visualizes the area impacts of the “Base Case” and the “Price Floor” on crop area. The maps represent the average percentage change of crops between the baseline and 2050. Crop production in the U.S. responds spatially and three distinctive patterns can be identified in the maps. In the eastern United States, counties reduce their crop area because a switch to forestry occurs. This is consistent with low cash rents in most counties in the Southeast and Northeast because of low agricultural net revenue. In western United States where afforestation potential is limited, crop area expands because landowners face higher output prices because of cropland contraction in the east of the country. Finally, and perhaps most notably, in the midwestern Corn Belt region of the United States there is an increase in corn and soybean planted area because of higher output prices and high net revenues which make afforestation in those area unattractive. In states where no afforestation is possible, cropland is expanded at the expense of pasture.

5. Conclusion

Concerns about climate change led to the introduction of the American Clean Energy and Security (ACES) Act of 2009 and the American Power Act (APA) of 2010 in the United States. Provisions in both bills allow landowners to convert “acreage not forested” to forests and sell the credits earned from carbon sequestration on the allowance market. This paper revisits the issue of land conversion and net revenue increases from the landowners perspective and extends the



(a) Base Case



(b) Price Floor

Figure 3: Absolute Change in Net Revenue by 2050

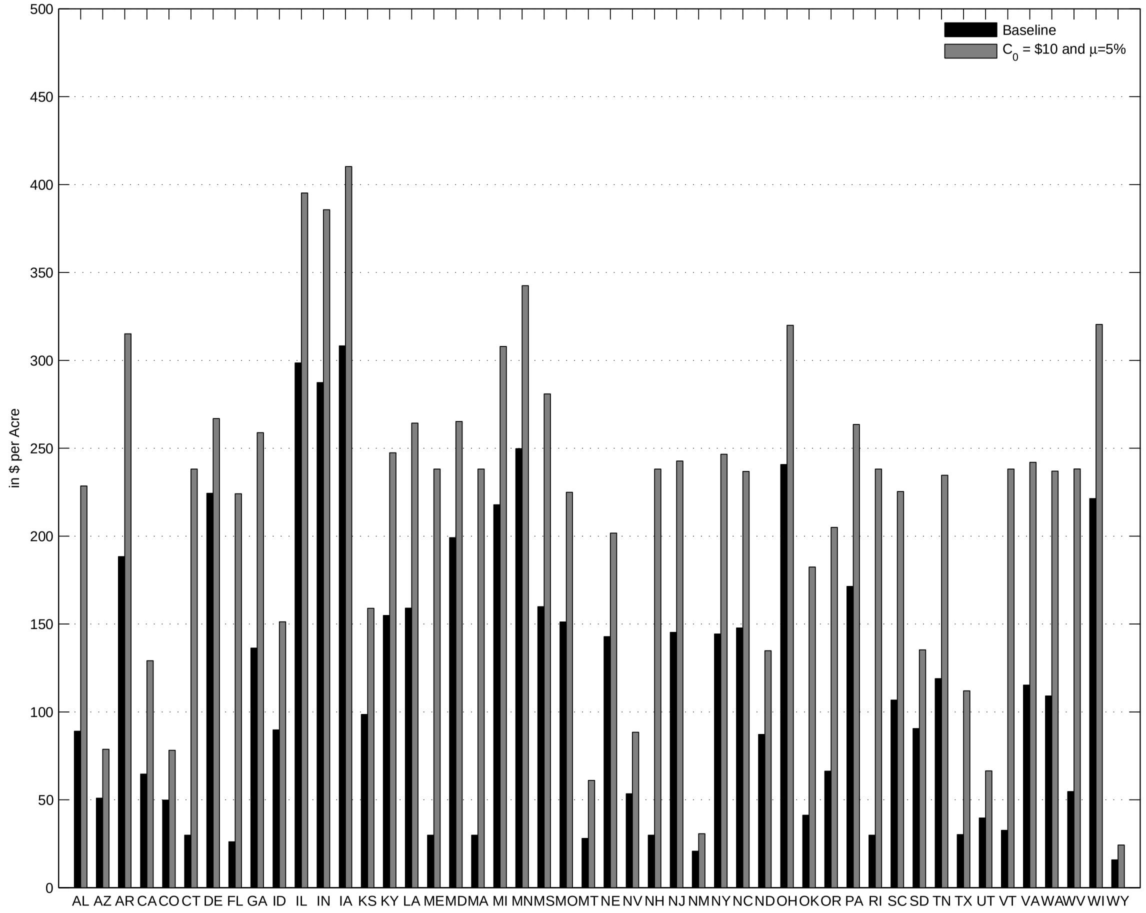


Figure 4: Scenario 1: Base Case by 2050

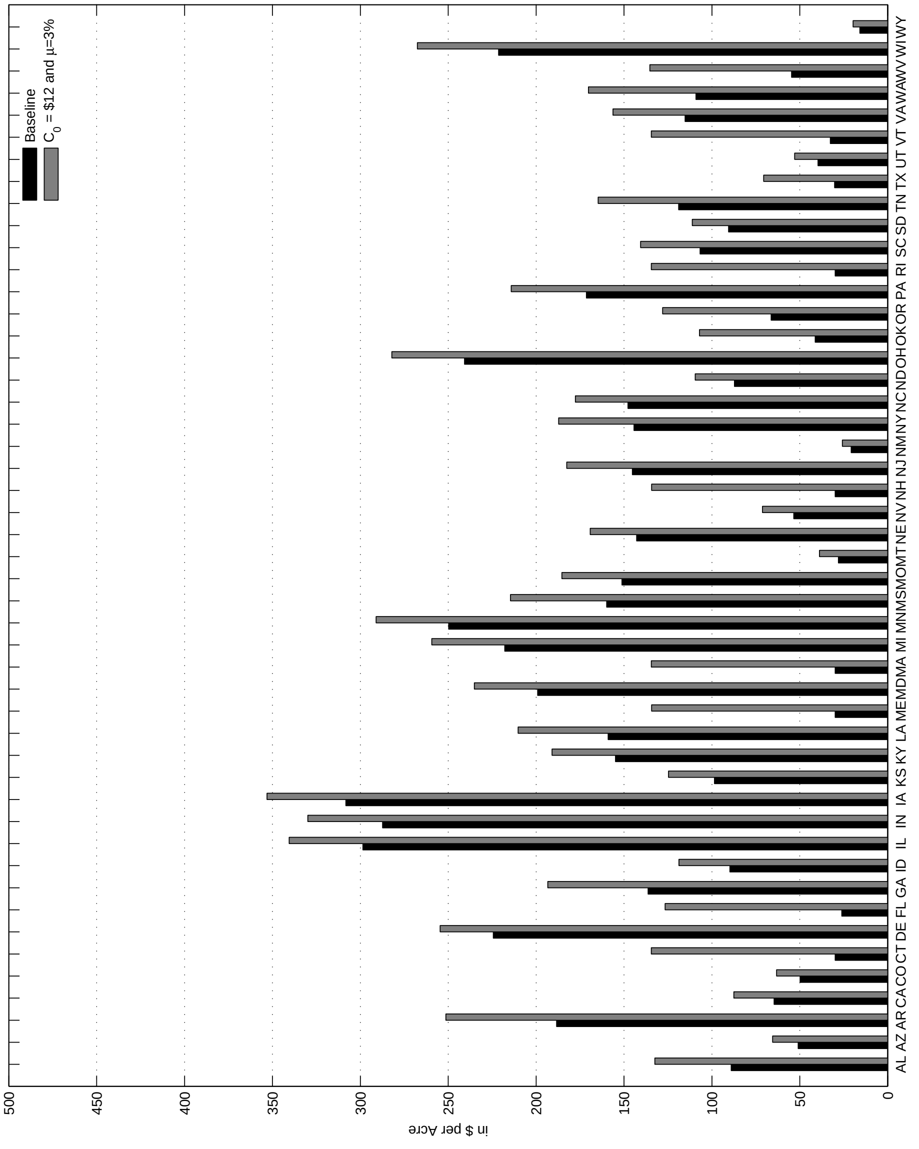
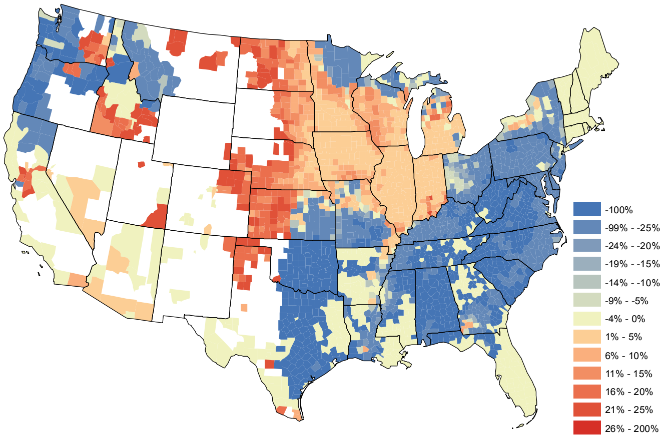
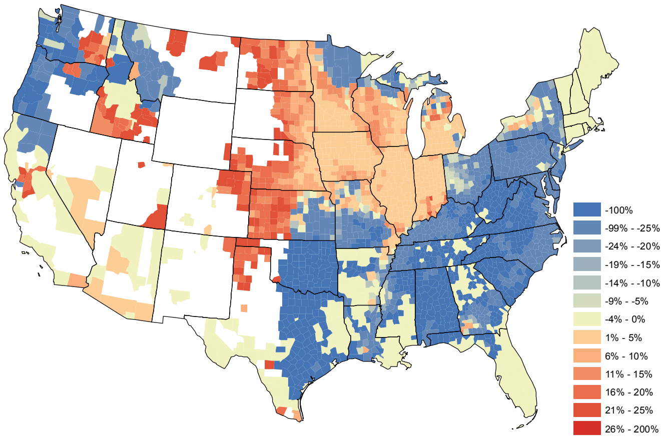


