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The effects of uncertainty under a cap-and-trade policy on afforestation in the United States

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Abstract

To combat climate change, cap-and-trade policies have been proposed and implemented in countries around the world. The stochastic carbon price that results from a cap-and-trade policy makes investment decisions in carbon mitigating and sequestering practices more complex. This letter illustrates the consequence of uncertainty by analyzing forest carbon offset credits under a potential cap-and-trade policy in the United States. The effects of uncertainty on afforestation, carbon sequestration, cropland allocation, and commodity prices using a real option framework are assessed. When compared with deterministic models, less land gets converted from cropland to forestry over the projection period of 40 years because landowners find it optimal to wait before changing land-use to gain more information about the carbon price evolution. The simulation shows that most afforestation occurs in the south and the northeast with almost no conversion in the Corn Belt. The lesson for policy makers is that under carbon price uncertainty, lower afforestation and carbon sequestration takes place. To foster afforestation, mechanisms are necessary to reduce uncertainty at the expense of higher commodity prices.

Keywords: land-use change, real options, greenhouse gas emissions, commodity prices, carbon sequestration

S Online supplementary data available from stacks.iop.org/ERL/8/044020/mmedia

1. Introduction

Raising concern about climate change has lead to the development of cap-and-trade policies around the world. Examples of emission trading systems covering greenhouse gases and air pollutants are found in Australia, the European Union, New Zealand, and the United States. Under a cap-and-trade system, the regulator sets a maximum quantity of emissions and distributes emission allowances equal to the cap. Entities subject to the regulation need allowances for each unit of emission but can trade the allowances among each other. Economic theory requires the allowance price[1] emerging from trading to be equal to the marginal abatement cost across all firms. Uncertainty in firms' abatement costs leads to a stochastic allowance price which makes the investment decisions in pollution abating and sequestering activities more complex. The present work illustrates the consequences associated with a stochastic allowance price by analyzing the afforestation decision of landowners to provide forest carbon offset credits under a potential cap-and-trade policy 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 in the US and either act would have established a

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[1] In this letter, the words 'carbon price' and 'allowance price' are used interchangeably. The carbon price is measured in CO_2-equivalent.

cap-and-trade system. Both proposals included the possibility for the agricultural sector to provide offset credits from carbon sequestration through afforestation. Carbon sequestration in forests is viewed as a low-cost way to mitigate climate change [1–3]. In June 2013, President Obama presented a climate action plan which includes the statement that 'America's forests play a critical role in addressing carbon pollution, removing nearly 12% of total US greenhouse gas emissions each year' and that the administration 'is working to identify new approaches to protect and restore our forests' [4]. Given the role attributed to forests in climate change policy and in view of potential future policy discussion, it is of interest to verify and quantify the potential of forest carbon sequestration in the presence of uncertainty.

The evolution of forest and cropland in the US has either been analyzed in a deterministic setting [5, 6] or in the absence of agricultural returns [7]. Previous literature calculated carbon sequestration supply functions and found that a time constant $100 per-acre subsidy for afforestation would double the forest area from 405 to 754 million acres over a 250 year simulation period [3, 5]. Other research has shown that given a deterministically increasing carbon price, it is optimal to delay afforestation projects because of non-linear carbon sequestration paths in wood [8]. This present research extends the aforementioned literature by assessing the role of uncertainty in a US afforestation model because a cap-and-trade system as the market-based policy for climate change policies will likely be the mechanism of choice.

Adding to the uncertainty from a stochastic carbon price is the inherent price, yield, and cost uncertainty associated with crop production or forestry. In addition, changing land-use from cropland to forest incurs switching costs related to soil preparation and planting. Once in forestry, it is costly to revert back to cropland because of the expenses associated with forest clearing. Given those factors, it might be optimal for a landowner to delay afforestation in order to gain more information about future prices and revenues and thus, the landowner holds a valuable option to wait [9]. Previous research has shown that the net present value (NPV) method is inadequate in the presence of uncertainty and costly reversibility and that the investment possibility should be treated as an option which can be exercised at some unknown time in the future [10]. To distinguish the option to invest from a financial option that can be traded, the term 'real option' is used. The real option framework requires a higher expected return from forestry before a change in land-use occurs than the NPV method due to a different switching decision as compared to a deterministic model [11].

The real option framework was previously used to examine the decision to switch land-use under return uncertainty and switching cost but without endogenous agricultural returns [12, 13]. The present analysis is similar to optimal regime switching models for industry entry and exit decisions where a landowner can 'exit' from agriculture and 'enter' forestry [11, 14, 15]. In this case, the 'exit' option does not lead to a return of zero as in the aforementioned literature but is characterized by the returns from forestry which includes carbon sequestration credits. Large-scale afforestation due to a major policy change has not occurred in the US over the last few decades making conclusions from econometric estimates difficult. To overcome this issue, a real option simulation model is applied to perfectly competitive markets as in previous literature [16–20]. Under perfect competition, the landowner realizes that the market will provide an equilibrium such that all market participants are indifferent between switching or staying in the current use. On one hand, a landowner has the incentive to stay in agriculture expecting agricultural prices to rise in the future due to other landowners switching to forestry. On the other hand, all other landowners have the same incentive and hence, commodity prices would be unchanged. This letter is the first to use a real option model with endogenous agricultural returns that simulates switching from cropland to forestry in a stochastic environment with costly reversibility.

The present results are fourfold: first, our model yields less afforestation than under deterministic models because landowners find it optimal to delay afforestation. This also leads to less carbon sequestered over the projection period of 40 years. Second, afforestation starts occurring early in areas characterized by low agricultural productivity, i.e., the southeast and the northeast. Third, the loss of cropland in those areas is compensated in part by an increase in production elsewhere, mostly in the western part of the country. Almost no land conversion takes place in the Corn Belt. And lastly, the increase in crop prices begins after 20 years and increases until the end of the projection period. This also suggests that commodity prices will be driven by carbon prices in the longterm. The lower and delayed afforestation results in smaller commodity price increases than previously estimated [21].

