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# The impact of forest offset credits under a stochastic carbon price on agriculture using a rational expectations and real options framework

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# The impact of forest offset credits under a stochastic carbon price on agriculture using a rational expectations and real options framework

by

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A dissertation submitted to the graduate faculty

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DOCTOR OF PHILOSOPHY

Major: Economics

Program of Study Committee:
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Bruce A. Babcock
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Ames, Iowa

2011

# DEDICATION

I dedicate this dissertation to my parents Monika and Robert Dumortier for giving me a loving upbringing and for making me the person I am today.

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# ACKNOWLEDGEMENTS

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# ABSTRACT

With climate change becoming an increasingly pressing issue and a world population expecting to reach seven billion people in 2011, policies to mitigate greenhouse gas emissions are likely to be enacted domestically as well as internationally. The possible interference of those policies with commodity supply, and hence food security, are the subject of this dissertation.

In 2009, a bill to reduce U.S. greenhouse gas emissions passed the House of Representatives but did not pass in the Senate. The bill would have established an emission trading system to reduce emissions from the energy, industrial, and transportation sectors. The bill also included an amendment which would have allowed the agricultural sector to provide the market with carbon offset credits to lower compliance costs for capped sectors and to compensate farmers for an expected increase in energy prices. Soon after the announcement of the offset provisions, concerns of higher commodity prices surfaced because the amendment allowed for credits from afforestation activities on cropland. This dissertation quantifies the effects of those offsets in terms of commodity prices, land allocation, landowner's welfare, and carbon sequestration.

The basic model involves a landowner whose plot of land can be in either of two regimes: agriculture or forestry. Revenues in both regimes are uncertain due to price and yield fluctuations while in agriculture and allowance price volatility while in forestry. The sunk cost associated with switching as well as the uncertainty motivates the use of a real option switching model. It might be optimal for a landowner to delay afforestation in order to gain more information about the future carbon price or agricultural revenue. Furthermore, the investment in planting a forest is difficult to reverse. Besides the high costs of forest clearing, the legislation requires a plot of land to be in forestry for several years in order to earn carbon credits.

In our model, the landowner observes each period's net revenue in both activities and forms expectations about the future evolution of prices and then decides whether switching to a different regime is optimal or not. A key aspect of our model is the presence of competitive markets. Real option models usually assume an exogenous stochastic process. In our case, revenues are influenced by the switching of landowners from one regime to the other and thus, are endogenous.

The model is calibrated to the contiguous United States and includes nine crops plus pasture while in agriculture. For forestry, we impose the type of trees to be planted and show when and where land conversion between agriculture and forests occurs under domestic forestry offsets. The analysis is done at the county level in the United States to take spatial heterogeneity and biophysical constraints such as sequestration rates and yields into account. The value of the wood is included in our analysis but is assumed to be non-stochastic which facilitates the computational analysis.

We show that in the presence of uncertainty, significantly less land gets converted from cropland to forestry over the projection period of 40 years. Pasture area is reduced because of low opportunity costs and because it serves as a land pool in the case of cropland expansion in counties which do not switch to forestry but increase crop area because of higher prices. In general, switching from agriculture to forestry starts occurring after a period of 25 years and leads to rising commodity prices thereafter. Ultimately, net revenue from agriculture and forestry start rising with the allowance price. Also, almost no afforestation takes place in the Corn Belt.

From a policy perspective, less afforestation leads to smaller welfare effects for farmers than previously estimated and to a higher carbon price because domestic offsets are not supplied in quantities that allows for a significant allowance price reduction.

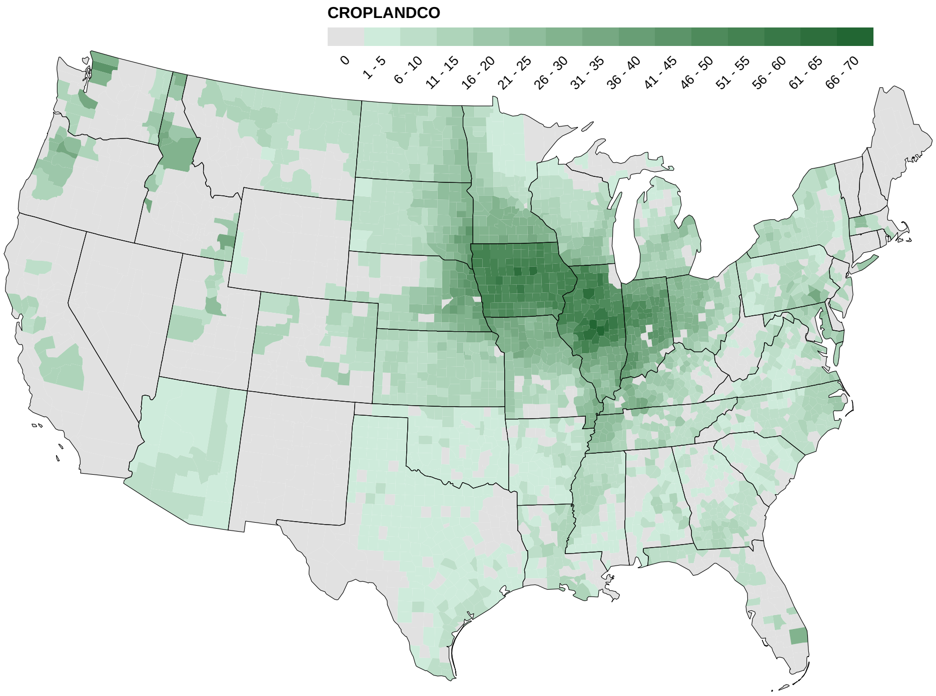
# CHAPTER 1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), agriculture and forestry (including deforestation) are responsible for 13.5% and 17.4% of global anthropogenic greenhouse gas (GHG) emissions in 2004 (IPCC, 2007). With climate change becoming an increasingly pressing issue, policies to mitigate GHG emissions are likely to be enacted internationally as well as domestically. 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. The ACES Act of 2009 passed the House of Representatives on June 26th, 2009 but did not make is through the Senate. A cap-and-trade system is established under both acts and requires reductions of GHG emissions 17% and 83% below 2005 emission levels by 2020 and 2050, respectively. Although agriculture is not capped, the proposals include the possibility for the agricultural sector to provide carbon credits. An initial list of eligible practices includes (among others) modified tillage practices, efficient nitrogen management, modified practices for animal management, winter cover cropping and other means to increase biomass returned to soil. In addition, changes in carbon stocks attributed to land-use change and forestry activities, i.e., afforestation and reforestation are included. The American Power Act of 2010 specifies that

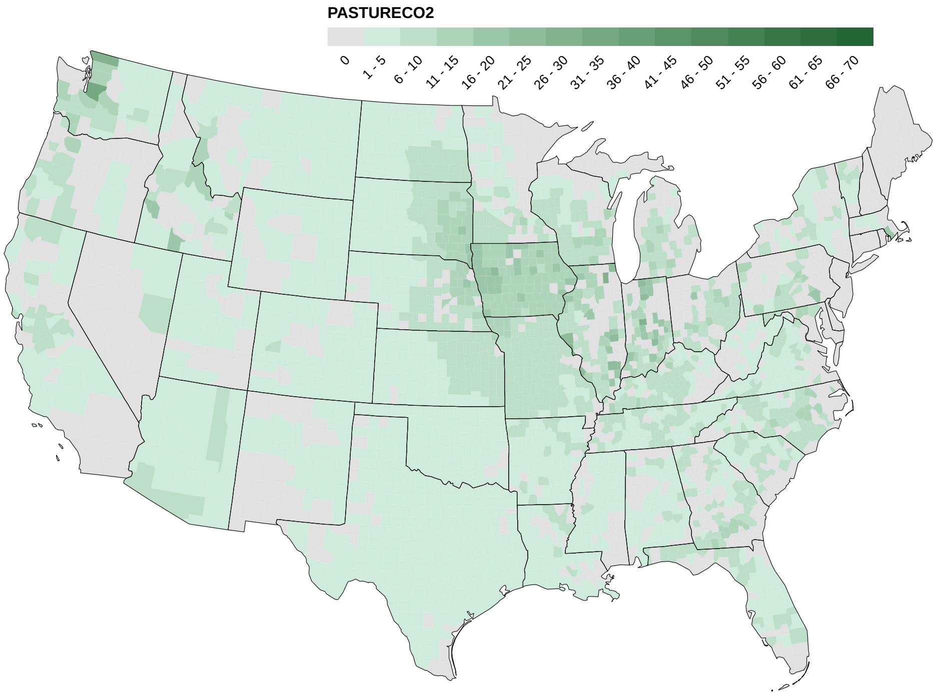
> ”...activities that provide emissions reductions, including [...] projects involving afforestation or reforestation of acreage not forested as of January 1, 2009...”

are eligible for offset credits. The offset provisions are intended to compensate farmers for an increase in energy costs from the legislation. Those forest offsets are of particular interest for three reasons: First, if large scale afforestation of cropland occurs in the United States, commodity prices will increase because of a reduction in crop supply. Second, welfare of farmers is altered by allowing them to have an additional or alternative source of revenue. And lastly, the offsets are intended to reduce the compliance cost of the capped sector by increasing the supply of emission allowances. The purpose of this dissertation is to develop a comprehensive and applied economic model to analyze those issues. Previous literature on offset provisions in the cap-and-trade proposals do not include the effect of uncertainty on the landowner's decision to switch from agriculture to forestry. Although the theoretical aspects of switching under uncertainty have been well analyzed, this model is the first to implement those findings for U.S. agriculture with endogenous revenue functions. This dissertation intends to fill this gap by modeling the regime change decision at the county level taking economic and biophysical constraints into account.

Ignoring conversion costs and the dynamic aspects of the problem, figure 1.1 serves as a simple illustration for the issue at stake by showing the ratio of 2009 cash rents for cropland and pasture to the typical sequestration rate (Smith et al., 2006) for counties in the United States. In the Corn Belt, $CO_2$ prices above \$50 per metric ton are needed to generate approximately the same revenue as under crop production. In the case of pasture, a $CO_2$ price of less than \$30 is needed to make afforestation a viable alternative. Those $CO_2$ prices are well within the range projected by the EPA (2009) and the EIA (2009) and hence, make forestry a potential alternative to agriculture. An analysis of the ACES Act in June 2009 projected an allowance price of up to \$30 per ton of $CO_2$-equivalent ($CO_2$-e) by 2020 (EPA, 2009). Together with forest sequestration rates ranging between 2.2 and 9.5 metric tons of $CO_2$-e acre$^{-1}$ year$^{-1}$ depending on various factors such as soil, climate, and management intensity (EPA, 2005) and domestic offset credits of up to 1 billion metric tons of $CO_2$-e, afforestation between 105 and 455 million acres could theoretically occur in the United States. To put the number in perspective; corn, soybeans, and wheat were planted on 201 million acres in 2007. In December 2009, the U.S. Department of Agriculture (USDA) published a report based on the Forest and Agricultural Sector Optimization Model (FASOM) by Bruce McCarl projecting the impact of the ACES Act on U.S. agriculture (USDA, 2009). The analysis finds significant afforestation activity leading to 59 million acres of additional forests by 2050. Approximately 60% of those



(a) Cropland



(b) Pasture

Figure 1.1 Ratio of 2009 cash rent (in \$) to typical $CO_2$ sequestration rate newly afforested acres are on cropland whereas the remaining acres were initially pasture. This contraction in cropland leads to considerable price increases for major commodities. We believe that there are at least two problems with the analysis conducted by the USDA: First, most of the land conversion takes place in the Corn Belt (Iowa, Illinois, Missouri, Indiana, and Ohio) and the Lake States (Minnesota, Wisconsin, and Michigan) which seems unlikely in view of figure 1.1. The high cash rents in those areas require a $CO_2$ price and/or carbon sequestration rates high enough to incentivize a landowner to give up crop production. Second, FASOM predicts a supply of afforestation offsets of 344 Mt of $CO_2$-e per year from 59 million acres. This implicitly assumes a sequestration rate of 5.83 tons of $CO_2$-e per year which is about 40% higher than literature estimates[1].

In this dissertation, we present a model which aims to overcome the shortcomings of previous cap-and-trade analysis by modeling the decision making at a finer spatial scale, i.e., the county level as opposed to the ten U.S. regions used in FASOM. Furthermore, we explicitly allow for uncertainty and rational expectations. Uncertainty is motivated by the fact that revenue will be uncertain due to cost, price, and yield fluctuations while in agriculture and $CO_2$ price variability while in forestry. Given the uncertainty, it might be optimal for a landowner to delay afforestation in order to gain more information about the future prices and revenues (Dixit and Pindyck, 1994). Previous analysis of large-scale land conversion decision relies on the net present value method which is known to underestimate the conversion threshold for switching land-uses. Rational expectations are of importance because the farmer realizes that her or his decision to switch from one activity to another has no effect on the price but that the aggregate decision of all landowners does indeed have an effect on commodity prices. If a landowner who is currently in agriculture believes that in the future many other landowners will switch to forestry, then it might be optimal to delay the conversion to reap profits in the future. We show however, that this effect can be ignored and that the decision threshold under myopic expectations is the same as under fully rational expectations. The myopic expectations concern only the number of landowners in the regimes but not about the future evolution of

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[1] The aforementioned 9.5 metric tons of $CO_2$-e acre$^{-1}$ year$^{-1}$ represent management intensive tree species in the West and are unlikely to be used for afforestation in the East due to biological constraints.

prices. The intuition behind this result is the atomistic nature of each individual landowner which provides an equilibrium where no landowner has the incentive to deviate from her or his strategy. This characteristic allows us to model the decision to switch at a much finer spatial scale.

The incentive to delay afforestation because of uncertainty is supplemented by the presence of sunk cost when switching land-uses. The investment in planting a forest is difficult to reverse because of high costs of forest clearing and the legislation which requires a plot of land to be in forestry for several years in order to earn carbon credits. The Chicago Climate Exchange which has been established as a voluntary carbon market in 2003, required land owners to sign a contract for 15 years in order to produce afforestation credits. Hence, a landowner deciding to get into forestry forgoes the flexibility of choosing the crop allocation for several years. The seminal article by McDonald and Siegel (1986) shows that the decision trigger to invest in an irreversible project is different under sunk cost and uncertainty than under certainty. This leads to the application of a real option switching model which follows closely the regime switching model presented by Brekke and Øksendal (1994).

The basic setup of the model involves a fixed number of landowners who choose among two regimes for their plot of land: agriculture or forestry. We assume that each landowner represents one county. While in agriculture, they allocate their land among a maximum of nine commodities (barley, corn, cotton, hay, oats, rice, soybeans, sorghum, and wheat) and pasture. In the empirical part of the dissertation, we will see that not all commodities compete for the available land in a particular county at the same time. Our analysis is done at the county level for the contiguous United States which captures not only spatial differences in land-use change but also the effects of cropland being pulled out of production in a particular county and how this affects prices and production elsewhere. The cropland allocation in agriculture is rational in the sense that it is consistent with the resulting price level. Our model includes demand functions for the commodities analyzed to evaluate the effect of cropland conversion on commodity prices and the net revenue from staying in agriculture. The finer spatial scale also allows to capture biophysical characteristics such as area constraints, yield potential, sequestration rates, and precipitation. Our model will restrict afforestation to areas which are suitable in terms of precipitation and historic forest coverage.

A particular aspect for this dissertation is the absence of any empirical data concerning the evolution of the allowance price. Economic theory requires the price of emission allowances to be equal to the marginal abatement cost across all firms. The uncertainty in firms' abatement costs leads to uncertainty in the $CO_2$ price. To model the fluctuations, we have to impose reasonable volatilities in the price of $CO_2$. All models predict an exponentially increasing price path for allowances but vary in level depending on the assumptions of technological availability, e.g., carbon capture and storage (CCS) technology, or the volume of offsets, in particular international offsets. The price path in the USDA analysis has been critiqued as being to low when compared to other calculations such as from the Energy Information Administration (EIA, 2009). However, both, the ACES and APA Act include a price collar to limit compliance costs. For the APA Act, the 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 (adjusted for inflation). EIA (2009) did not include the price collars in their analysis.