Figure 5: Scenario 2: Price Floor by 2050



(a) Scenario 1: Base Case



(b) Scenario 2: Price Floor

Figure 6: Change in Crop Area by 2050

previous literature by adopting a real options framework to model the decision of U.S. landowners to switch from agricultural land-use to forestry.

Uncertainty leads to a higher investment threshold than under certainty. A key aspect of our model is the endogenous modeling of net revenues when a landowner switches from agriculture to forestry. One effect of switching is the increase in net revenues for landowners remaining in agriculture and thus, every time a conversion to forest takes place, the conversion threshold for the remaining landowners increases. The rational expectations component of our model allows us to recalculate the net revenue streams faced by landowners in each period. Perfectly competitive agricultural markets make the landowner a price taker, however, the area allocation is consistent with the demand function and the aggregate production.

We see smaller increases in commodity prices than previously estimated because planting a forest is an uncertain and irreversible commitment. The afforestation which occurs takes place in the Southeast which already has lower agricultural revenues and hence lower opportunity costs when planting a forest. Net revenues in all counties increase but at different rates. The counties which profit the most are those which switch from agriculture to forestry. And lastly, with the expansion in forestry in the eastern part of the country, crop production increases in the west of the country where afforestation is not possible because of biological constraints.

Offset revenue from afforestation is lower than previously estimated leading likely to lower total welfare for the farm sector. And third, an offset provision would lower the compliance cost for the capped sector (such as energy and industry) by supplying carbon credits to the market and hence lowering the allowance price. The paper shows that in the presence of carbon payments, a clear relationship between carbon/energy, forest, and agricultural markets exist.

Large uncertainties are involved in the carbon price evolution but also in the technological change that might come to agriculture in the future. In this paper, the expected carbon price is modeled as exponentially increasing but the argument can be made that technological discoveries might make the carbon price mean-reverting at some long run price. Given the modeling in this paper, we think that there will be only a negligible commodity price increase in the short- to medium run, i.e., 10 years, from a cap-and-trade policy.

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