The lessons for policy makers is that investment in afforestation is hindered under a stochastic carbon price and that different incentive mechanisms are necessary to decrease fluctuations in carbon payments for landowners. Additionally, these results show that higher commodity prices as an argument against agricultural offset credits has less validity. Lastly, there is a tradeoff between amount of new forest and commodity prices.

2. Methods

The detailed mathematical modeling can be found in the supplementary material (available at stacks.iop.org/ERL/8/044020/mmedia) and we limit our exposition in this section to the general framework. The model covers counties in the contiguous United States and four commodities: corn, hay, soybeans, and wheat. We focus on those commodities because they represented 87% of crop area in the United States in 2010 and are major food and feed commodities. At time t, there is a representative landowner in each county i who can be in either of two regimes: agriculture (A) or forestry (F). Each regime $k \in A, F$ is affected by a random disturbance ϵ_k which follows a stochastic process. Let q_t be the total amount of land available for agriculture in the United States at time t. Let $B_{i,\mathrm{A}}(q_\mathrm{t}, \epsilon_\mathrm{A}(t))$ and $B_{i,\mathrm{F}}(\epsilon_\mathrm{F}(t))$ be the per-acre net return from agriculture and forestry in county i, respectively. We assume that $B_{i,\mathrm{A}}(q_\mathrm{t}, \epsilon_\mathrm{A}(t)) = R_i(q_\mathrm{t}) \times \epsilon_\mathrm{A}(t)$ where $R_i(q_\mathrm{t})$ is a deterministic function calculating the per-acre net return based on q_t and calibrated to include yield, cost, land availability, etc for county i and all other counties. Given q_t, a competitive, price-taking equilibrium in terms of prices, demand, and cropland allocation can be derived. The calibration of $R_i(q_\mathrm{t})$ is described in detail in the supplementary information and has been used in previous literature [22]. Note that $\partial R_i/\partial q_\mathrm{t} < 0$, i.e., a reduction in available land for crop production increase net returns. For $\epsilon_\mathrm{A}(t)$, we assume a mean reverting process consistent with the perfectly competitive nature of agriculture [19]. This implies that if q_t remains unchanged over time, the per-acre net return fluctuates around an 'average value' in county i due to price, yield, and cost fluctuations. The stochastic return function for forestry $B_{i,\mathrm{F}}(\epsilon_\mathrm{F}(t))$ is determined by the carbon price $\epsilon_\mathrm{F}(t)$ and calibrated for each county based on carbon sequestration rate, tree type, and stumpage prices. The stochastic process for the carbon price is modeled as a geometric Brownian motion (GBM) which results in an exponentially increasing carbon price over time. This is consistent with a tightening cap under a cap-and-trade system. At each time step, new realizations of the disturbance terms are drawn based on the stochastic processes. Based on the draw and the total land available q_t, the landowner can calculate the net return on both regimes and can then decided whether to switch to forestry or stay in agriculture.

The decision based on the real option model for a generic landowner at some time t is illustrated in figure 1. The expected growth rate of forestry returns is set to 5% with a volatility parameter of $\sigma = 0.04$. Switching costs are assumed to \$659. Assume that for the current q_t, net returns from agriculture are fluctuating around a mean of \$150 in the long-run and that returns from forestry are increasing at an expected annual rate of 5%. Without uncertainty, the net present value rule would trigger a switch to forestry at approximately \$75. Under uncertainty, the landowner finds it optimal to wait in order to gather more information which leads to a higher investment threshold of \$225 instead of \$75.

The three scenarios analyzed differ in terms of allowance price growth rates and starting price. The USDA/EPA bases its analysis on a carbon price starting at \$10 per ton in 2010 increasing at 5% per year [21]. The scenarios 'price floor' and 'price ceiling' serve to determine the lower and upper bound of our estimates in terms of area allocation, carbon sequestration, and prices because 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. Figure 3 shows 100 possible allowance price paths for the three scenarios.

The landowner gets paid yearly for the forest carbon sequestered. The model allows the landowner to switch to forestry only once and hence, no breach of contract is possible over the time frame. The model does not allow for the forest to be cut down for selling the timber. However, the stumpage value is included, i.e., the value of the standing forest, in our analysis.

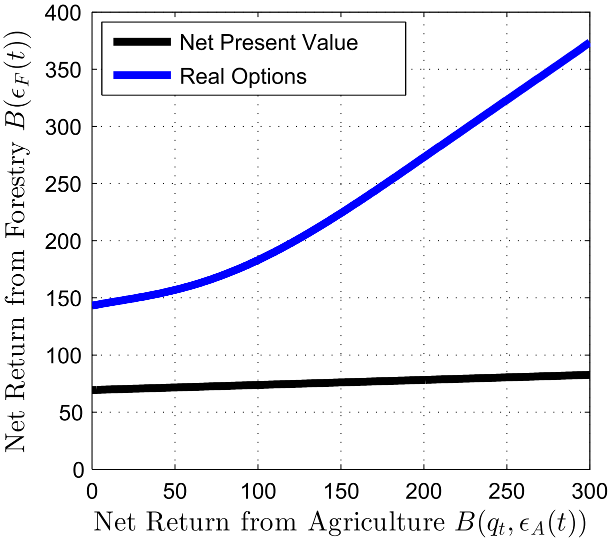


Figure 1. Illustration of the real option framework on the investment threshold. The long-run equilibrium for agricultural returns is set to \$150 with a standard deviation of $\sigma = 25$. In the real option framework, the landowner switches to forestry if the net return from forestry is above the 'real option' line for a given net return from agriculture.

The model is at the county level and homogeneous land-quality is assumed for the entire county, i.e., there are no within county differences in terms of crop yield, carbon sequestration, or cost. This assumption is justified because most of the analysis and results are driven by counties in the eastern part of the United States where counties are relatively small compared to counties in the western part of the country. Afforestation is restricted to areas with more than 700 mm of average annual precipitation and which had previous forest coverage (figure 2). Table 1 summarizes the assumptions for the forestry component in our model based on the regions in figure 2. Legislation would distribute carbon credits based on additional forest and not on existing forest and hence, we include only counties that had crops harvested in at least five years between 2000 and 2010. A limitation of the model is that neither the demand functions nor the yield include a time trend as a state variable because it would increase computational time exponentially. Implicit in this assumption is that any yield increase is offset by an increase in demand leaving the crop area unchanged in the long-run. Over the last few years, there has been a slight downward trend in wheat area and an upward trend in corn and soybean area but total cropland for the four crops has been fluctuating between 243 and 270 million acres over the last 20 years. The yield and production levels are calibrated to 2022 as the base year ($t = 0$) which represents the current long-run equilibrium projected by the Food and Agricultural Policy Research Institute [23]. The discount rate for the model is set to 8%. The numerical analysis for this model is computationally intensive thus we limit our Monte Carlo simulation to 500 runs a period of 40 years.