To allow for comparison with the USDA/FASOM analysis, we replicate their price path evolution which starts at \$10 but also analyze a high carbon price scenario which is more consistent with the price ceiling. The first scenario focuses exclusively on agriculture and does not take pasture into account. This is to single out the effect of incorporating uncertainty and a finer spatial scale on afforestation. Pasture is included in the second scenario and is comparable to the USDA analysis (USDA, 2009). The third scenario is a high carbon price scenario which starts at \$25 and is increases at 5% over the projection period and replicates the price ceiling in the sense that the expected allowance price is equivalent to the price ceiling over the projection period. However, due to uncertainty, the shocks can rise above the ceiling. This scenario is closer to the high cost scenarios analyzed by EIA (2009) and allows us to analyze a worst case scenario. Our last scenario is a sensitivity analysis of the second scenario in the sense that we chose a tree type yielding a high carbon sequestration rate and high timber value rents for the Corn Belt region. This scenario is intended to test whether the Corn Belt is susceptible to cropland conversion in the case of higher forest values (in terms of timber and carbon). It turns out that slightly more forest gets planted in the Corn Belt under this scenario but that our results are robust in terms of very low forest conversion in the Corn Belt.

The results contradict the previous analysis in several aspects: First, significantly less afforestation is observed in the United States because landowners find it optimal to delay afforestation in order to gain more information concerning the carbon price and the evolution of revenue from agriculture. Second, besides the difference in the magnitude of afforestation, we also find differences in the timing of afforestation. Afforestation starts occurring after 25 years in the low carbon price scenario. Third, 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. All those results lead to a much lower commodity price increases than previously estimated. Counties which have low agricultural net revenue profit the most from switching whereas counties which stay in agriculture can profit only form the increase in commodity prices.

To the best of our knowledge, this is the first model to assess land conversion under a stochastic $CO_2$ price for U.S. agricultural land using a real options framework. Agriculture is modeled as a competitive industry characterized by price-taking behavior of landowners. Despite the competitive nature of the industry, landowners have rational expectations with respect to agricultural prices. In addition, it provides a realistic tool to measure potential cropland reduction and commodity price increases due to cap-and-trade. We show that the presence of uncertainty in agriculture and forestry together with an endogenous net revenue significantly lowers the conversion rate from agriculture to forest with moderate effects on prices.

Besides calculating the effects of a stochastic carbon price in agriculture, we also intend to provide a tool for policy makers to assess the impact of offset credits on commodity prices and land allocation. There are three lessons for policy makers from our analysis. First, higher commodity prices as an argument against agricultural offset credits seems to have less validity in light of our results. Second, farmers'/landowners' welfare increases in the long-run because net revenue from agriculture as well as from forestry is driven by the $CO_2$ price. And third, previous analysis show a reduction in the price for emission allowances in the presence of offset credits. Given the lower supply of domestic agricultural forestry offset credits, the allowance price will be higher.

Although climate change policy is not a top priority on the political agenda at the time when this dissertation was finished, we believe that climate change and cap-and-trade policy remains an important issue in the future. This dissertation is part of the scientific community's effort to deliver well-founded answers to policymakers for the next round of climate change policy proposals.

The remainder of the dissertation is organized as follows. Chapter 2 presents background information on forestry and agriculture in the United States, the land conversion and carbon sequestration literature as well as a review of previous work on cap-and-trade legislation and real options. Chapter 3 describes the theoretical model used in our analysis. Chapter 4 introduces the data and data sources in terms of agricultural production (e.g., yield potential, demand function calibration, etc.) and forest characteristics (e.g., carbon sequestration rates, conversion cost, etc.). The same chapter also outlines the assumptions concerning the $CO_2$ price dynamics. Chapter 5 will present and discuss the results whereas the conclusion can be found in chapter 6.

# CHAPTER 2. BACKGROUND AND REVIEW OF LITERATURE

This dissertation covers a variety of economic as well as biophysical aspects. The purpose of this chapter is to provide a background on forestry, agriculture, and carbon sequestration in the United States as well as presenting a literature review showing the contribution of this dissertation to previous work on real options and rational expectations. The first sections introduces basics about forestry and agriculture in the United States. Sections 3 and 4 present the land conversion and carbon sequestration literature. Previous analysis about cap-and-trade policies, i.e., impacts of the ACES Act of 2009 and the APA of 2010 on agriculture, are reviewed in the fifth section. The last parts outline the theoretical aspects of real option models and the impact of competitive markets on the decision making of agents.

## 2.1 Forestry in the United States

Forest area in the United States declined from approximately 988 million acres in 1630 to around 748 million acres in 2002. Since 1907, forest area has been relatively stable ranging from 736 to 761 million acres[1]. Especially the eastern part of the United States (including the Corn Belt) are responsible for most of the deforestation before the $20^{\text{th}}$ century. The original forest cover in the U.S. is depicted in figure 2.1[2]. The detailed breakdown for selected forest types can be found in appendix B. According to the EPA (2010), U.S. forests sequestered 863.1 Mt $CO_2$-e in 2009 which is more than twice the emissions from the agricultural sector, i.e., methane and nitrous oxide emission from livestock and agricultural soil management. Although forest area

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[1] The greenhouse gas inventory from the U.S. Environmental Protection Agency reports a total of 677 million acres of forestland in the United States. The difference is due to the exclusion of forestland which is not considered forest-use, e.g., parks.

[2] The data was retrieved on June 19th, 2011 from http://ims.missouri.edu/gfwmetadataexplorer/. The original data is global in cover and was modified to cover the 48 contiguous states. The data was compiled by the Global Forest Watch and the World Resources Institute.

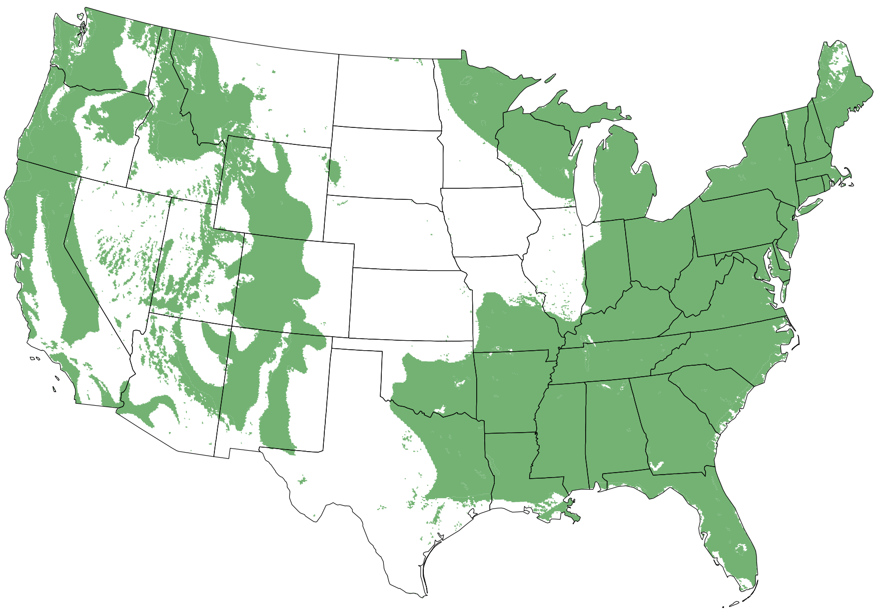

Figure 2.1 Original forest cover in the United States

remained constant, land-use change and transitions between forest, agriculture, and urban can be observed (Smith and Darr, 2004). An important trend in U.S. forestry is the expansion of pine plantations in the South spiking in the 1950's and 1980's due to the Soil Bank Program and the Conservation Reserve Program (Haynes, 2003).

## 2.2 Agriculture in the United States

The empirical analysis in the next chapters depends crucially on the correct calibration and data input. As mentioned in the previous chapter, the FASOM model underlying the 2009 USDA report allocates forestland to areas which are not susceptible to conversion due to high net revenues earned in those areas (see figure 1.1). Figures A.1-A.8 represent the area harvested as a percentage of the total county area by crop in 2007. This representation is also consistent if production was used instead of area. Given the location of potential forests from figure 2.1, we would expect only small decreases in the production of barley, sorghum, and wheat which are cultivated in areas which had historically not much forest area. Corn and soybeans areas represent potential locations for forestland but given the high net revenues in those counties, we would necessitate a high $CO_2$ price and/or high sequestration rates to trigger conversion.

Figure 2.2 shows the real (2008 US-$) per acre net returns for eight commodities. Area, price, yield, and production data are obtained from the USDA National Agricultural Statistics Service whereas the costs are obtained from USDA's Economic Research Service. Prices and costs were deflated by the producer price index. Two distinct patterns can be observed: First, over the period from 1980 to 2005, net returns seem to fluctuate around a mean. Second, structural changes and a high crude oil price over the past five years raised net revenues for most commodities, especially corn, soybeans, wheat and barley. The mean reverting pattern is observed because counties with a low yield might find it more profitable to switch to a different land-use such as forestry or the Conservation Reserve Program leading to an exit of counties out of crop production and hence, keeping the net revenue constant. In 1975, 2896 counties were engaged in at least one of the crops analyzed in this dissertation. By 2008, only 2120 counties were still in agriculture. There has been a continuous downward trend of counties dropping out of agriculture. In the empirical section of this dissertation, we will capture those patterns by fitting a mean-reverting stochastic process to agriculture and by including the demand for corn ethanol. In addition to counties exiting agriculture, Odening et al. (2007) argue that a mean reverting process is more consistent with economic theory in the presence of competitive markets independent if the price process passes a unit-root test or not[3]. A geometric Brownian motion with increasing returns would cause landowners to enter crop production, expand supply, and hence decreasing net revenue. Thus, a geometric Brownian motion is not consistent with entry and exit.

## 2.3 Land Conversion Literature

The most commonly used method to estimate land-use change is the logit model in which the endogenous variable (i.e., share in a particular land-type) is regressed on explanatory

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[3] The presence of a unit-root precludes the use of a mean reverting process.

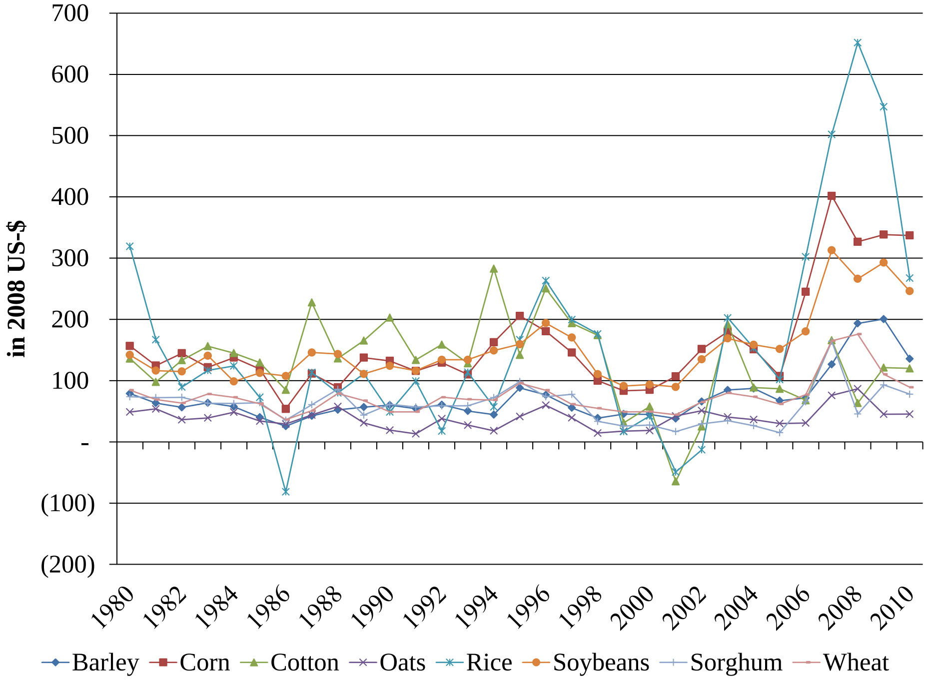

Figure 2.2 Historical net revenue in 2008 U.S. dollars

variables such as forest and/or agricultural revenue, soil quality, and population. Examples of such models are Hardie and Parks (1997) for the southeastern United States, Parks et al. (2000) for the mid-Atlantic region, and Alig (1986) for the Southeast.

The National Resources Inventory (NRI) forms the basis for land transition models. Land-use data is collected at 800,000 data points throughout the United States at an interval of 5 years with 2007 being the most recent survey year. Probably the most comprehensive study of land-use change in the United States using the NRI data is done by Lubowski (2002) who distinguishes among six land-use change categories (cropland, pasture, forest, urban, range, and Conservation Reserve Program land). The analysis is conducted at the county level and examines the land-use change probabilities with respect to land-use profits using historical data. Based on Lubowski (2002), Plantinga et al. (2007) attempt to project land-use change in the United States from 1997 to 2030. They predict an increase in forest and urban area by 4.6% and 89%, respectively and a decline in cropland (8.4%), pasture (5.3%), Conservation Reserve Program (48.7%), and rangeland (8.2%). The largest increase in forest area is projected to be in the Corn Belt, the Northern Plains, the Southern Plains, and the Mountain region. In the discussion of the results, the authors raise concerns about the large movement of land into forest in regions which had historically not seen marginal shifts between forest and other uses, e.g., the Corn Belt. They suggest that those results may occur because (a) the estimates are at the national scale and might not perform well at the regional level, and (b) that estimates are driven by a conversion of large amounts of forest during the period 1992 to 1997.

More structural models covering global (Sohngen and Mendelsohn, 1998) and U.S. timber markets (Sohngen and Mendelsohn, 2003) use dynamic programming to evaluate the extend of timberland. Both articles underline the importance of the dynamic aspects of modeling forest which is inherently a perennial optimization problem. These models predict the planting and harvesting decisions of landowners but do not take agricultural revenue into account.

We extend the previous models on land conversion in two important ways. First, we will use estimates of agricultural production at the county level to simulate future land-uses more realistically. We have not seen large-scale afforestation activities in the United States over the last decades which makes the drawing of conclusion from econometric estimates difficult. Second, none of the above mentioned studies includes uncertainty in the revenue process from agriculture and/or forestry. For numerical purposes, our model is limited to two land-use categories. An extension to three or more categories is possible but would increase the computational time exponentially.

## 2.4 Carbon Sequestration

Carbon sequestration in forests as a low-cost way to mitigate climate change has been presented in Stavins (1999), Plantinga et al. (1999), and Richards and Stokes (2004). The previously mentioned analysis by Lubowski (2002) forms the basis for analyzing the carbon sequestration supply functions in the case of carbon payments to landowners (Lubowski et al., 2006). The authors find that a $ 100 per acre subsidy for afforestation would double the forest area from 405 to 754 million acres over the 250 year simulation period. A key feature of the analysis is the modeling of endogenous commodity prices. However, the effects of the large scale afforestation on those prices are not reported in the article. Furthermore, the emission allowance price in our model is stochastic and growing over times as opposed to the constant carbon subsidy/tax assumed in Lubowski et al. (2006).

The paper by van 't Veld and Plantinga (2005) shows that in the absence of uncertainty, it is optimal to delay carbon sequestration projects in the presence of an increasing $CO_2$ price whereas the amount of carbon abatement is independent of the $CO_2$ price path. Their model is driven by the assumption of a non-linear sequestration path in forest, i.e., more carbon is sequestered at an early stage during the forest growth period. Hence, it is optimal to delay carbon sequestration projects in order to profit from higher carbon prices later when planting a forest. The paper by Feng et al. (2002) is cited as a special case in the analysis by van 't Veld and Plantinga (2005) in the sense that Feng et al. (2002) assume an instant carbon sequestration which leads to the incentive to immediately sequester all carbon. Our analysis presents uncertainty as an additional incentive to delay afforestation projects when $CO_2$ prices are rising.