3. Results

A summary of the key assumptions, parameters, and results for forest area and CO_2 sequestration for all three scenarios

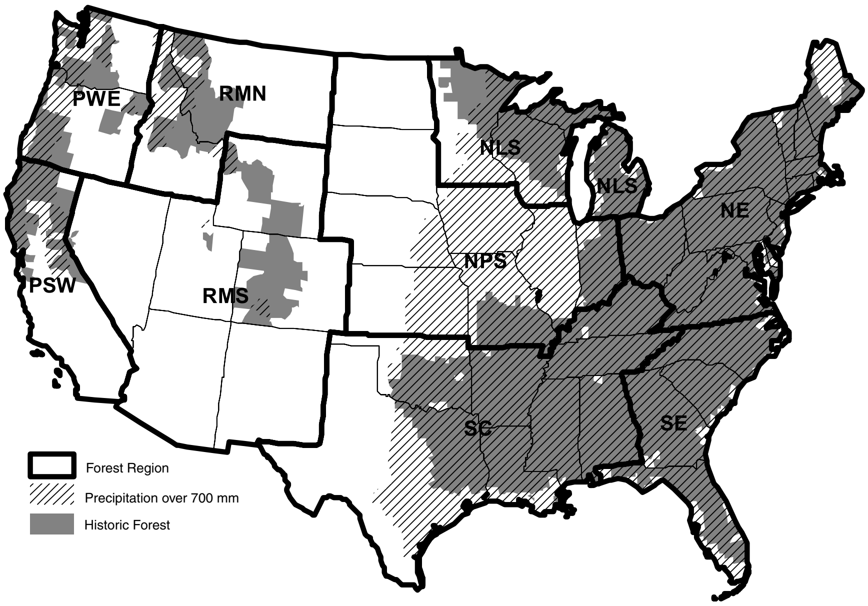


Figure 2. Geographic coverage with historic forest coverage and precipitation over 700 mm: the average annual precipitation between 1960 and 2008 for the United States was obtained from the PRISM Climate Group at Oregon State University. Historic forest cover was obtained from 'Global Forest Watch' and the forest regions correspond to Smith *et al* [32]. The eight regions modeled are the northeast (NE), the northern lake states (NLS), the northern plain states (NPS), the Pacific south west (PSW), the Pacific northwest (PWE), Rocky mountains north (RMN), southeast (SE), and south central (SC).

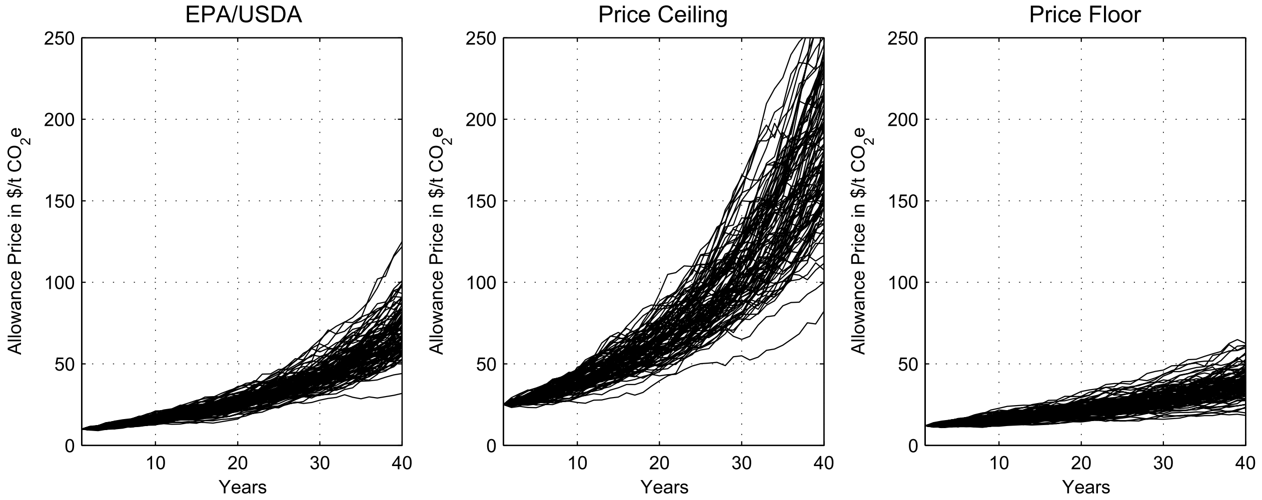


Figure 3. Allowance price simulations ($n = 100$). To reflect the recent uncertainty in the EU emission allowance price, we set σ_F to 0.04.

Table 1. Forest rent and sequestration. Notes. '\$/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. The annual sequestration rate is found in the column 'CO_2-e yr^{-1}'. 'Cost' is the per-acre switching cost.