The interaction between forest harvest decisions and carbon benefits are subject of Chladná (2007) and Guthrie and Kumareswaran (2009). Both studies conclude that the rotation length depends on the type of carbon payments (e.g., actual carbon sequestration versus potential long-run carbon sequestration) and the type of carbon price process (increasing, constant, stochastic). The presence of increasing and stochastic carbon prices lengthens the rotation period whereas other assumptions and policies shorten the rotation period. In this dissertation, we assume a predetermined rotation period to calculate the net present value of merchantable timber.

Sohngen and Brown (2006) analyze the share and future trends of softwood and hardwood plantations in three states (Arkansas, Louisiana, Mississippi) which experience an increase in forest plantations, especially pines. They find that softwood pine plantations are likely to increase over the next decades at the expense of natural pine and hardwood forests. Softwood pines store less carbon than hardwood forests and hence, without a price on $CO_2$, a decline in the carbon pool is expected.

Our paper focuses on carbon sequestration only and ignores the environmental benefits which arise from forest planting such as bio-diversity, wildlife habitat, and water quality. Furthermore, we will not cover the possibility of leakage. Leakage occurs if cropland is reduced in the United States and the subsequent expansion of crop production and deforestation in other parts of the world. The current proposals exclude the inclusion of leakage in the calculation of carbon offset credits. In addition, the amount of leakage is difficult to quantify and any number attached to the effect would be subject to a large error bounds (Dumortier et al., 2011).

### 2.5 Cap-and-Trade

Several studies by the U.S. Energy Information Adminstration (EIA), the U.S. Department of Agriculture (USDA), and the Environmental Protection Agency (EPA) have been analyzing the economic impacts of H.R. 2454. Especially the latter two focus more on agriculture, however, there is significant overlap in model assumptions and methods, e.g., FASOM developed by Bruce McCarl was used for both studies.

The agricultural sector will likely face higher costs due to a cap-and-trade bill because of an increase in the price of direct (diesel fuel, electricity, natural gas) as well as indirect energy consumption (fertilizer). In 2009, fertilizer expenses and fuel expenses accounted for 45% and 10% of total operating cost for corn. For wheat, the share was 48% and 14%, respectively. Soybeans require less fertilizer and thus, the energy related expenses for fertilizer (18%) and fuel (10%) are lower[4]. However, provisions in H.R. 2454 provide trade-vulnerable sectors such as the fertilizer industries with allowance rebates to avoid an increase in imports from countries with higher carbon emissions. Those rebates limit the extent of input price increases for the agricultural sector.

A study by Baker et al. (2009) estimates the average annual percentage increase in corn and soybean prices by 39.5% and 16.5%, respectively at a $CO_2$ price of \$50 per t $CO_2$-e. In addition, the loss of cropland to forestland ranges from 8.3 to 39 million acres by 2030 given a $CO_2$ price range from \$15-\$50 per ton of $CO_2$-e. For the same price range, the estimates

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[4] U.S. Department of Agriculture Economic Research Service (ERS) - Commodity Costs and Returns database: www.ers.usda.gov/Data/CostsAndReturns.

| | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|
| Allowance Price (in $) | 16.31 | 26.54 | 43.37 | 70.40 |
| Afforestation (Mt $CO_2$e) | 132 | 170 | 372 | 344 |
| Gross Revenue (in billion $) | 2.10 | 4.50 | 16.10 | 24.20 |
| Forest (in million acres) | 16.6 | 26.6 | 43.7 | 59.0 |
| - Corn Belt | 4.9 | 9.7 | 16.3 | 22.5 |
| - Lake States | 3.1 | 7.0 | 10.6 | 15.1 |
| - South Central | 3.3 | 2.0 | 6.0 | 10.0 |
| Cropland | -6.0 | -14.6 | -28.3 | -35.0 |
| - Corn Belt | -4.2 | -8.5 | -15.5 | -20.6 |
| - Lake States | -2.2 | -5.2 | -8.7 | -12.1 |
| - South Central | -2 | -2.1 | -3.1 | -6.4 |
| Pasture | -8.3 | -11.9 | -15.3 | -23.9 |

Table 2.1 Summary of results from the FASOM/USDA Analysis about the impact of H.R. 2454

for pasture conversion to forest are much more narrow ranging from 15 to 16.5 million acres. Note that most of the analysis related to H.R. 2454 and agriculture used the FASOM model from Bruce McCarl including Baker et al. (2009), Murray et al. (2009), USDA (2009), and Alig et al. (2010). This section focuses on the USDA (2009) analysis which used as a benchmark in subsequent chapters.

A summary of results of the USDA (2009) can be found in table 2.1. Cropland is decreasing by 14.6 million acres (2030) and 35 million acres (2050) for an estimated $CO_2$ price of $27 and $70, respectively. Most of the cropland reduction takes place in the Corn Belt (Iowa, Illinois, Missouri, Indiana, and Ohio), the Lake States (Minnesota, Wisconsin, and Michigan), and South Central (Kentucky, Tennessee, Alabama, Louisiana, Arkansas, and parts of Texas and Oklahoma). An increase in cropland can be observed in the South West. Pasture area decreases by 23.9 million acres compared to the baseline. The study projects that by 2050, nearly 20.6 million acres are afforested in the Corn Belt alone. In the early years of the policy, most afforestation is predicted to occur on pasture land. Major price increases are observed for barley (56.5%), oats (45.1%), sorghum (39.8%), corn (28.1%), and soybeans (20.9%).

The area allocated to the Conservation Reserve Program (CRP) is held constant at 30 million acres. The CRP program addresses issues such as soil erosion, wildlife habitat, water quality improvement, and carbon sequestration. It is uncertain how a cap-and-trade legislation with offset provisions would take those lands into account.

## 2.6 Real Option Theory

The real option theory is closely related to the option-pricing theory in finance. Traditional investment theory is based on the net present value method (NPV) which assumes that the threshold for investment is given by the present value of the return being greater than the investment cost. In addition, the net present value is calculated for a particular point in time with the investment possibility given at that point. In reality, an investor has the opportunity to postpone the decision to invest. We need to attach a value to the option to defer the investment and wait for more information about the evolution of the return. In the real options theory, the threshold to invest is reached when the expected present value of the investment is greater than the investment cost plus the option to wait.

To illustrate the concept, suppose that a unit of land can generate profits from agriculture ($A$) or forestry ($F$). The returns in both activities grow at constant rates $\mu_A$ and $\mu_F$. If the land is currently in agriculture then the value at $t = 0$ of the unit of land which can be converted at some point in time $T$ to forest is written as:

$$V(0) = \int_0^T Ae^{(\mu_A - r)t}dt + \int_T^\infty Fe^{(\mu_F - r)t}dt - C_{AF}e^{-rT} \tag{2.1}$$

where $r$ is the discount rate and $C_{AF}$ is the cost for switching from agriculture to forestry. Solving and rearranging terms leads to:

$$V(0) = \underbrace{\frac{A}{r - \mu_A}}_{\text{Value from Agriculture}} + \underbrace{\left[F\frac{e^{(\mu_F - r)T}}{r - \mu_F} - A\frac{e^{(\mu_A - r)T}}{r - \mu_A} - C_{AF}e^{rT}\right]}_{\text{Option Value}} \tag{2.2}$$

As noted in Tegene et al. (1999), the value of the land at $t = 0$ is composed of the perpetual profit from agriculture, i.e., $A/(r - \mu_A)$, and the option value to convert into forests. A similar model was used by Plantinga et al. (2002) to decompose the value of current agricultural

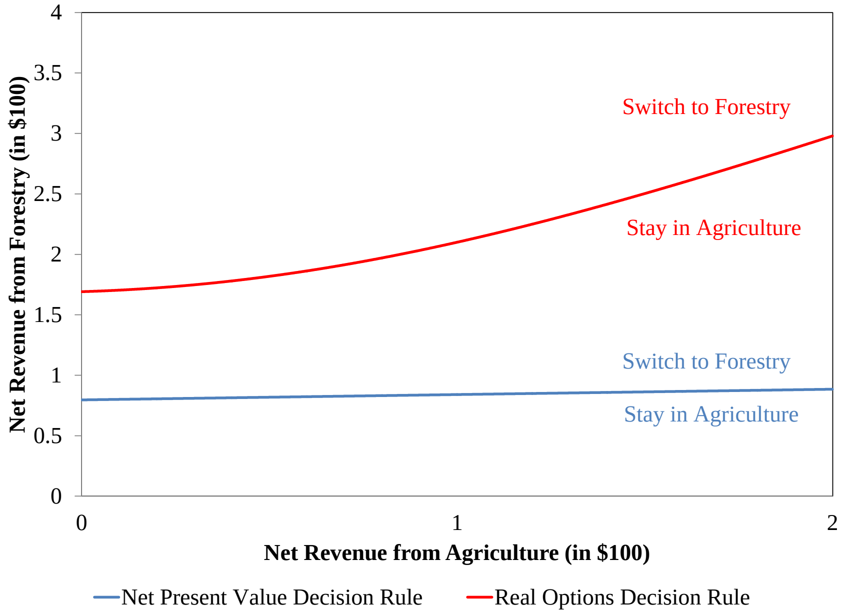


Figure 2.3 Example of a Real Options Switching Model

farmland into the value from agricultural returns and the option value to develop the land in the future. The option value to develop farmland in the future is especially high for counties near urban centers. In general, the option value to convert agricultural land to some other use has to be taken into account in the private land-use decision. Plantinga et al. (2002) finds that up to 82% (New Jersey) of current agricultural land value is composed of the option value for future development. The estimation of potential future land development on current land prices can be found in Plantinga and Miller (2001). All those models find that the option value in determining land valuations can be significant. In the absence of uncertainty, equation (2.2) can be solved explicitly for $T$. However, if the returns in one or both activities follow a stochastic process, equation (2.1) can not be solved analytically and numerical methods are necessary.

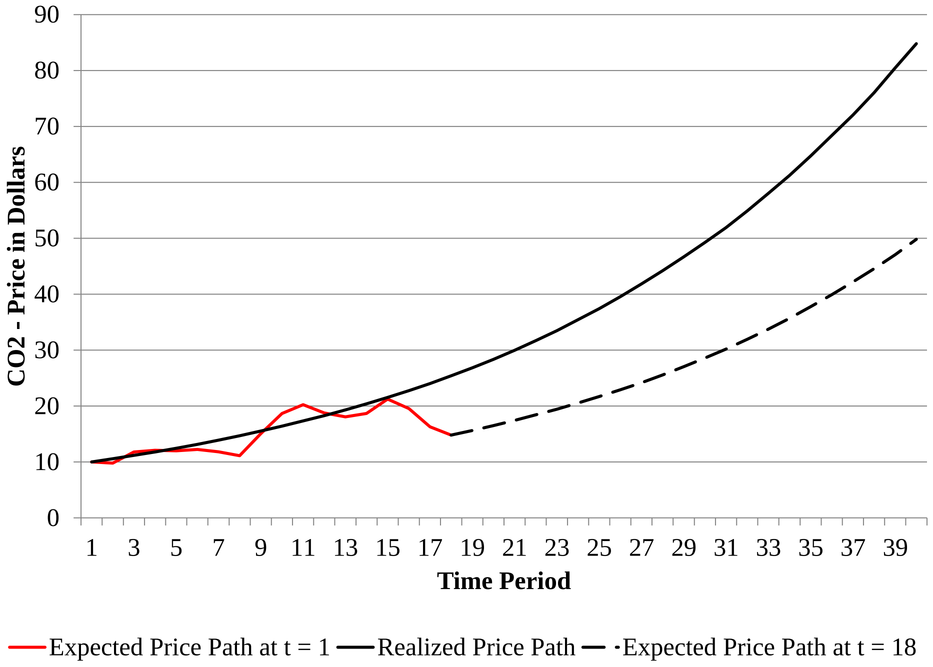
Figure 2.3 represents the real option concept under uncertainty graphically. In figure 2.3 it is assumed that the net revenues from agriculture are reverting to a long-run value of \$150 with a volatility of $\sigma_F = 25$. Net revenues from forestry increase at a rate of 5% per year with a volatility parameter of $\sigma_F = 4$. Implicit in the graph is a switching cost to forestry of \$ 1,000.

The red line is the switching threshold under the real options approach and the blue line is the threshold under the net present value method. Suppose the net revenue from agriculture currently \$100 (which corresponds to a value of 1 in the graph) then the net revenue from forestry has to be approximately \$80 under the net present value analysis (blue line) or \$170 under the real option valuation (red line).

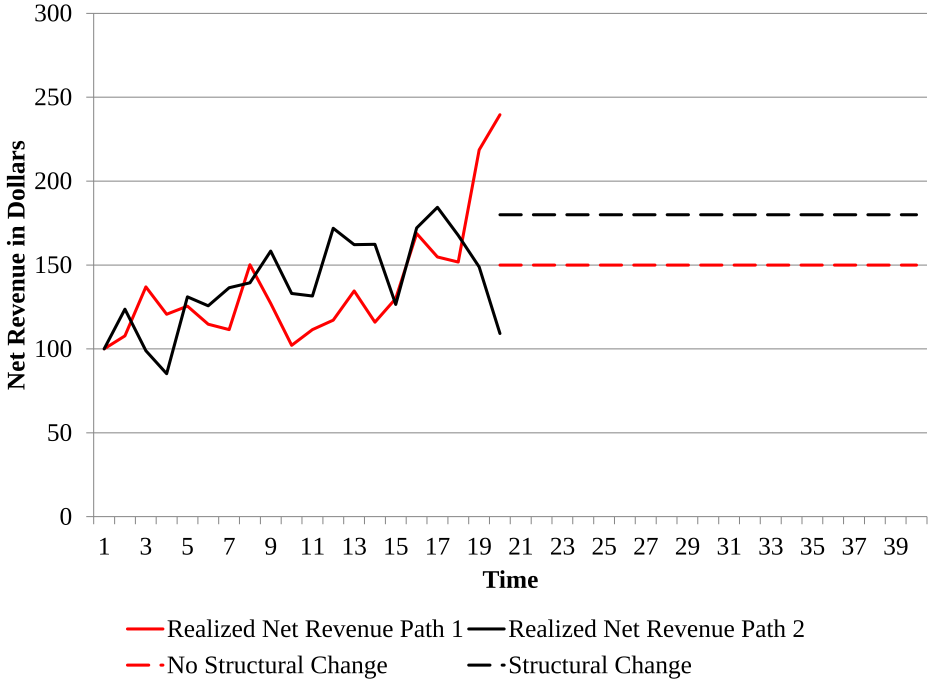
Figure 2.4 illustrates the learning in the real option literature. Suppose that in period $t = 1$, the landowner assumes a starting price of \$10 and an increase at 5% per year with a volatility parameters of $\sigma = 0.04$. The expected price path is represented by the solid black line in panel (a) of figure 2.4. If the landowner observes a price of \$14.81 in period $t = 18$, she or he adjusts her or his expectations downwards to the dashed black line in panel (a) because the realized price path is below the initial expected path. A similar concept holds for a mean reverting process (panel (b) of figure 2.4). A landowner who expects a long-run net revenue of \$150 does not adjust her or his expectations even if the realized price path leads to a current net revenue of \$239 (solid red line). The landowner continues to expect a long-run net revenue of \$150 (dashed red line). However, if afforestation occurs and the landowner expects a long-run net revenue of \$180 due to this structural change in period $t = 18$, then this expectations will persists even if the net revenue is \$109 in period $t = 18$.

Most closely related to the switching problem in our case is the industry entry and exit literature which assumes a zero revenue in the *exit* regime. Examples using the mining industry, i.e., opening and closing a mine, can be found in Slade (2001), Mason (2001), and Brekke and Øksendal (1994).

The real options framework was used previously to examine the decision to change land-use in agriculture under return uncertainty and sunk switching cost (Schatzki, 2003; Tegene et al., 1999; Behan et al., 2006; Price and Wetzstein, 1999; Towe et al., 2008). However those works analyze either the theoretical aspect of real options or ignore the endogeneity of the revenue process. An article by Song et al. (2011) analyzes the farmer's decision to switch from food to energy crops under stochastic prices for both crops. This paper is the most closely related to our analysis with important differences. The Song et al. (2011) paper does not include an



(a) $CO_2$ price learning



(b) Mean reversion learning

Figure 2.4 Learning in the real options model endogenous revenue process and it is not calibrated to U.S. counties. Our analysis is closely related to the optimal switching model by Brekke and Øksendal (1994). The same model has been applied by Nøstbakken (2006) for the entry and exit decision in fisheries.

## 2.7 Real Options under Competitive Markets

The majority of real options literature analyzes the investment decision in isolation. The source of uncertainty is exogenous and the decision maker has the exclusive right to exercise the option (Odening et al., 2007). However, this is not the case in a competitive market such as agriculture. The entry and exit of competitors influences the market outcome and the price process. If we assume a mean reverting process for agriculture, then the mean is influenced by the number of landowners in the industry. We have seen in the literature review that a shift to ethanol raises the mean of agricultural net revenues. The same can be expected when large-scale afforestation is introduced into the model. The question becomes whether an individual landowner has the incentive to stay in agriculture knowing that others will switch to forestry driving up rents in agriculture. That is, a landowner facing a demand function of the form $p_t = D(q_t, x_t)$ (with $x_t$ being the stochastic process) should take the entry and exit decisions affecting the amount produced ($q_t$) into account.

The seminal paper by Leahy (1993) shows that the investment threshold is unaffected by the presence of entry and exit. The landowner realizes that under perfect competition, the market will provide an equilibrium such that all market participants are indifferent between switching or staying in the current use. 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 only myopic about the number of industry participants but behaves rationally by forming expectations about the future evolution of prices.

Leahy (1993) assumes that all market participants face the same price shock. Zhao (2003) extents this assumption by allowing idiosyncratic shocks and showing that the result from Leahy (1993) still holds. Extensions of the general model can be found in Baldursson and

Karatzas (1997) and Caballero and Pindyck (1996). This result allows us to simulate the decisions of each individual landowner ignoring the future entry and exit decisions of other landowners and its effect on production. Only the current level of aggregate production (which is implicitly determined by the number of landowners), and thus net revenue, is a determinant in the decision to switch.

# CHAPTER 3. THEORETICAL MODEL

This chapter presents the theoretical aspects of the real option switching model under an endogenous revenue process. A key feature of the model is the presence of several landowners which alters the real option problem in the sense that entry and exit, i.e., switching, has to be taken into account. The first section describes the model setup to enhance the understanding in the subsequent sections. After providing a brief overview on stochastic processes, we focus on the optimal switching decision. The numerical solution procedure can be found in in the last section of the chapter.

## 3.1 General Model Characteristics

Figure 3.1 serves as a schematic representation of the problem in this dissertation. At time $t$, the landowner of spatial unit $i$ 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 ($\pi_A$) and forestry ($\pi_F$) which include the revenue received from crop production minus the cost in the case of agriculture and the profit from selling carbon credits and the annualized wood value in the case of forestry. In addition to the net revenue observations, the stochastic processes governing the net revenue disturbance and the $CO_2$ price are known. Based on this information, the farmer 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 variable in the model is the regime $k \in \{A, F\}$. If a switch occurs, switching cost are incurred. Although the model presented in this chapter 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 (Song et al., 2011; Chladná, 2007). Between

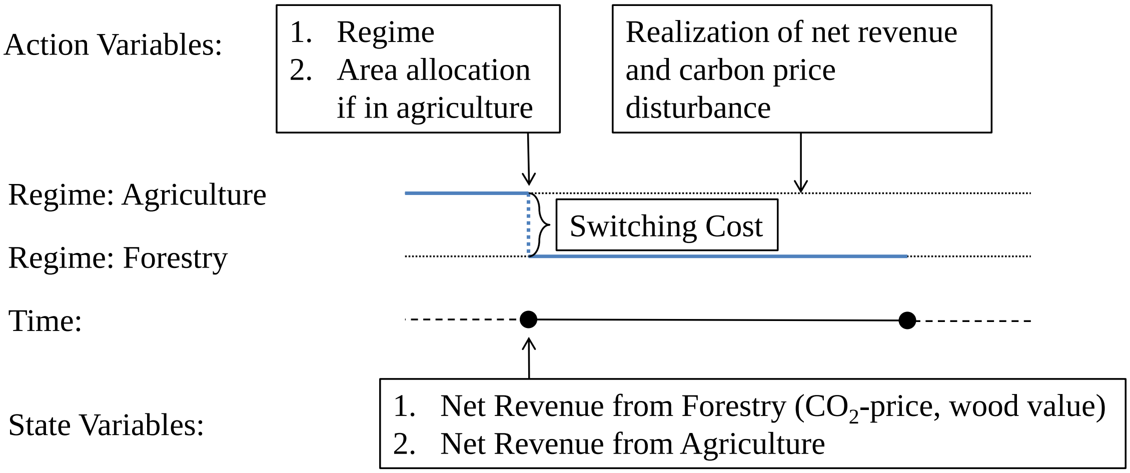


Figure 3.1 Two-regime switching model

the time steps, the net revenue disturbances for both regimes are realized and the decision process continues for the next period. If a landowner decides to stay in agriculture, the land allocation among the crops is based on rational expectations about commodity prices, i.e., the crop prices adjust according to the number of farmers in agriculture. Figure 3.1 represents the case of a landowner who is initially in agriculture and then switches to forestry. Note that most models in chapter 2 assume that the two regimes are *active* and *idle* with no revenue flow in the *idle* regime. We will keep the model description in this section general in terms of functional forms. The specific parametrization of the functions and the solution algorithm can be found in chapter 4.

## 3.2 Stochastic Processes

The revenue disturbance as well as the price of carbon evolve according to the following general stochastic process:

$$dx = \mu(x, t; \Omega)dt + \sigma(x, t; \Omega)dz$$

where $\mu(x, t; \Omega)$ is the drift rate and $\sigma(x, t; \Omega)$ represents the variance. The drift rate and the variance depend on the stochastic variable $x$, the time variable $t$, a set of parameters denoted

$\Omega$. The increment of a Wiener process is denoted $dz$. To model net revenue and $CO_2$ price, we need to decide what functional forms to use for $\mu(x, t; \Omega)$ and $\sigma(x, t; \Omega)$. Commonly used specifications are the geometric Brownian motion (GBM) and some form of mean reverting process (MRP). Consider the following stochastic processes:

$$dx = \eta(\bar{x} - x)xdt + \sigma xdz \tag{3.1}$$

$$dx = \eta(\bar{x} - x)dt + \sigma xdz \tag{3.2}$$

where $\eta$ is the speed of mean reversion, $\bar{x}$ is the long run value of the process and $\sigma$ represents the variance. In this dissertation, we focus on stochastic processes of the form 3.2 for three reasons. First, equation 3.2 encompasses a geometric Brownian motion if $\bar{x} = 0$ and $\eta = -\mu$ and hence allows for more flexibility in specifying the stochastic process. Second, the stochastic process in equation 3.1 is not homogenous of degree one in the pair $(\bar{x}, x)$ meaning that if the output price of one unit of a particular good follows 3.1 and reverting to $\bar{x}$ than the price of two units does not revert to twice $\bar{x}$ (Tsekrekos, 2010). And third, equation 3.2 allows us to express the net revenue from agriculture in terms of the net revenue itself and not the stochastic disturbance $\epsilon_A$.

For our model, we denote the disturbance terms as $\epsilon_A$ and $\epsilon_F$ for agriculture and forestry, respectively. We will see that $\epsilon_F$ represents directly the emission allowance price. With agricultural revenue being mean reverting and an increasing carbon price over time, the following stochastic processes for agriculture and forestry are assumed throughout the dissertation

$$d\epsilon_A = \eta(\bar{\epsilon}_A - \epsilon_A)dt + \sigma_A \epsilon_A dz_A \tag{3.3}$$

$$d\epsilon_F = \mu \epsilon_F dt + \sigma_F \epsilon_F dz_F \tag{3.4}$$

where $\bar{\epsilon}_A = 1$ and the correlation between the processes is $E(dz_A, dz_F) = \rho$.

## 3.3 Net Revenues 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 spatial unit $i$ when in agriculture is written as (the subscript $i$ is dropped for notational convenience):

$$\pi_A(\mathbf{a}_A, \epsilon_A) = \max_{\mathbf{a}_A} \sum_{j=1}^{J} \left[p_j a_{A,j} y_{A,j} - K_{A,j}(a_{A,j})\right] \epsilon_A \tag{3.5}$$

where $y_{A,j}$ and $a_{A,j}$ are the crop yield and area allocated to is the crop $j$ and $K_{A,j}(a_{A,j})$ is a cost function with increasing marginal cost. The uncertainty in the net revenue is introduced by $\epsilon_A$ which follows the stochastic process previously described and is the same for all spatial units[1]. The disturbance term $\epsilon_A$ can be thought of as summarizing all uncertainties due to yield, output price, and cost fluctuations. 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.

While in forestry, there are two sources of revenue: First, the standing forest represents a value in terms of wood 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:

$$\pi_F(a_F, \epsilon_F) = R_F(a_F, y_F, p_F) + a_F \cdot h \cdot \epsilon_F \tag{3.6}$$

where $R_F$ is the non-carbon net revenue function, $a_F$ is the area in forestry, $y_F$ yield in terms of timber growth per years, $p_F$ is the stumpage price, $h$ is the county specific sequestration rate, and $\epsilon_F$ represents the stochastic carbon price. We do not model the harvest decision, the rotation timing of a forest, and the type of forest to plant in a particular county explicitely.

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[1] 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 is possible as shown by Zhao (2003) but would increase the computational time significantly by requiring to simulate potentially a 3070 by 3070 covariance matrix at each step during the simulation.

The function $R(\cdot)$ in equation 3.6 incorporates the information concerning the harvest decision and the rotation period implicitly by representing the land rent for a spatial unit per year. To determine the value of forest on an annual basis, we calculate the net present value of a type of forest based on the stumpage price and the volume growth (see chapter 4).

## 3.4 Regime Switching under Endogenous Revenue Processes

This section follows closely the steps and logic from Leahy (1993), Zhao (2003), and Baldursson and Karatzas (1997) to determine the switching decision under an endogenous revenue process. We describe a slightly more general and simpler model for exposition of the concept than used in the empirical part. That is, we assume only one commodity in each regime and a slightly modified revenue process for forestry than equation 3.6. Equation 3.5 defines the net revenue process as a function of the area planted by the landowner of spatial unit $i$. However, given the demand function for the agricultural commodity $Q_A = D(p_A)$ and the fact that the individual landowner allocates land such that the aggregate quantity produced by all landowner who are in agriculture is consistent with demand, equation 3.5 can be rewritten as

$$\pi_A(Q_A, \epsilon_A) = R(Q_A)\epsilon_A$$

meaning that the net revenue process while being in agriculture is a function of the total quantity produced which depends on the number of landowners in agriculture. If $Q_A$ remains constant, then the net revenue fluctuates around a mean which, as shown later, can be written as $\bar{\pi}_A(Q_A)$. The same argumentation can be applied to the case of forestry where the revenue depends on how many landowners are in forestry and on their aggregate production in terms of carbon offset credits and timber. Hence, equation 3.6 can be rewritten as[2]:

$$\pi_F(Q_F, \epsilon_F) = R(Q_F)\epsilon_F$$

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[2] Note the simplification by incorporating the wood as well as the carbon value in the revenue function multiplied by the disturbance. This does not change the proof but simplifies notation.

Applying Itô's Lemma, we find that the net revenue from agriculture and forestry evolve as

$$\pi_A = \frac{\partial \pi_A(Q_A, \epsilon_A)}{\partial Q_A} dQ_A + \eta(\bar{\epsilon} - \epsilon)R_A(Q_A) + \frac{1}{2}\sigma_A \epsilon_A R_A(Q_A) dz$$

which can be rewritten as

$$\pi_A = \frac{\partial \pi_A(Q_A, \epsilon_A)}{\partial Q_A} dQ_A + \eta(\bar{\pi}_A(Q_A) - \pi_A)dt + \frac{1}{2}\sigma_A \pi_A dz \tag{3.7}$$

Similar calculations for forestry lead to:

$$\pi_F = \frac{\partial \pi_F(Q_F, \epsilon_F)}{\partial Q_F} dQ_F + \mu_A \pi_F(Q_F)dt + \frac{1}{2}\sigma_F \pi_F dz \tag{3.8}$$

Equations (3.7) and (3.8) are each composed of two terms. The first term on the righthand side, i.e., $\partial \pi_k(\cdot)/\partial Q_k dQ_k$, of both equations is the influence of quantity variations, i.e., the effect of other landowners switching and its affect on the quantity produced, on the revenue processes. The last two terms in both equations are the standard shocks to the net revenue if there were no entry and exit, that is, if $dQ_k = 0$. For each landowner, there have to be switching triggers $\overline{\pi_A}(Q_A)$, $\underline{\pi_A}(Q_A)$, $\overline{\pi_F}(Q_F)$, and $\underline{\pi_F}(Q_F)$ for which a switch to a different regime occurs. The solution to the problem is to find those trigger policies in addition to the price process. For example, if a landowner is currently in agriculture, there is a net revenue in agriculture ($\underline{\pi_A}(Q_A)$) and forestry ($\overline{\pi_F}(Q_F)$) which trigger a switch to forestry.

As noted by Leahy (1993) and Zhao (2003), calculating a competitive equilibrium based on the trigger policies is a very difficult task because it involves searching for a fixed in point at which the expectations about the entry and exit of other landowners are consistent with the trigger policies. In his seminal article, Leahy (1993) proves that the individual firm can ignore the switching decisions of others. The switching occurs at the same point as the fully rational decision when the switching of other landowners is ignored. In the original article, the argument is made for a firm deciding to enter and exit an industry but can be extended to the case where where both regimes yield a return. Zhao (2003) applies the concept to increasing and decreasing capital investments in abatement technology given a fluctuating emission permit price. In equilibrium, the possibility of other firms switching to forestry reduces the payoff of investing in forestry. At the same time however, the value of waiting is reduced as well by the same magnitude (Leahy, 1993). Thus the landowner can base the decision to switch on the exogenous price process, i.e., $dQ_k = 0$, and still make the correct decision. To do so, it is necessary to start from the current level of net revenues given the number of landowners in the regime agriculture, i.e., in each time step, the level of $\bar{\pi}$ and the $CO_2$ price needs to serve as the new starting point of the stochastic process (Zhao, 2003). So the revenue process for both regimes is written as Leahy (1993); Dixit and Pindyck (1994); Zhao (2003):

$$\hat{\pi}_A = \eta(\bar{\pi}_A - \hat{\pi}_A)dt + \frac{1}{2}\sigma_A\hat{\pi}_A dz \tag{3.9}$$

$$\hat{\pi}_F = \mu_A\hat{\pi}_F dt + \frac{1}{2}\sigma_F\hat{\pi}_F dz \tag{3.10}$$

where $\hat{\pi}_k$ refers to net revenue process not bounded by the entry and exit decision of others. There are two important implication of equations 3.9 and 3.10: First, if the number of landowners in agriculture stays the same, net revenue is mean reverting as shown in figure 2.2. However, if landowners switch from agriculture to forestry, prices and hence net returns will increase to a new mean reverting level $\bar{\pi}_A$. The shift to a new $\bar{\pi}_A$ can also occur if we change the level of biofuel production. This is consistent with what is depicted in figure 2.2 which shows a shift in the level of net revenue after 2005. The individual land owner adjusts the area such that that the acreage and the resulting production is consistent with the quantity demanded and prices.