Region	Forest type	$/t	Rent	NPV	CO_2-e yr^{-1}	Cost
NE	Oak–hickory	45	53.87	673.42	3.39	937
NLS	Oak–hickory	25	34.41	430.17	2.13	638
NPS	Elm–ash–cottonwood	15	21.72	271.56	2.06	614
PSW	Fir–spruce–mountain hemlock	15	22.19	277.39	1.85	850
PWE	Douglas–fir	15	18.89	236.13	4.47	850
RMN	Douglas–fir	35	47.04	588.01	2.52	652
SC	Loblolly–shortleaf pine	30	34.27	428.32	3.25	325
SE	Loblolly–shortleaf pine	30	34.27	428.32	3.19	260

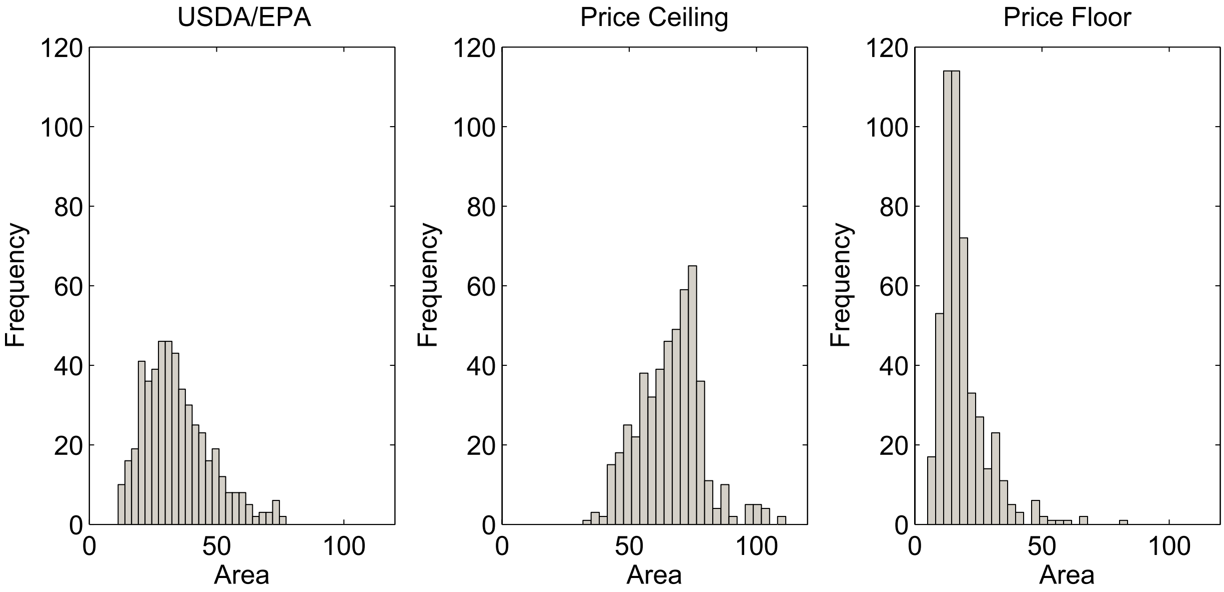


Figure 4. Histogram of forest area in million acres at $t = 40$ after 500 simulations.

Table 2. Key scenario parameters and results. The volatility parameters σ_A and σ_F are set to 0.25 and 0.04, respectively. The mean reversion of agriculture is set to $\eta = 0.6$.

	USDA/EPA	Price ceiling	Price floor
Initial CO_2 price	\$10	\$25	\$12
CO_2 price growth rate (%)	5	5	3
Expected CO_2 price in $t = 40$	\$73.89	\$184.73	\$39.84
Mean forest area in million acres ($t = 40$)	34.39	67.00	18.52
CO_2 sequestration ($t = 40$)	111.07	208.16	60.22

is provided in table 2. A key premise of this model is that agricultural markets in the US are in the long-run equilibrium at the beginning of the simulation period which is 2022. Hence, any reference to the baseline refers to the prices and quantities in the base year. In the description of the results, the focus is mostly on the scenario 'USDA/EPA' which represents the middle path between the price floor and the price ceiling and it makes our analysis comparable to the USDA/EPA carbon price path [21]. The figures only show counties in the eastern part of the US which represent the majority of corn, hay, soybean, and wheat area as well as afforestation activity.

3.1. Forestry and carbon sequestration impact

The uncertainty in returns translates directly in the forest area planted which ranges from 11.35 to 77.29 million acres in the 'USDA/EPA' scenario (figure 4). In the 'price ceiling' scenario, forest area increases considerably in the first years, i.e., 21.3% of the total acreage afforested occurs in the first 5 years. We will see later that this does not manifest itself in the commodity prices, which leads to the conclusion that the counties switching initially represent 'low hanging fruits' because of low crop yields and low acreage.

Previous analysis showed a significant impact of forestry offsets on carbon sequestration with over 1835 Mt of CO_2-equivalent sequestered at a deterministic price of roughly \$80 [5]. This is substantially higher than our estimate of 111.07 Mt of CO_2-equivalent at a price of \$74 (figure 5). The spread associated with carbon sequestration over the projection period of 40 years is represented in figure 5. Planting of new forest will likely take place in the western parts of Kentucky and Ohio, eastern parts of the Carolinas, at the border of Texas and Oklahoma, and to some extent in the southeast. The switching in the aforementioned areas is due to the relatively low net return from agriculture compared to the non-carbon rents and the carbon sequestration rates. Note that even in the high allowance price scenario, almost no conversion occurs in the Corn Belt (figure 6).

The carbon sequestration in the scenario of interest ('USDA/EPA') is 111.07 Mt of CO_2-equivalent. The supply is lower than previously estimated [24, 5] due to uncertainty associated with the allowance price and the increase of commodity prices and thus, net return. From an environmental policy perspective, the shortage of afforestation misses the goal of increasing carbon sequestration because of a policy instrument that leads to investment uncertainty.

3.2. Crop area impact

Crop production in the US responds spatially and three distinctive patterns can be identified (figure 7). In the eastern United States, counties reduce their crop area because a