## 3.5 Optimal Switching Model

The problem of the landowner is characterized by the possibility of switching from a regime which yields a stochastic return to a new regime which results in a flow of profits with different stochastic properties. Those problems are also called *optimal stopping problems* and refer mostly to the entry and exit decision in an industry. Recall from the previous section, that we have two stochastic processes:

$$d\epsilon_A = \eta_A(\bar{\epsilon}_A - \epsilon_A)dt - \sigma_A \epsilon_A dz_A \tag{3.11}$$

$$d\epsilon_F = \mu_F \epsilon_F dt - \sigma_F \epsilon_F dz_F \tag{3.12}$$

In addition, there is a flow of returns given by $\pi_k(\epsilon_A(t), \epsilon_F(t))$. Given the initial values of the state variables at $t = 0$ as $\epsilon_A$ and $\epsilon_F$, the general maximization problem is written as (Brekke and Øksendal, 1994; Vath and Pham, 2007):

$$J^k(\epsilon_A(t), \epsilon_F(t), \alpha) = E\left[\int_0^\infty e^{-rt}\pi_k(\epsilon_A(t), \epsilon_F(t))dt - \sum_{n=1}^{\infty} e^{-r\tau_n} H(\kappa_{n-1}, \kappa_n)\right] \tag{3.13}$$

where $r$ represents the discount rate, $k$ denotes the regime, and $H(\cdot)$ is the cost of switching. In what follows, let $H(A, F) \equiv C_{AF}$ and $H(F, A) \equiv C_{FA}$. Switching costs are positive to avoid infinite profit making. The dynamic problem of the land owner can be thought of as a finding a sequence of $n$ stopping times $(\tau_n)$ and new regimes $(\kappa_n)$ in order to maximize the payoff from a unit of land. Those stopping times and new regimes cannot be found explicitly but are determined by the impulses $\epsilon_A$ and $\epsilon_F$ received by the land owner. The sequences $\alpha$ can be represented as:

$$\alpha = (\tau_1, \tau_2, \ldots, \tau_N, \kappa_1, \kappa_2, \ldots, \kappa_N) \tag{3.14}$$

Brekke and Øksendal (1994) show that the optimality condition if currently in regime $k$ can be written as:

$$\underbrace{rV^k(\epsilon)}_{\text{Rate of return}} \geq \sup_{a_k}\left\{ \underbrace{\pi_k(a_k)}_{\text{Current return}} \underbrace{+\sum_k \mu_{\epsilon_k}\frac{\partial V^k}{\partial \epsilon_k} + \frac{1}{2}\sum_i\sum_j \Psi \frac{\partial^2 V^k}{\partial \epsilon_i \partial \epsilon_j}}_{\text{Expected rate of capital appreciation}} \right\} \tag{3.15}$$

$$V^k(\epsilon_k) \geq V^m(\epsilon_m) - C_{k,m} \quad k \neq m \tag{3.16}$$

where $V^k(\epsilon)$ is the value function from being in regime $k$ when the current state vector is $\epsilon$ and $\Psi$ is the variance-covariance matrix of the stochastic processes. 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 the first equation in 3.15 holds with equality, then the landowner stays in the current regime because the rate of return from regime $k$ is equal to the current return and the expected capital appreciation. The expected capital appreciation plays an important role in the option valuation. The determines how the future value of the current use will evolve. In addtion to the first equation holding with equality, the second equation holds with inequality meaning that the value from staying in regime $k$ is bigger than the value from the other regime 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).

To apply the method described, define the infinitesimal generator of state process as follows (Balikcioglu et al., 2011) and correlation coefficient $\rho$:

$$\mathcal{L} = \eta_A(\bar{\epsilon}_A - \epsilon_A)\frac{\partial}{\partial \epsilon_A} + \mu_F \epsilon_F \frac{\partial}{\partial \epsilon_F} + \frac{1}{2}(\sigma_A \epsilon_A)^2 \frac{\partial^2}{\partial \epsilon_A^2} + \frac{1}{2}(\sigma_F \epsilon_F)^2 \frac{\partial^2}{\partial \epsilon_F^2} + \rho \sigma_A \epsilon_A \sigma_F \epsilon_F \frac{\partial^2}{\partial \epsilon_A \partial \epsilon_F} \tag{3.17}$$

If currently in agriculture, Brekke and Øksendal (1994) show that the Hamilton-Jacobi-Bellman equation for (3.13) results in (if currently in agriculture):

$$rV^A(\epsilon) \geq \sup_{a_A} \left\{ \pi_A(a_A) + \mathcal{L}V^A \right\} \tag{3.18}$$

and

$$V^A(\epsilon) \geq V^F(\epsilon) - C_{AF} \tag{3.19}$$

If the landowner is currently in forestry, the conditions are:

$$rV^F(\epsilon) \geq \pi_F(a_F) + \mathcal{L}V^F \tag{3.20}$$

and

$$V_F(\epsilon) \geq V_A(\epsilon) - C_{FA} \tag{3.21}$$

The maximum condition for equation (3.18) is $p_{jt}y_{ijt} = K'_{jt}(a_{ijt})$, i.e., before switching to forestry, landowners left in agriculture have the flexibility to expand the area planted and thus increasing commodity prices. Equations (3.18) and (3.19) are summarized as follows:

$$0 = \min\left\{rV^A(\epsilon)\mathcal{L}V^A - \pi^A_{it}(a_{ijt}, \epsilon_{ijt}), V^A(\epsilon) - V^F(\epsilon) + C_{AF}\right\} \tag{3.22}$$

The solution to equation (3.22) subdivide the $\pi^A$-$\pi^F$ space into three regions corresponding to “staying in current use”, “switching to forestry”, and “switching to agriculture”. The algorithm was previously applied to fisheries (Nøstbakken, 2006) and energy crops (Song et al., 2011). In our model, we restrict the switch from forestry to agriculture assuming that there is some sort of “sodsaver” policy which prohibits the conversion from forest to grassland (Claassen et al., 2011).

## 3.6 Numerical Solution

No explicit solution exists and numerical methods are implemented. We heavily rely on the collocation method extensively discussed in Miranda and Fackler (2002) and Fackler (2004). The solution approach proposed by Brekke and Øksendal (1994) and the collocation method are implemented by Fackler (2004) based on the MATLAB computer routines by Miranda and Fackler (2002). Those sources also serve as the basis for the numerical implementation described below.

The basic idea behind the collocation method is to approximate the unknown value function by a function which is composed of known functions. In our case, we approximate the value function $V^k(\epsilon^A, \epsilon^F) \approx \phi(\epsilon^A, \epsilon^F)\theta^k$ where $\phi(\epsilon^A, \epsilon^F)$ represents a set of $n$ so called base functions and $\theta^k$ represents a vector of $n$ approximating coefficients. Each regime has a set of base functions and approximating coefficients. Note that the base functions are predetermined and known and that the numerical solution consists of finding the approximating coefficients. Recall that our solution conditions are

$$0 = \min\left\{rV^A(\epsilon) - \eta(\bar{\epsilon} - \epsilon)\frac{\partial V^A}{\partial \epsilon_A} - \frac{1}{2}\sigma_A\epsilon_A^2\frac{\partial^2 V^A}{\partial \epsilon_A \partial \epsilon_F}, V^A(\epsilon) - V^F(\epsilon) + C_{AF}\right\} \tag{3.23}$$

and

$$0 = \min\left\{rV^F(\epsilon) - \mu_F\frac{\partial V^A}{\partial \epsilon_F} - \frac{1}{2}\sigma_F\epsilon_F^2\frac{\partial^2 V^F}{\partial \epsilon_A \partial \epsilon_F}, V^F(\epsilon) - V^A(\epsilon) + C_{FA}\right\} \tag{3.24}$$

Define the approximate differential operator

$$\beta^k(\epsilon_A, \epsilon_F) = r\phi(\epsilon_A, \epsilon_F) - \mu\phi'(\epsilon_A, \epsilon_F) - \frac{1}{2}\sigma_k^2\epsilon_k^2\phi''(\epsilon_A, \epsilon_F)$$

where $\mu = \eta_A(\bar{\epsilon}_A - \epsilon_A)$ if $k = A$ and $\mu = \mu_F$ if $k = F$. The problem can now be written as:

$$\beta^k\theta^k - \pi_k(\epsilon_A, \epsilon_F) \geq 0 \tag{3.25}$$

$$\phi^k(\epsilon_A, \epsilon_F)\theta^k - \phi^m(\epsilon_A, \epsilon_F)\theta^m - C_{k,m} \geq 0 \quad k \neq m \tag{3.26}$$

Applying the collocation method consists of solving the problem for a fixed number of points in the state space. 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. Let $\Phi$ and $B_k$ be matrices of $\phi$ and $\beta^k$ evaluated at the $40 \times 25$ points. In addition, let $\Pi_k$ be the reward function evaluated at the same points. The problem can be formulated as an Extended Vertical Linear Complementarity problem (EVLCP) as follows:

$$0 = \min\left\{M_A z + q_A, M_F z + q_F\right\} \tag{3.27}$$

where $M_k$ is written as $M_k = e_k e_k^\top \otimes B_k + (I_m - 1_m e_k^\top) \otimes \Phi$ where $1_m$ is a column vector of ones and $e_k$ is the $k$th column of a 2-by-2 identity matrix. So

$$M_A = \begin{pmatrix} B_A & 0 \\ -\Phi & \Phi \end{pmatrix}, M_F = \begin{pmatrix} \Phi & -\Phi \\ 0 & B_F \end{pmatrix}, q_A = \begin{pmatrix} -\Pi_A \\ C_{AF} \end{pmatrix}, q_F = \begin{pmatrix} C_{FA} \\ -\Pi_F \end{pmatrix}$$

The solution to equation 3.27 has been implemented by Fackler (2004) in the MATLAB routine *ossolve*.

# CHAPTER 4. EMPIRICAL MODEL

The purpose of this chapter is to present the empirical model in terms of input data, assumptions, and numerical analysis. After introducing the geographic coverage in the first section, we outline the components of the agricultural and the forestry model in the next sections as well as the $CO_2$ price dynamics. Section 4.5 covers the simulation algorithm and the last section summarizes the data sources.

## 4.1 Geographic Coverage

Our analysis is done for the contiguous United States which covers 3070 counties. Legislation would distribute carbon credits based on additional forest and not on existing forest. Hence, we assume that at the beginning of our projection period, a fixed number of counties are in agriculture. For each county, we calculate the average area harvested over the last five years in which crop production took place and ignore counties which were not in crop production after the year 2000. For the crops covered in our model, 2562 counties were engaged in the production of at least one of the crops if we focus on field crops and 3014 if we include pasture as well[1]. Only those counties can switch to forestry and no entry of other counties into agriculture or forestry occurs over the projection period. In order for afforestation to take place in a particular county, there had to be historic forest cover based figure 2.1 or sufficient annual precipitation. Figure 4.1 shows all counties in which we allow for afforestation based on historic forest coverage of at least 50% of the county area and sufficient precipitation, i.e., only the counties marked in figure 4.1 can switch to agriculture. In particular, all counties in Iowa, Illinois, Missouri, Minnesota, and Wisconsin are included although some of those counties

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[1] The number of 2120 counties in crop production from chapter 1 refers to the year 2008 whereas we use the average over five years. Hence, some counties are included which might not have been in agriculture in 2008

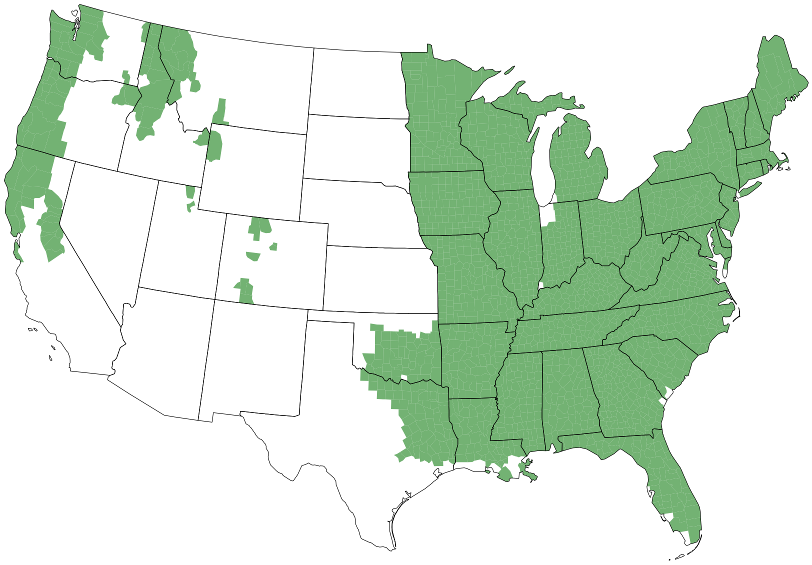

Figure 4.1 Counties with historic forest coverage or sufficient precipitation

have not seen historic forest coverage. In our model, each county is owned by a representative landowner who makes the decision for that county. Land is homogenous within the county, i.e., there are no differences in terms of yield and carbon sequestration rates. The available county area for crop production or forestry is the maximum crop area in the period from 2000 to 2008. If a county switches to forestry, then the maximum area goes to forestry (all-or-nothing). We will see that this is implied by the net revenue function from forestry which is linear in revenue and no costs are involved.

## 4.2 Agricultural Model

The agricultural net revenue function has two important components: the commodity demand functions and the net revenue function.

### 4.2.1 Commodity Demand

The nine crops included in our demand analysis are barley (BA), corn (CO), cotton (CT), hay (HY), oats (OA), rice (RI), soybeans (SB), sorghum (SG), and wheat (WH). For each commodity, there are up to four demand sectors: food/domestic, feed, exports, and biofuels. For simplicity, we assume a constant elasticity demand function which is of the general form:

$$q_{jm} = \alpha_0 \prod_{j=1}^{N} p_j^{\alpha_{jm}} \tag{4.1}$$

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 inclusion of cross-price elasticities allows capture of the 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. For corn, we assume a constant ethanol production over the projection period which is set at 4.254 billion bushels or 11.62 billion gallons of ethanol. Hence, the demand for corn (in million bushels) is appended by the consumption for biofuels: $q_{corn} = \tilde{q}_{corn} + 4,254$ where $\tilde{q}_{corn}$ represents the corn demand for food, feed, and exports.