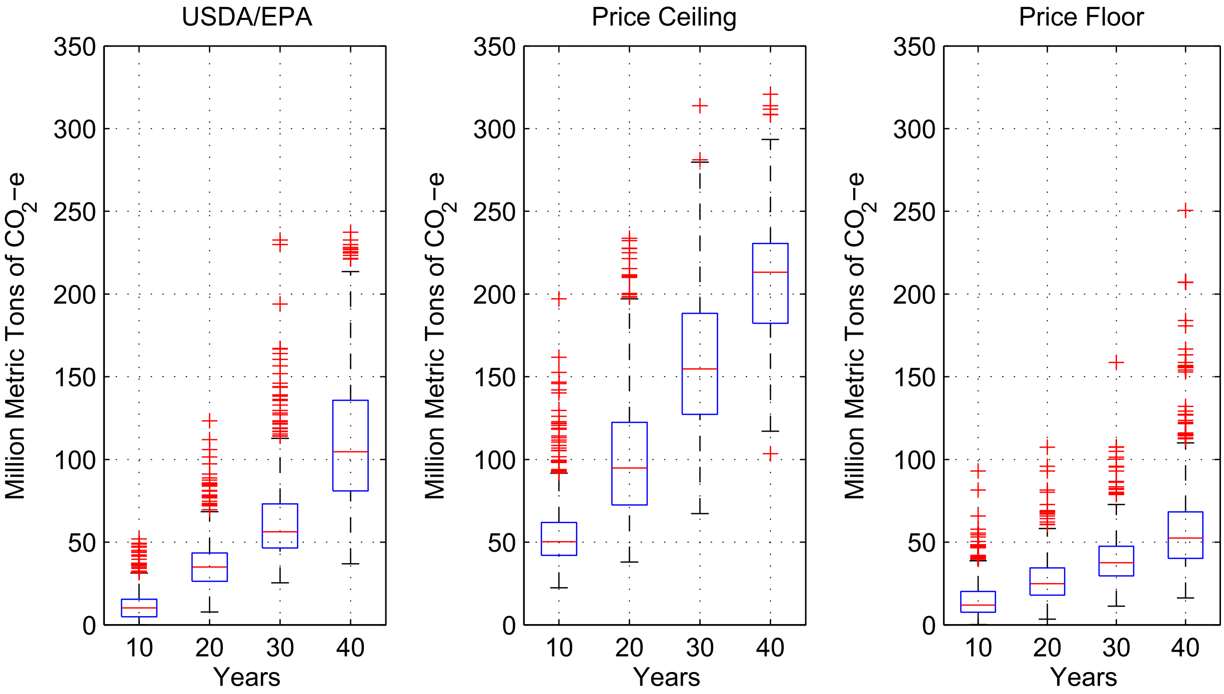


Figure 5. Carbon sequestration in CO_2-equivalent over 500 simulation runs. The central mark for each box represents the median value of the 500 runs. The size of the box is the interquartile range (IQR), i.e., between the 25th and 75th percentile, and the whiskers extends either 1.5 times the IQR or extends to the minimum (maximum) observation if that observation is within 1.5 times the IQR. The hash marks are considered outliers or extreme values.

switch to forestry occurs. Eastern and Mid-Atlantic states stretching from New York to Georgia are predicted to have significant declines in crop acreage. This is consistent with low agricultural net return in most counties in the southeast and northeast. Second, in the western United States where afforestation is potential limited, crop area expands for certain crops because landowners see higher prices because of cropland contraction in the eastern United States. If cropland is reduced in one part of the country, prices increase, serving as a signal to landowners/farmers in other parts of the country to increase their production. Finally, there is an increase in corn and soybean area in the Corn Belt as a result of high crop prices and high net returns making afforestation in those areas unattractive. The same can be observed in the case of the 'price floor' and 'price ceiling' scenarios. In general, afforestation activity in the US would shift agricultural production more towards the western United States.