#### 4.2.1.1 Demand System Estimation

To calculate the demand elasticities, we use the Linear Approximation of the Almost Ideal Demand System (LA/AIDS) proposed by Deaton and Muellbauer (1980) which expresses the demand for commodity $i$ in terms of its budget share. Implicit in the LA/AIDS model is the assumption of a representative consumer spending her or his income on a fixed number of goods. The evolution of the budget shares for food and feed between 1980 and 2010 is shown in figures 4.2 and 4.3. Prices and quantities demanded are obtained from FAPRI Agricultural Outlook Model (see section 4.6). All prices are deflated using the producer price index with 2008 serving as the base year. The demand elasticities are estimated for two sectors using the LA/AIDS model: food/domestic and feed. We include a trend variable to capture a change in the expenditure share over time. The share equation to be estimated for each commodity can be written as:

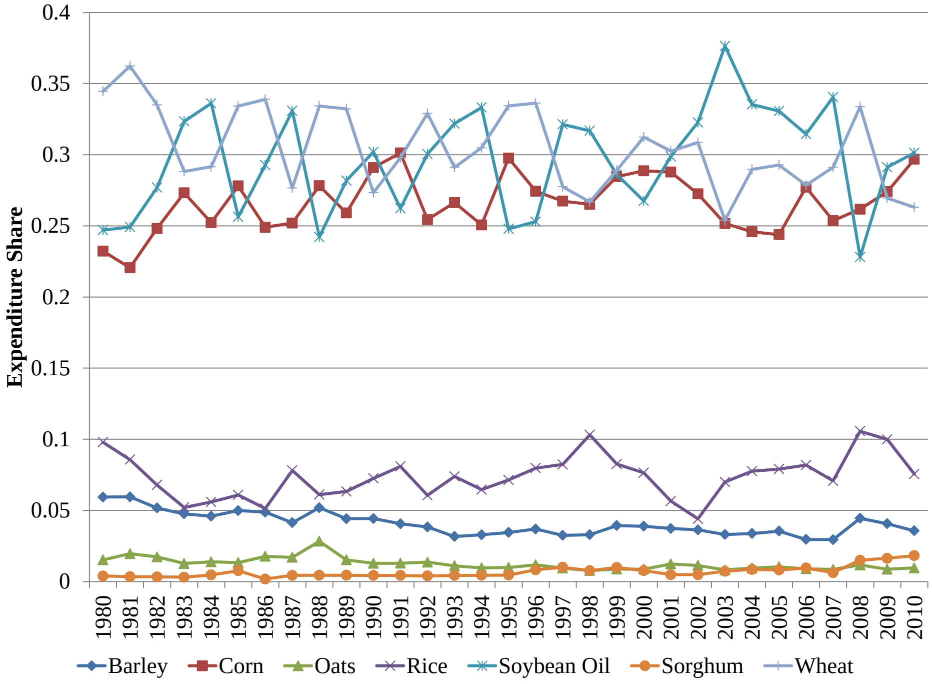

Figure 4.2 Food Expenditure Shares

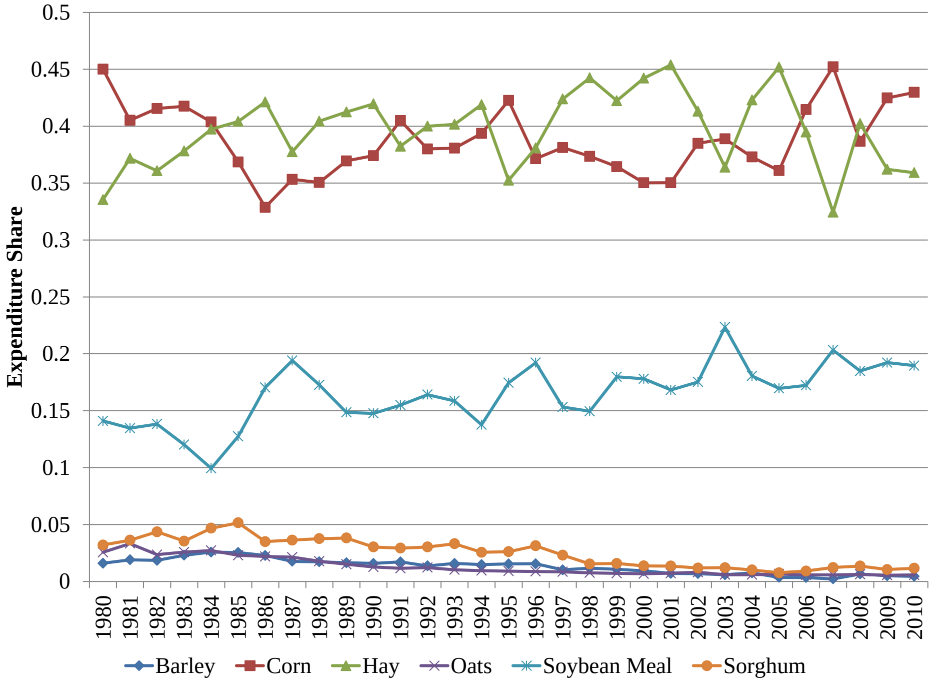

Figure 4.3 Feed Expenditure Shares

$$w_i = \alpha_i + \sum_{j=1}^{n} \gamma_{ij} \ln p_j + \beta_i \ln\left(\frac{X}{P}\right) + \alpha_i^t t$$

where $\alpha_i$, $\gamma_{ij}$, $\beta_i$, and $\alpha_i^t$ represent coefficients to be estimated. The variable $w_i$ is the expenditure share of good $i$, $p_j$ are the prices, $X$ is the total expenditure on all commodities and $P$ is a price index[2] defined as:

$$\ln P = \sum_{i=1}^{n} w_i \ln p_i$$

The properties of the cost function from which the share equation is derived imposes three restrictions on the parameters:

1. Homogeneity of degree zero in prices and income, i.e.,
$$\sum_{j=1}^{N} \gamma_{ij} = 0$$
2. Adding up, i.e.,
$$\sum_{i=1}^{N} \alpha_i = 1; \quad \sum_{i=1}^{N} \gamma_i = 0; \quad \sum_{i=1}^{N} \gamma_i = 0.$$
3. Slutsky symmetry, i.e., $\gamma_{ij} = \gamma_{ji} \ \forall i \neq j$.

Once the above system is estimated using a seemingly unrelated regressions (SUR) model, the Marshallian price elasticities can be calculated as follows (Green and Alston, 1990):

$$\epsilon_{ij} = \frac{\gamma_{ij}}{w_i} - \beta_i \frac{w_j}{w_i} - \delta_{ij}$$

where $\delta_{ij} = 1$ if the own price elasticity is calculated and $\delta_{ij} = 0$ otherwise.

|  | $p_{BA}$ | $p_{CO}$ | $p_{RI}$ | $p_{OA}$ | $p_{SO}$ | $p_{SG}$ | $p_{WH}$ | $\ln(\frac{X}{P})$ | $\alpha^t$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $w_{BA}$ | 0.036 | -0.021 | 0.000 | 0.006 | -0.028 | 0.015 | -0.008 | -0.048 | 0.000 | 0.473 |
|  | (4.72) | (-1.96) | (0.11) | (1.33) | (-4.83) | (2.62) | (-0.98) | (-4.64) | (-0.40) | (5.65) |
| $w_{CO}$ | -0.021 | 0.180 | -0.027 | -0.004 | -0.003 | -0.013 | -0.112 | 0.142 | -0.001 | -0.708 |
|  | (-1.96) | (8.30) | (-4.74) | (-0.64) | (-0.30) | (-1.25) | (-7.79) | (7.53) | (-2.20) | (-4.64) |
| $w_{RI}$ | 0.000 | -0.027 | 0.075 | 0.003 | -0.047 | 0.012 | -0.016 | -0.027 | 0.001 | 0.286 |
|  | (0.11) | (-4.74) | (19.45) | (1.02) | (-8.17) | (3.99) | (-2.60) | (-2.48) | (5.73) | (3.25) |
| $w_{OA}$ | 0.006 | -0.004 | 0.003 | 0.015 | -0.006 | -0.005 | -0.009 | -0.006 | 0.000 | 0.078 |
|  | (1.33) | (-0.64) | (1.02) | (3.26) | (-1.17) | (-1.30) | (-1.34) | (-0.64) | (-1.47) | (1.10) |
| $w_{SO}$ | -0.028 | -0.003 | -0.047 | -0.006 | 0.171 | -0.035 | -0.052 | -0.055 | 0.002 | 0.364 |
|  | (-4.83) | (-0.30) | (-8.17) | (-1.17) | (7.78) | (-1.64) | (-2.48) | (-1.38) | (2.15) | (1.14) |
| $w_{SG}$ | 0.015 | -0.013 | 0.012 | -0.005 | -0.003 | 0.003 | -0.008 | -0.009 | 0.001 | 0.060 |
|  | (2.62) | (-1.25) | (3.99) | (-1.30) | (-0.58) | (0.44) | (-1.07) | ( -0.94) | (2.89) | (0.75) |

Table 4.1 Estimation results for food demand

#### 4.2.1.2 Estimation Results

The commodities included for food demand are barely, corn, rice, oats, soybean oil (SO)[3], sorghum, and wheat. The results of the estimations are summarized in table 4.1 with the $z$-values in parenthesis. Note that the wheat equation was deleted to avoid singularity issues during the estimation process. All the own price elasticities and 15 out of 36 cross-price elasticities are significant at the 5% level. In addition, corn, rice, soybean oil, and sorghum show a statistically significant time trend. The feed grain demand system includes barley, corn, hay, soybean meal (SM), and sorghum. The estimation results are presented in table 4.2. The feed demand elasticities as well as the food demand elasticities are short-run elasticities estimated from yearly data. We assume that those elasticities remain unchanged over the projection period.

The elasticities for feed demand are found in table 4.4. The demand elasticities for cotton are obtained from the POLYSYS model (University of Tennessee) and are set to -0.05 for mill demand and -1 for export demand. We use the same model to obtain the export elasticities

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[2] For estimation purposes, it is more convenient (Deaton and Muellbauer, 1980) to use a linear approximation then the price index originally proposed which is:

$$\ln P = \alpha_0 + \sum_{i=1}^{n} \ln p_i + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \gamma_{ij} \ln p_i \ln p_j$$

[3] A bushel of soybean yields 11 pounds of soybean oil and 47 pounds of soybean meal.

| | $p_{BA}$ | $p_{CO}$ | $p_{HY}$ | $p_{OA}$ | $p_{SM}$ | $p_{SG}$ | $\ln(\frac{X}{P})$ | $\alpha^t$ | $\alpha$ |
|---|---|---|---|---|---|---|---|---|---|
| $w_{BA}$ | -0.005 | 0.040 | -0.007 | 0.002 | -0.007 | -0.023 | -0.022 | -0.001 | 0.242 |
| | (-0.53) | (2.76) | (-1.27) | (0.52) | (-1.41) | (-2.46) | (-1.73) | (-5.71) | (2.11) |
| $w_{CO}$ | 0.040 | 0.050 | -0.099 | -0.001 | -0.029 | 0.040 | 0.130 | 0.001 | -0.109 |
| | (2.76) | (1.48) | ( -8.34) | (-0.14) | (-2.97) | (1.88) | (4.89) | ( 5.56) | (-0.45) |
| $w_{HY}$ | -0.007 | -0.099 | 0.179 | -0.011 | -0.061 | -0.001 | -0.068 | -0.002 | 0.549 |
| | (-1.27) | (-8.34) | (17.46) | (-2.75) | (-9.29) | (-0.10) | (-3.59) | (-9.60) | (3.43) |
| $w_{OA}$ | 0.002 | -0.001 | -0.011 | 0.017 | -0.008 | 0.001 | 0.007 | -0.001 | 0.052 |
| | (0.52) | (-0.14) | (-2.75) | (4.13) | (-2.33) | (0.13) | (0.79) | (-6.51) | (0.66) |
| $w_{SM}$ | -0.007 | -0.029 | -0.061 | -0.008 | 0.091 | 0.014 | -0.058 | 0.002 | 0.363 |
| | (-1.41) | (-2.97) | (-9.29) | ( -2.33) | (13.77) | (1.85) | (-4.07) | (17.39) | (2.94) |

Table 4.2 Estimation results for feed demand

| Crop | $p_{BA}$ | $p_{CO}$ | $p_{RI}$ | $p_{OA}$ | $p_{SO}$ | $p_{SG}$ | $p_{WH}$ |
|---|---|---|---|---|---|---|---|
| Barley | -0.100 | - | - | - | - | - | - |
| Corn | - | -0.389 | 0.001 | - | 0.002 | - | 0.003 |
| Rice | 0.208 | 0.016 | -0.380 | - | - | - | 0.003 |
| Oats | 0.081 | - | - | -0.7892 | - | - | - |
| Soybean Oil (SO) | - | - | - | - | -0.604 | - | - |
| Sorghum | - | - | - | - | - | -0.827 | - |
| Wheat | - | 0.004 | - | - | 0.001 | - | -0.137 |

Table 4.3 Food Demand Elasticities

| Crop | $p_{BA}$ | $p_{CO}$ | $p_{HY}$ | $p_{OA}$ | $p_{SM}$ | $p_{SG}$ |
|---|---|---|---|---|---|---|
| Barley | -2.167 | 1.08 | - | 0.545 | - | - |
| Corn | 0.094 | -0.883 | - | - | 0.09 | - |
| Hay | - | 0.07 | -0.491 | - | - | - |
| Oats | 0.4104 | 0.79 | - | -0.62 | - | - |
| Soybean Meal (SM) | - | 0.081 | - | - | -0.513 | - |
| Sorghum | - | 3.401 | - | 0.074 | 1.204 | -3.611 |

Table 4.4 Feed Demand Function Elasticities

| | BA | CO | CT | RI | SB | SG | WH |
|---|---|---|---|---|---|---|---|
| Export | -0.50 | -0.42 | -1.00 | -0.48 | -0.57 | -0.50 | -0.38 |

Table 4.5 Export Demand Elasticities

which are reported in table 4.5. The constant $\alpha_0$ is determined by matching the price level in $t = 0$ which is assumed to be the long-run equilibrium from the 2010 FAPRI outlook with the resulting production from the yield and area by conty when all counties considered in our model are in agriculture. There is no time trend included in the demand function. In the next section, we will see that our crop yield function does not include a trend either. Implicit in those assumptions is that any yield increase is offset by an increase in demand leaving the crop area unchanged.

Some elasticities were adjusted because the estimates from the LA/AIDS were inconsistent with economic theory. The own-price food elasticities for barley and rice, and the own-price feed elasticity for oats were corrected using data from agricultural trade and production models such as the Food and Agricultural Policy Research Institute (FARPI), the Economic Research Service/Pennsylvania State trade model (Stout and Abler, 2004) or the Policy Analysis System (POLYSYS) from the University of Tennessee (Agricultural Policy Analysis Center, 2011). In addition, cross-price food elasticities for wheat and corn demand were replaced with values from the FAPRI model. The same is true for cross-price feed demand elasticities for oats and soybean meal.

#### 4.2.1.3 Pasture

There is no demand function for pasture and the net revenue form an acre of pasture is linked to the price of hay (Lubowski et al., 2006). Iowa State University's extension service[4] recommends 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 2008 cash rent collected from USDA's NASS[5] 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. We use the category *Pastureland* (excluding woodland and cropland) which includes approximately 384 million acres[6].

### 4.2.2 Net Revenue Dynamics

This section focuses on the individual landowner's decision and aggregate production. Although we model the net revenue from agriculture for the individual landowner $i$ as mean reverting if no switching of other landowners occurs, the mean itself is influenced by the number of counties in the regime *agriculture* which is endogenous to the model.

In a first step, we obtain 1975-2008 yield data from the NASS and fit a linear trend for each county and each commodity to determine the potential yield by crop and county in 2008. We do not include a trend in the yield over the projection period and assume a constant yield from the year 2008. This assumption plus the time invariant demand allows us to avoid additional state variables in our numerical simulation which makes the model solvable in a reasonable amount of time.

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

[5] Accessed on 23 April 2011 (`quickstats.nass.usda.gov`)

[6] The 2007 NRI data reports 409 million acres of rangeland and 119 million acres of pasture. The NRU defines pasture as land managed for forage production whereas rangeland is barely managed and includes grasslands, savannas, wetlands, deserts, and tundra. In this dissertation, the distinction between managed and unmanaged pasture/rangeland is not made. As long as the land falls within the region established in figure 4.1, it is eligible for conversion. In our case, this amounts to approximately 66 million acres.

Cost and return data is obtained from the USDA's Economic Research Service (USDA Economic Research Service, 2011). The total cost in our model is represented as:

$$K_i(a_{ij}) = \alpha_{1i} a_{ij} + \frac{1}{2}\alpha_{2i} a_{ij}^2$$

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 is not available and hence the direct estimation of the county specific parameters $\alpha_{1i}$ and $\alpha_{2i}$ is not possible. To obtain county specific parameters, we proceed in two steps. In a first step, we obtain data from the 2008 USDA/ERS cost and return database on operating cost by crop and farm resource region[7] and set the parameter $\alpha_{1i}$ 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 $\alpha_{1i}$. The values are represented in table 4.6. Assuming profit maximizing but price taking behavior allows the calculation of the county specific parameters $\alpha_{2i}$ in the second step because the landowner sets marginal revenue equal to marginal cost:

$$p_j \cdot y_{ij} = \alpha_{1i} + \alpha_{2i} a_{ij}$$

We obtained planting time expected prices for corn, oats, rice, soybeans, and wheat from the Chicago Board of Trade [8]. For the other commodities, we assume that the long-run equilibrium price is equal to the futures price. Expected yield data is calculated by fitting a county specific trend yield to historical data from 1980 to 2008. The acreage planted is obtained from National Agricultural Statistical Service. Given, $p_j$, $y_{ij}$, $\alpha_{1i}$, and $a_{ij}$ enables us to obtain $\alpha_{2i}$ for the year 2008.