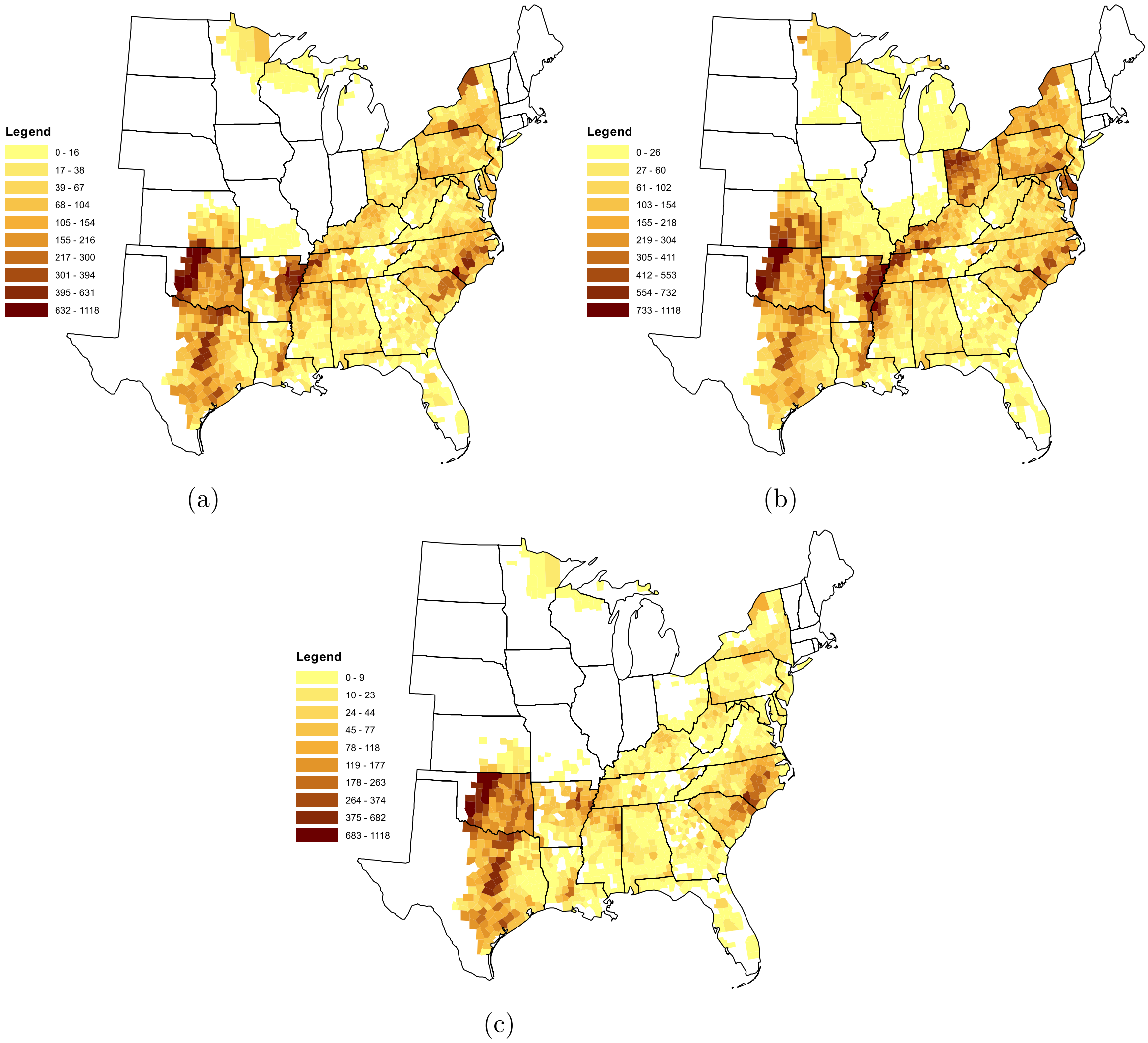
3.3. Commodity price impacts

Apart from the 'price ceiling' scenario, commodity prices do not start to increase immediately but rather after 20 years (figure 8). At the beginning, the allowance price is too low to make a switching to forest profitable. The option to delay afforestation and wait for more information about the carbon price and the net return 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 return from agriculture during this period. From a political and economic perspective, the finding of overall lower price impacts on crops is important in evaluating the impacts of a cap-and-trade policy on agriculture. This research suggests that there will be only a negligible commodity price increase in the short- to medium-run, i.e., 15–20 years, from a cap-and-trade policy.

The scenario 'price ceiling' simulates a very high carbon price with a mean of close to \$185 after 40 years and the resulting price impacts after 40 years are important, especially for hay, soybeans, and wheat when compared with previous scenarios. The price impact for all commodities is moderate in the low price scenarios because the net returns for corn and soybeans are relatively high and almost no conversion takes place at a low carbon price. However, an increase of the carbon price to levels seen in the 'price ceiling' scenario makes conversion profitable in places that did not switch in the previous scenarios.

3.4. Sensitivity analysis

We need to impose restrictive assumptions on the model and the model parameters because at the core of the model are multiple partial differential equations that are solved numerically. Besides being time intensive to solve, adding more state variables to the model increases the risk of non-convergence to a numerical solution. This section provides a qualitative assessment of the results' sensitivity with respect to some of those assumptions especially the endogeneity of the forest returns, the correlation of the



(a) (b)

(c)

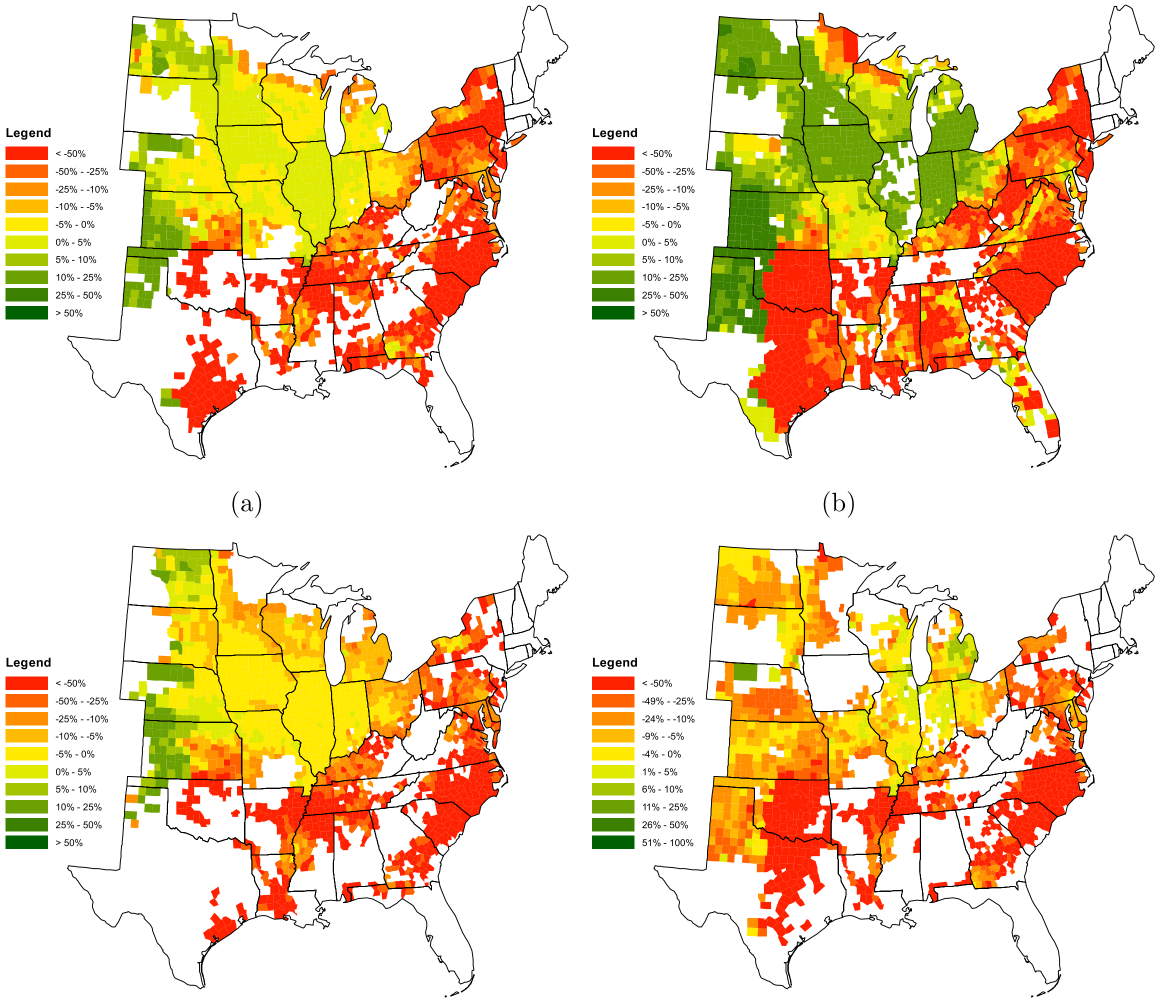
Figure 6. Average annual per county carbon sequestration in 1000 metric tons of CO_2-equivalent after 40 years simulated 500 times. (a) EPA/USDA. (b) Price ceiling. (c) Price floor.

stochastic processes, the irreversibility, the evolution of the allowance price, and changes in crop management.