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[7] 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.

[8] The futures data was obtained from Barchart Advanced Commodity Service (http://acs.barchart.com/) on 27 May 2011.

| Region | Barley | Corn | Cotton | Oats | Rice | Sorghum | Soybeans | Wheat |
|---|---|---|---|---|---|---|---|---|
| Basin and Range | 76.21 | | | | | | | 65.36 |
| Eastern Uplands | | 108.85 | | | | | 80.62 | |
| Fruitful Rim | 123.21 | | 483.72 | | 351.50 | 73.47 | | 131.95 |
| Heartland | 62.80 | 119.44 | 384.12 | 68.49 | | 58.78 | 78.15 | 63.78 |
| Mississippi Portal | | | 333.51 | | 253.58 | | 114.19 | |
| Northern Crescent | 77.68 | 133.82 | | 71.10 | | | 87.26 | 83.62 |
| Northern Great Plains | 56.78 | 130.32 | | 45.63 | | 37.87 | 81.35 | 49.82 |
| Prairie Gateway | | 193.03 | 223.27 | 40.91 | | 100.69 | 109.72 | 65.78 |
| Southern Seaboard | | 119.43 | 286.96 | | | | 74.17 | |
| United States | 74.87 | 131.32 | 282.70 | 60.98 | 327.04 | 91.80 | 86.94 | 63.85 |

Table 4.6 2008 Operating Cost except Fertilizer and Chemicals

The maximization problem of the individual landowner $i$ while in agriculture in its most general form is written as

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

The Lagrangian for this problem is

$$L = \sum_{j=1}^{N} p_j a_{ij} y_{ij} - K(a_{ij}) + \lambda(\bar{a}_i - \sum_{j=1}^{N} a_{ij})$$

which is similar to the problem statement used in Zhang et al. (2000). The Kuhn-Tucker conditions for this problem are:

$$\frac{dL}{da_j} = p_j - \frac{dK(a_{ij})}{da_{ij}} - \lambda \leq 0, \quad (p_j - \frac{dK(a_{ij})}{da_{ij}})a_j = 0$$
$$\frac{dL}{d\lambda} = \bar{a}_i - \sum_{j=1}^{N} a_{ij} \geq 0, \quad (\bar{a}_i - \sum_{j=1}^{N} a_{ij})\lambda = 0$$

If the area constraint is binding, the farmers allocates land such that the marginal product between any two crops is equal, i.e.;

$$\frac{p_j}{p_k} = \frac{dK(a_{ik})/da_{ik}}{dK(a_{ij})/da_{ij}}, \quad j \neq k \tag{4.2}$$

Because in reality, idle cropland can be used as pasture or CRP which generate revenue in terms of cash rents or payments from the government, the constraint 4.2 always holds. Data about agricultural activity (planted area, harvested area, and yield) is taken from the National Agricultural Statistical Service (NASS) of the U.S. Department of Agriculture (USDA) for the year 2008. In the absence of switching to forestry, net revenue from agriculture will fluctuate around a mean in the long-run. In chapter 3, we referred to this mean by $\bar{\pi}_i(Q)$ for the individual land owner. The quantity $Q$ is the total production based on yield (which is assumed to be constant), area (choice variable of the landowner), and the number of landowners in the regime *agriculture* which is determined by the real options switching 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 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.

## 4.3 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. 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 will be 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 will be exogenously determined.

### 4.3.1 Merchantable Timber Value

The net revenue function for forest $R_F(a_F, y_F, p_F)$ is calibrated using yield data from the U.S. Forest Service and stumpage price data from various sources including state agencies, university extension services, and private industry sources. The forest regions according to Smith et al. (2006) are represented in appendix B. Stumpage prices for South Central (SC) were taken from the Timber Mart South (TMS), Southeast (SE) prices were obtained from TMS, the Louisiana Department of Agriculture and Forestry, and the Mississippi State University Extension which gets the data from Forest2Market. Northeast (NE) prices are provided by the New York Department of Environmental Conservation. For the Western part of the country (PSW, PSW), we obtained stumpage prices from the Bureau of Business and Economic Research of the University of Montana, and the Washington Department of Revenue. For the central part of the country (NLS, NPS, RMS, and RMS), we used stumpage prices collected from the University of Missouri (Missouri Timber Price Trends). Forest yield data and growth data were taken from Smith et al. (2006) which bases its information on a national level forest carbon accounting model (FORCARB2), a timber projection model (ATLAS), and the U.S. Forest Service's Forest Inventory and Analysis (FIA). For computational reasons, we assume that the forest growth rate, the stumpage price, and the forest sequestration rate remain constant over the projection period. To determine the optimal rotation period and thus the final period for the net present value analysis, we use the Faustmann formula to determine the optimal harvest time. Table 4.7 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. Sohngen et al. (2009) estimates the net present value of southern pine plantation to be \$53.75 per acre per year whereas we determine a rent of \$66.07. For natural growing pine, the we calculate a rent of \$25.95 (Sohngen et al. (2009): \$6.13).

|  | Growth/year |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| Forest type | ft3/ac | tons | t $CO_2$e | $/t | CF | NPV | Rent |
| North East |  |  |  |  |  |  |  |
| Maple-beech-birch (H) | 32.38 | 0.62 | 2.81 | 43.75 | 26.96 | 363.87 | 29.11 |
| *Oak-hickory (H) | 47.86 | 0.91 | 3.41 | 43.75 | 39.85 | 537.94 | 43.04 |
| Northern Lake States |  |  |  |  |  |  |  |
| Maple-beech-birch (H) | 29.37 | 0.56 | 2.97 | 25.00 | 13.97 | 188.61 | 15.09 |
| *Oak-hickory (H) | 31.16 | 0.59 | 2.97 | 25.00 | 14.82 | 200.11 | 16.01 |
| Northern Plain States |  |  |  |  |  |  |  |
| *Elm-ash-cottonwood (H) | 35.28 | 0.41 | 3.07 | 15.00 | 6.13 | 82.76 | 6.62 |
| Maple-beech-birch (H) | 25.21 | 0.48 | 2.51 | 15.00 | 7.20 | 97.14 | 7.77 |
| Oak-hickory (H) | 17.37 | 0.33 | 1.91 | 15.00 | 4.96 | 66.93 | 5.35 |
| Pacific Southwest |  |  |  |  |  |  |  |
| *Fir-spruce-mountain hemlock (S) | 55.19 | 0.64 | 3.89 | 14.63 | 9.32 | 125.84 | 10.07 |
| Mixed conifer (S) | 49.22 | 0.63 | 3.43 | 14.63 | 9.21 | 124.31 | 9.95 |
| Pacific Northwest (East) |  |  |  |  |  |  |  |
| *Douglas-fir (S) | 53.18 | 0.75 | 3.68 | 15.88 | 11.86 | 160.07 | 12.81 |
| Fir-spruce-mountain hemlock (S) | 42.11 | 0.49 | 2.82 | 14.63 | 7.11 | 96.02 | 7.68 |
| Lodgepole pine (S) | 39.01 | 0.51 | 2.06 | 14.25 | 7.28 | 98.34 | 7.87 |
| Ponderosa pine (S) | 28.12 | 0.33 | 1.90 | 17.53 | 5.84 | 78.89 | 6.31 |
| Pacific Nortwest (West) |  |  |  |  |  |  |  |
| *Douglas-fir (S) | 156.02 | 2.19 | 8.52 | 39.00 | 85.43 | 1153.27 | 92.26 |
| Douglas-fir (S,1) | 176.58 | 2.48 | 8.52 | 39.00 | 96.69 | 1305.17 | 104.41 |
| Hemlock-Sitka spruce (S) | 187.46 | 2.51 | 8.98 | 35.75 | 89.90 | 1213.58 | 97.09 |
| Hemlock-Sitka spruce (S,1) | 240.47 | 3.23 | 11.01 | 35.75 | 115.33 | 1556.81 | 124.54 |
| Rocky Mountains (North) |  |  |  |  |  |  |  |
| Douglas-fir (S) | 42.24 | 0.59 | 2.96 | 36.13 | 21.43 | 289.25 | 23.14 |
| *Fir-spruce-mountain hemlock (S) | 46.74 | 0.54 | 2.94 | 35.54 | 19.18 | 258.86 | 20.71 |
| Rocky Mountains (South) |  |  |  |  |  |  |  |
| *Douglas-fir (S) | 27.70 | 0.39 | 2.57 | 36.13 | 14.05 | 189.70 | 15.18 |
| Fir-spruce-mountain hemlock (S) | 23.96 | 0.28 | 2.02 | 35.54 | 9.83 | 132.71 | 10.62 |
| Lodgepole pine (S) | 23.34 | 0.31 | 1.51 | 37.88 | 11.58 | 156.37 | 12.51 |
| Ponderosa pine (S) | 20.02 | 0.24 | 1.59 | 32.63 | 7.75 | 104.56 | 8.37 |
| South Central |  |  |  |  |  |  |  |
| *Loblolly-shortleaf pine (S) | 47.57 | 0.80 | 2.54 | 30.00 | 24.04 | 324.39 | 25.95 |
| Oak-hickory (H) | 40.36 | 0.77 | 3.03 | 22.00 | 16.90 | 227.93 | 18.23 |
| Oak-pine (M) | 43.23 | 0.69 | 2.87 | 25.50 | 17.54 | 236.63 | 18.93 |
| Southeast |  |  |  |  |  |  |  |
| *Loblolly-shortleaf pine (S) | 47.57 | 0.80 | 2.75 | 30.00 | 24.04 | 324.39 | 25.95 |
| Longleaf-slash pine (S) | 47.57 | 0.61 | 2.72 | 30.00 | 18.25 | 246.22 | 19.70 |
| Longleaf-slash pine (S,1) | 126.85 | 1.62 | 2.94 | 30.00 | 48.67 | 626.83 | 50.15 |
| Oak-hickory (H) | 40.36 | 0.77 | 3.10 | 22.00 | 16.90 | 227.93 | 18.23 |
| Oak-pine (M) | 43.23 | 0.69 | 2.92 | 25.50 | 17.54 | 236.63 | 18.93 |

Table 4.7 Annual Forest Growth, Prices, and Revenue

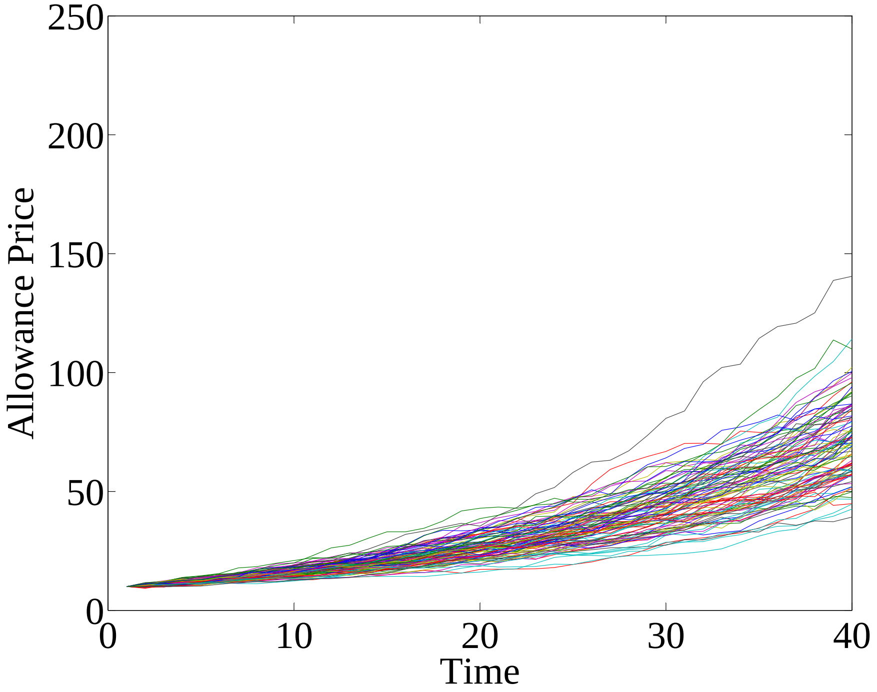
### 4.3.2 Carbon Sequestration Rates

The carbon sequestration rates for afforestation are obtained from Smith et al. (2006). We use the average sequestration rate over the first 95 or 125 years depending on the forest type. The current distribution of selected forest types is depicted in figure B.4. Our choice of forests in a particular county is based on the type which is most likely to be planted given the historic presence type, the non-carbon rent and the carbon sequestration. 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. The tree selected for our analysis are marked with "*" in table 4.7.

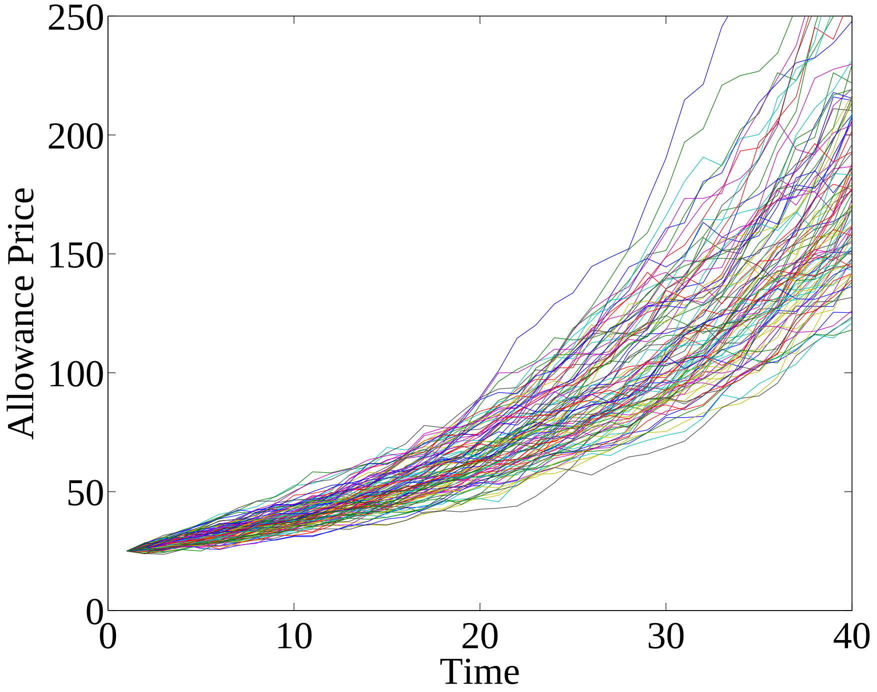
The assumption of a constant sequestration rate simplifies the computations in the empirical section of the paper because the dependency on $t$ is avoided. The growth of commercial wood harvest can be described as a S-shaped curve (Gorte, 2009a). The relationship between the wood produced and the carbon sequestered however is not proportional and varies among tree species. In addition, an important portion of carbon is stored in plants other than the tree itself (e.g., grasses, other herbaceous plants) Gorte (2009a). Appendix B shows that the biomass and carbon volume for the tree species considered in this model.

### 4.3.3 Conversion Cost

The importance of switching cost are highlighted by Schatzki (2003) who shows that the conversion threshold is significantly higher under uncertainty and sunk cost in a land-use change model. Afforestation cost range from \$600 to \$5000 depending on the geographical and biological aspects (Gorte, 2009b). We assume a uniform switching cost of \$1000 from agriculture to forestry and assume that no switching is possible from forestry to agriculture. 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.



(a) Low Carbon Price



(b) High Carbon Price

Figure 4.4 Example of possible carbon price evolutions from 2010 to 2050

## 4.4 $CO_2$ Price Dynamics

The lack of data concerning the $CO_2$ price makes the analysis more difficult. USDA bases its analysis on the average $CO_2$ price starting at \$5 per ton in 2010 increasing at 5% per year and a price starting at \$15 per ton in 2010 increasing at the same rate. This results in a $CO_2$ price of US-\$ 70.40 by 2050. EIA (2009) runs different scenarios achieving allowance price ranging from US-\$ 41.90 to US-\$ 190.52 by 2030. The allowance price in the baseline scenario is US-\$ 64.38 by 2030. An important driver in their results is the use of international offsets and assumptions about the availability of technologies to mitigate carbon emissions such as nuclear, carbon capture and storage, and biomass. Note that the prices in the EIA analysis are significantly higher than from the USDA report because the price collar is ignored in the EIA analysis.