This letter models agriculture endogenously while the forest sector, as well as the allowance price, are exogenous. In reality, if forest area increases, forestry returns will decline because more forest products such as timber will become available in the long-run and decrease the price. In addition, increasing the supply of carbon offset credits would lower the allowance price. Addressing both issues in our model would require an additional set of assumptions and would increase computational time exponentially. The allowance price is not endogenously modeled but in general one would expect a low impact on the allowance price given low afforestation activity even in the absence of endogeneity. Related to the evolution of the stochastic processes is the possible correlation between allowance price and commodity returns. Although we assume zero correlation, the past years have shown that energy and agricultural markets are linked through the presence of biofuels. Higher energy prices would affect agriculture leading to higher returns [25] but would also affect the allowance price. Given higher energy prices, firms would reduce energy intensive inputs and would thus most likely require less emission allowances leading to a lower allowance price. A positive correlation would provide an even lower incentive to switch to forestry.

The landowner in this model can change land-use, i.e., switch to forestry, only once. Allowing a two-way conversion, i.e., the possibility to switch back to agriculture, would lead to more forestry because 'a real option model that allows only one-way conversion will predict significantly greater farmer reluctance to convert than a two-way model' [9] (p 777).

The emission allowances price increases at a constant rate in this letter as well as in previous analysis [21]. It is questionable that this is true in the time horizon usually considered. Mitigation technologies develop and firms would adopt different input mixes for production. Over time, it is therefore more likely to see a mean reverting carbon price. This would be a disincentive for landowners to invest in forestry. An additional disincentive for landowners to switch is the change of crop management practices (e.g., more efficient fertilizer application) to earn offset credits. Those



(a) (b)

(c) (d)

Figure 7. Average percentage change of crop area between $t = 0$ and 40 for the 'USDA/EPA' scenario. (a) Corn. (b) Hay. (c) Soybeans. (d) Wheat.

changes in production practices are not considered in our model but would generate additional revenue while in crop production.

The reluctance of farmers to switch from agriculture to afforestation is due to the presence of uncertainty in our model. A reduction (increase) in either forestry or agriculture makes a switch to that activity more attractive (less attractive). For example, a reduction of the allowance price fluctuations due to the introduction of hedging instruments would make the switch to forestry more likely. The analysis is complicated by the fact that the actual legislation imposes binding price floors and ceilings which makes the problem slightly different than in our analysis

4. Discussion

The results of the previous section warrant some discussion on the effects of environmental or climate change policy with stochastic returns on investments such as afforestation. Reducing the uncertainty associated with forest carbon sequestration or any other sequestration or mitigation project will be key to triggering investment as part of a climate policy. A cap-and-trade system is a so-called 'quantity instrument' because the emission quantity is known a priori but the resulting allowance price remains unknown when the policy is put in place. An alternative climate instrument is an emission tax where the regulator collects a set tax rate on each unit emitted. It can be shown that each firm abates until their marginal abatement cost is equal to the tax rate. An emission tax is considered a price instrument because the price per unit of emission is per-determined but the quantity abated is unknown. From an economic perspective, both policies, cap-and-trade and an emission tax, are equivalent in the sense that they are achieving the same least cost solution of emission abatement. From a political perspective, those instruments are not equivalent because under the emission tax, revenue is transferred from the firms to the government. The advantage of an emission tax is that the price per ton of CO_2-equivalent is determined and could serve as a non-stochastic payment for forest offset credits and thus, trigger more afforestation. Alternatively, under a cap-and-trade system, we would expect a futures market to be formed for the carbon price. This would

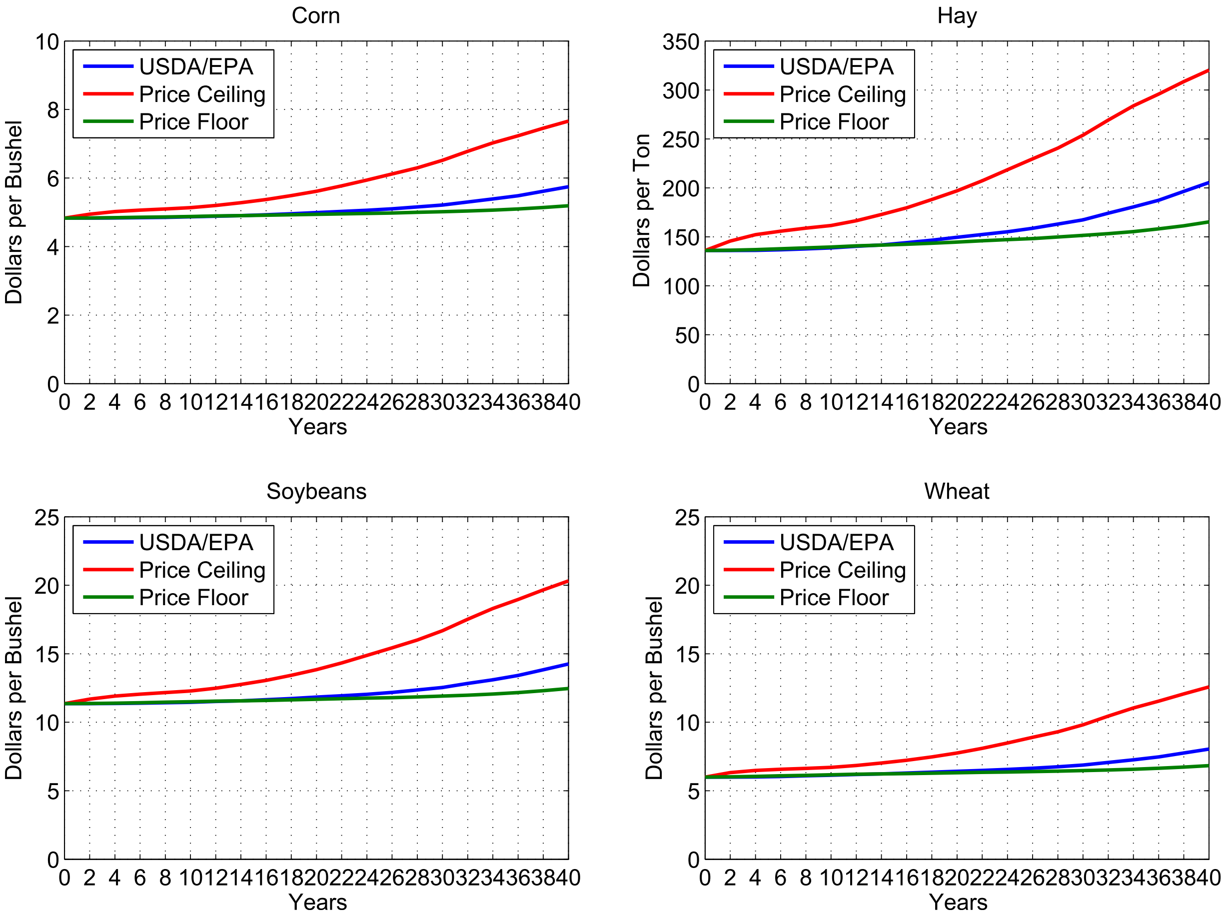


Figure 8. Price evolution for the four commodities over the projection period of 40 years.

lock-in future carbon prices for landowners reducing the risk of carbon price fluctuations. The presence of agricultural subsidies has the potential to increase the returns from agriculture making the switch to forestry less attractive. In addition, crop insurance bounds the potential losses implicitly limiting the downside risk of agriculture.

Besides uncertainty, other issues include the role of pasture, farmers' welfare, and 'land sparing'. Pasture serves as additional area for cropland expansion as the loss of cropland to afforestation in one county can be offset by expansion of cropland into pasture in another county. According to the US Department of Agriculture, there are between 384 and 409 million acres of pasture in the United States depending on the definition. Pasture could be reduced significantly because of (a) afforestation and (b) cropland expansion because of higher commodity prices. We hypothesize that including pasture in our model would add significant amounts of forest to the landscape. It is not clear what the afforestation of pasture would do to livestock herds that depend on grazing areas but this is an obvious subject for future research. In states where no afforestation is possible, cropland is expanded at the expense of pasture. Pasture can serve as a reserve pool for cropland expansion and thus, pasture can be used to offset the crop production which is lost in parts of the country due to afforestation.

An important consideration for including forest offset credits in the legislation is to improve the welfare of landowners and farmers. Improving welfare includes at leas three key issues. First, counties with a high probability of switching gain more from the afforestation program than counties staying in agriculture although net return increases for both. Counties switching to forestry do so because of higher returns associated with forestry than with agriculture. Low agricultural productivity does not translate into low carbon sequestration rates for trees. For example, the northeast has a low agricultural productivity but 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, welfare increases for all landowners because commodity prices increase for landowners staying in agriculture and landowners switching to forestry face a higher return than from staying in agriculture. Third, because of lower afforestation than previously estimated, the price increases are less and thus the welfare increase is less than previously estimated. Related to the issue of farmers' welfare are the political consequences of a possible shift in cropland in the United States. Although difficult to evaluate, the example of the Conservation Reserve Program (CRP) can be used and its political implications as described in [26, 27]. The mechanisms to allocate CRP funds and the determination of the Environmental Benefit

Index, which in turn influences the fund allocation, reflects the preferences of different interest groups, e.g., politicians, farmers, and so on. The shift of agricultural production would happen to a lower extent even in the absence of uncertainty.

A second issue which is not addressed in the letter is the possibility of a 'natural attrition' of cropland. 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. The concept of 'land sparing' has been analyzed previously and leads to two opposing effects. In one case, less land is necessary for the same amount of production if yields increase [28]. Alternatively, higher yields make it more attractive to increase the amount of land in production [29]. The latter effect can be limited because commodity demand is limited and hence, the amount of land that can be put in production is limited as well. Data from USDA's National Agricultural Statistics Service shows that the number of counties engaged in agricultural production has been declining over the last 30 years. The yield increase in the long-run can also be accelerated by the increase in commodity prices. Previous literature rejects the null hypothesis of price having no effect on yields in the long-run [30] and the effects in terms of land-use change can be substantial [31]. Because commodity prices do increase in our scenarios, the possibility of higher yields is given.

5. Conclusion

A cap-and-trade mechanism is the preferred policy to combat climate change in the United States and elsewhere. The resulting uncertainty in the carbon price and its effects on investment in carbon sequestering and mitigating options are illustrated in this letter using the example of forest carbon offset credits. Previous research has analyzed afforestation and forest carbon sequestration in deterministic settings and found significant increases in forest area in the United States. In addition to uncertainty, planting a forest is costly to reverse and the landowner looses the flexibility to adapt land to market conditions. Hence, the landowner holds a valuable option to wait before making the decision to switch.

The consequence of holding the option to wait is delayed afforestation and lower carbon sequestration. These three scenarios differ in terms of the initial carbon price and the carbon price growth rate. Two of the scenarios are setting the lower and upper boundaries in terms of afforestation, carbon sequestration, and commodity prices. In all scenarios, almost no afforestation takes place in the Corn Belt. This also explains the finding of less than a 40% increase of corn, soybeans, and wheat prices in the two scenarios. The incentive to wait for further information about the evolution of net returns in agriculture and forestry leads to a delay of over 20 years before an increase in commodity prices is observed in all scenarios expect 'price ceiling'. Afforestation takes place in the southeast due to lower agricultural revenues and hence lower opportunity costs when planting a forest. With the expansion in forestry in the eastern part of the country, crop production increases in the western part of the country where afforestation is not possible because of biological constraints.

From a policy perspective, the appropriateness of a market-based mechanism such as cap-and-trade for climate policy must be carefully evaluated. The decision to wait before investing is not limited to forest offset credits but expands to all investments whose return is stochastic. For the case of afforestation, the impact on commodity prices and shift of agricultural production in the US should be evaluated by policy makers. Due to delayed and lower afforestation rates, offset revenue and hence, improved conditions for the farm sector will likely be low. The letter shows that in the presence of carbon payments, a clear relationship between carbon/energy, forest, and agricultural markets exists.

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