The longest and most liquid emission trading scheme for $CO_2$ allowances is the European Union Emission Trading Scheme (EU ETS). Studies revealed that the allowance price in the EU does not exhibit mean reversion (Meade et al., 2009). Fuss et al. (2008) estimate parameters for the $CO_2$-price in the European Union to be $\mu_C = 0.0568$ and $\sigma_C = 0.0287$. The market for emission allowance in the European Union has been characterized by a collapse in price in the spring of 2006 due to over-compliance in the first phase of the regulation. Another example of an emission treading scheme is the market for sulphur oxide ($SO_2$) in the United States which was introduced with the 1991 Clear Air Act. When the regulation was introduced, firms had no historical data on allowance prices and reasonably expected the price for allowance to be volatile and upward trending due to a rising demand for energy (Insley, 2004). Ellerman and Montero (1998) find that the prices for $SO_2$ allowances remained low because of a decline in rail rates for low sulfur coal from the western parts of the country. In their analysis of the cap-and-trade scheme in New Zealand, Meade et al. (2009) assume a mean reverting price process because the level and variability of the allowance price are limited.

In view of the aforementioned literature, we run scenarios with different assumptions about the allowance price evolution. In order to make our study comparable to previous work, we assume a geometric Brownian motion which leads to an increase in price over time. The two carbon price paths *Low Carbon Price* and *High Carbon Price* are picture in figure 4.4 which depict 100 possible price evolutions starting at \$10 and \$25, respectively.

## 4.5 Numerical Simulation

The numerical analysis for this model is computationally intensive and we have to impose certain restrictions. First, our Monte Carlo simulation includes 100 runs simulating agriculture and forestry over a period of 40 years. Second, 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 integer values for the mean value when calculating the decision threshold, e.g., 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 model initialization takes place for the year 2011. The two key component 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 $\mathbf{s}$ is of size $3070 \times 1$ and $i$ 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 $\mathbf{p}$ 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 $C_0 = \$10$ 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 $\eta = 0.6$ and $\sigma = 0.25$. 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 decide which regime to be in, a new vector $s_{t+1}$ is created

**Step 3:**

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

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 $\mathbf{s}$, 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 4.2 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.

## 4.6 Data Sources

Data on agricultural production in the United States was obtained from the FAPRI Agricultural Outlook Model (http://www.fapri.iastate.edu/outlook/). The utilization data from 1980 onwards was collected from the archived 2000 outlook and data from 2000 onwards was taken from the 2010 outlook. The quantity produced in the base year is determined by the yield and the initial area allocation. The constant of the demand functions are calibrated such that storage is included. Hence, we implicitly assume that the difference in beginning stock and ending stocks is small, i.e., the amount stored over time is constant.

The stumpage prices for South Central and Southeast were taken from *Timber Mart South Market News Quarterly* (Volume 1st Quarter 2010 Vol. 15 No. 1) and the *Softwood and Hardwood Saw Timber Stumpage Value - Statewide Averages Louisiana Quarterly Report for Forest Products* (http://www.ldaf.state.la.us/portal/Offices/Forestry/ ForestryReports/QuarterlyReportofForestProducts/StateAveragesofForestProducts/

tabid/458/Default.aspx). The New York Department of Environmental Conversation provided stumpage prices in *Stumpage Price Report* (Winter 2011 #78). For Western Montana, we use data collected from the Bureau of Business and Economic Research at the University of Montana (Montana Saw Log and Veneer Log Price Report January - March 2011). Stumpage prices for large parts of the Central U.S. are obtained from the *January - March 2011 Missouri Timber Price Trends* of the University of Missouri.

The producer price index (PPI) is obtained from the Bureau of Labor Statistics (BLS) (http://www.bls.gov/ppi/) and set to 1 for 2008.

# CHAPTER 5. RESULTS

Given the theoretical model in chapter 3 and the model calibration from chapter 4, we analyze four scenarios in this chapter to evaluate the impact of a cap-and-trade policy on agricultural production, commodity prices, forest area, and pasture in the United States. The four scenarios analyzed differ in terms of emission allowance price path, the inclusion of pasture as a land pool, and a change in tree types planted in the Midwest.

1. **Low Carbon Price (LCP)**: The emissions allowance price starts at \$10 and is increasing at 5% per year with a standard deviation of 0.04. Those parameters replicate the FASOM/McCarl analysis from chapter 2 in terms of initial allowance price and growth rate. We focus only on cropland and assume that no pasture is available.
2. **Low Carbon Price with Pasture (LCP Pasture)**: This scenario is equivalent to the previous in terms of emission allowance price evolution but includes pasture as a pool of land which serves two purposes: It can either be converted to forestry or can be used as a reserve pool of land if crop expansion is profitable.
3. **High Carbon Price with Pasture (HCP Pasture)**: This scenario includes pasture as well but the emission allowance price starts at \$25 with a growth rate of 5% and a standard deviation of 0.04. The expected allowance price moves along the upper price ceiling under the proposed cap-and-trade policies.
4. **Sensitivity Analysis (SA)**: For this scenario, we replace the elm-ash-cottonwood tree type in the Northern Plain States (NPS) with the oak-hickory type from the North East. The non-carbon rent for elm-ash-cottonwood trees is low for the NPS and we would like to test whether a higher yielding tree type changes the outcome in the Corn Belt.

| | LCP | LCP Pasture | HCP Pasture | SA |
|---|---|---|---|---|
| $CO_2$ price growth rate | | 5% | | |
| Standard deviation | | 0.04 | | |
| Initial allowance price | \$10 | \$10 | \$25 | \$10 |
| Stochastic process: Agriculture | | Mean reversion | | |
| Stochastic process: Carbon | | Geometric Brownian motion | | |
| Pasture | no | yes | yes | yes |
| Expected $CO_2$ price in 2050 | \$73.89 | \$73.89 | \$184.73 | \$73.89 |
| Tree type in the Midwest | | Elm-ash-cottonwood | | Oak-Hickory |

Table 5.1 Key scenario assumptions and parameters

A summary of the key assumptions and parameters for all four scenarios is provided in table 5.1. 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 2011. We will focus the exposition of the results in this chapter on the scenario *Low Carbon Price with Pasture (LCP Pasture)* because it is the most comparable to the FASOM/McCarl analysis.

## 5.1 Switching Probability

Figures 5.1-5.4 depict the switching probability after 100 runs of the four scenarios. in the absence of pasture, afforestation will likely take place in the Northeast, the northern parts of Minnesota and Wisconsin, southern Missouri, at the border of Texas and Oklahoma, and to some extent in the Southeast. The high switching probability in the Northeast is due to the combination of low net revenue from agriculture and high non-carbon rents and high carbon sequestration rates. Although we have seen afforestation in the Southeast in the past (Haynes, 2003), the revenue from carbon sequestration and the non-carbon rents are lower and do not trigger land conversion to forests. This situation changes if pasture is included in the analysis as can be seen in figure 5.2. The availability of large amounts of pasture in the Southeast reduce the net revenue from agricultural land and lead to more counties switching from agriculture to pasture especially in Alabama, Northern Mississippi, the Carolinas, and Eastern Kentucky.

| | Baseline | LCP | LCP Pasture | HCP | SA |
|---|---|---|---|---|---|
| Barley ($/bu) | 4.21 | 5.37 | 4.64 | 5.49 | 4.65 |
| Corn ($/bu) | 3.87 | 4.39 | 4.27 | 6.79 | 4.33 |
| Cotton ($/lbs) | 0.66 | 0.75 | 0.72 | 0.86 | 0.72 |
| Hay ($/ton) | 117.16 | 155.48 | 146.51 | 188.97 | 148.33 |
| Oats ($/bu) | 2.41 | 3.59 | 2.93 | 4.23 | 2.96 |
| Rice ($/cwt) | 10.03 | 11.43 | 11.26 | 17.65 | 11.25 |
| Soybeans ($/bu) | 10.20 | 11.90 | 11.67 | 21.20 | 11.89 |
| Sorghum ($/bu) | 3.58 | 4.83 | 3.95 | 5.15 | 3.97 |
| Wheat ($/bu) | 5.06 | 6.72 | 5.72 | 6.98 | 5.76 |

Table 5.2 Average scenario results: Absolute price levels for the baseline (2011) and the scenarios (2050)

Although very high conversion probabilities are observed in the *High Carbon Price with Pasture* scenario, Corn Belt states like Iowa, Illinois, and Indiana are still unlikely to switch to forestry.

Table 4.7 reports low non-carbon rents for the Northern Plain States (i.e., Corn Belt) and we need to test whether our results are driven by those low values. Figure 5.4 indicates that even at the carbon sequestration rate and the non-carbon rent from Northeast oak-hickories, the Corn Belt does see very little conversion forestry when compared with the *LCP Pasture* scenario.

## 5.2 Price and Production Impacts

Tables 5.2 and 5.3 summarize the scenario results in terms of prices and quantities in absolute terms whereas figures 5.5 and 5.6 present the scenario differences in relative terms compared to the baseline[1]. The scenarios are simulated 100 times and the results reported are the average across those runs. Although the scenario *Low Carbon Price (LCP)* is the most restrictive by ignoring pasture, the results (with the exception of oats, rice, and wheat) are lower than in the previous analysis by USDA (2009) and Alig et al. (2010) which both

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[1] Figures 5.5 and 5.6 do not include the sensitivity analysis because the results are almost identical to the *Low Carbon Price with Pasture* scenario.

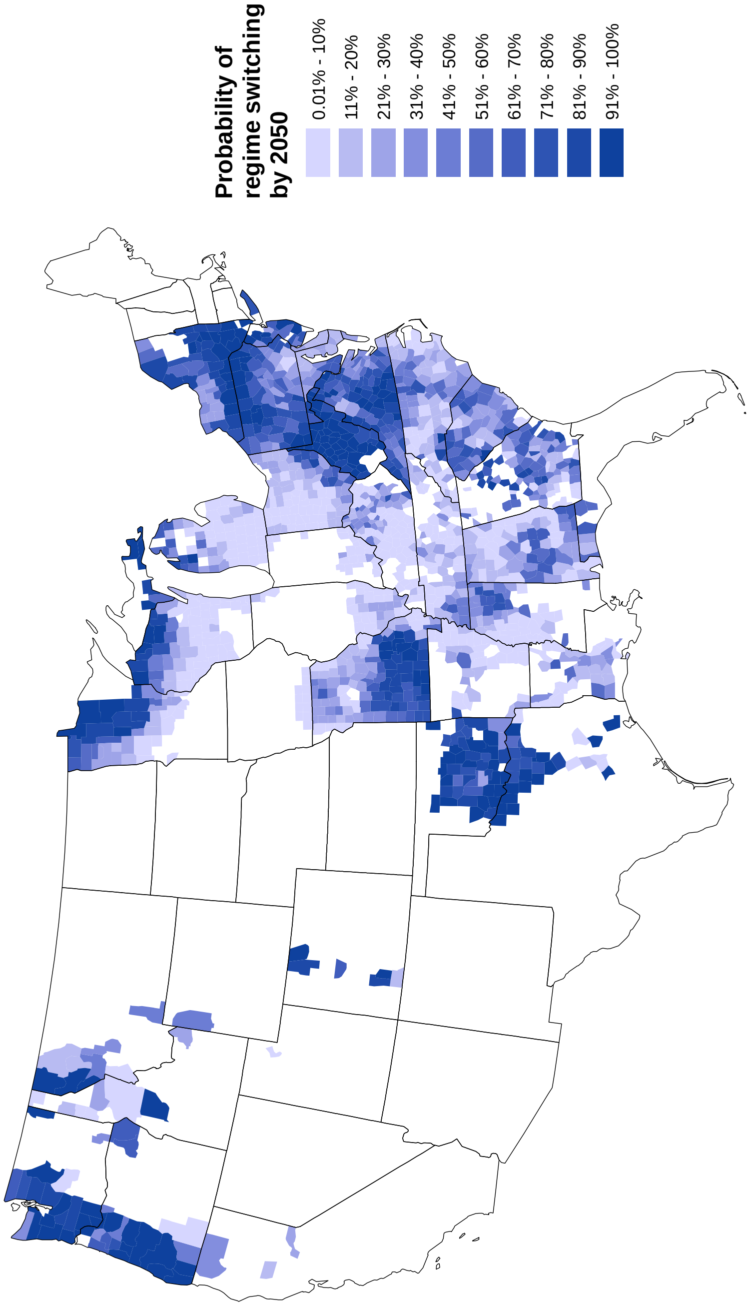


Figure 5.1 LCP: Probability of switching to forestry by 2050

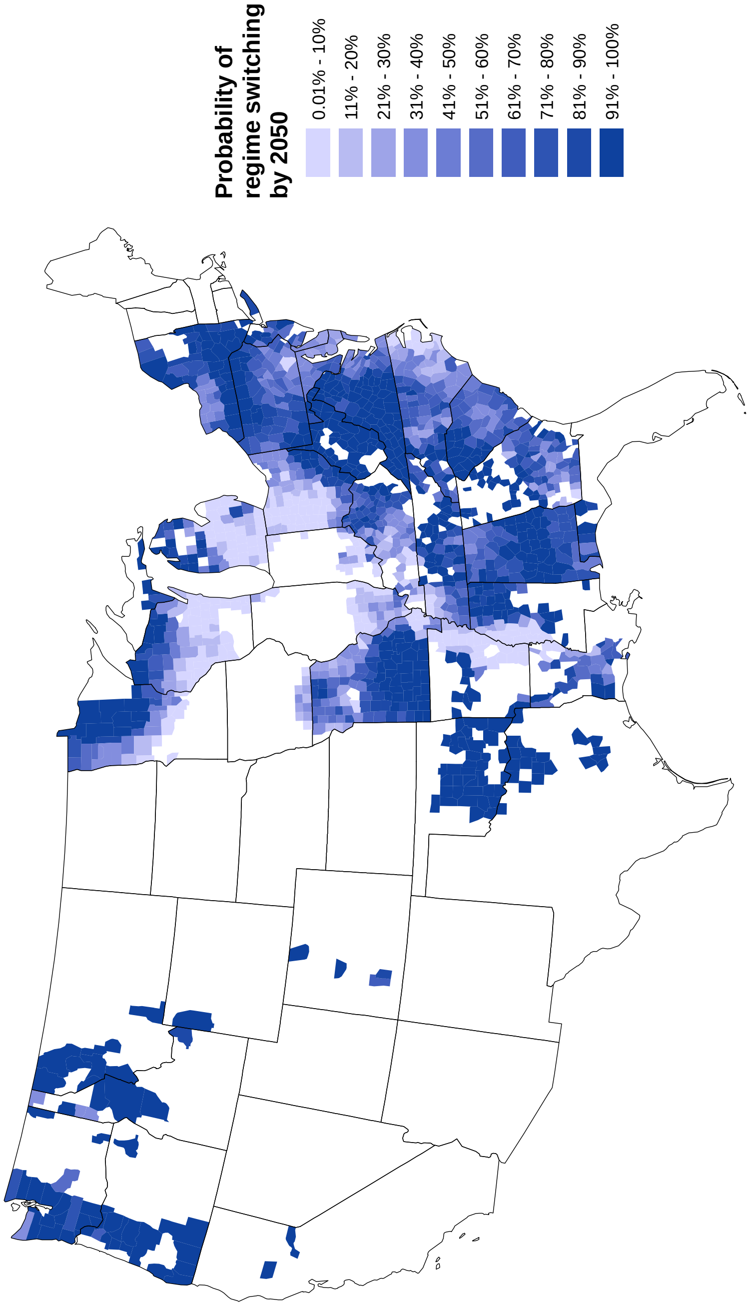


Figure 5.2 LCP Pasture: Probability of switching to forestry by 2050

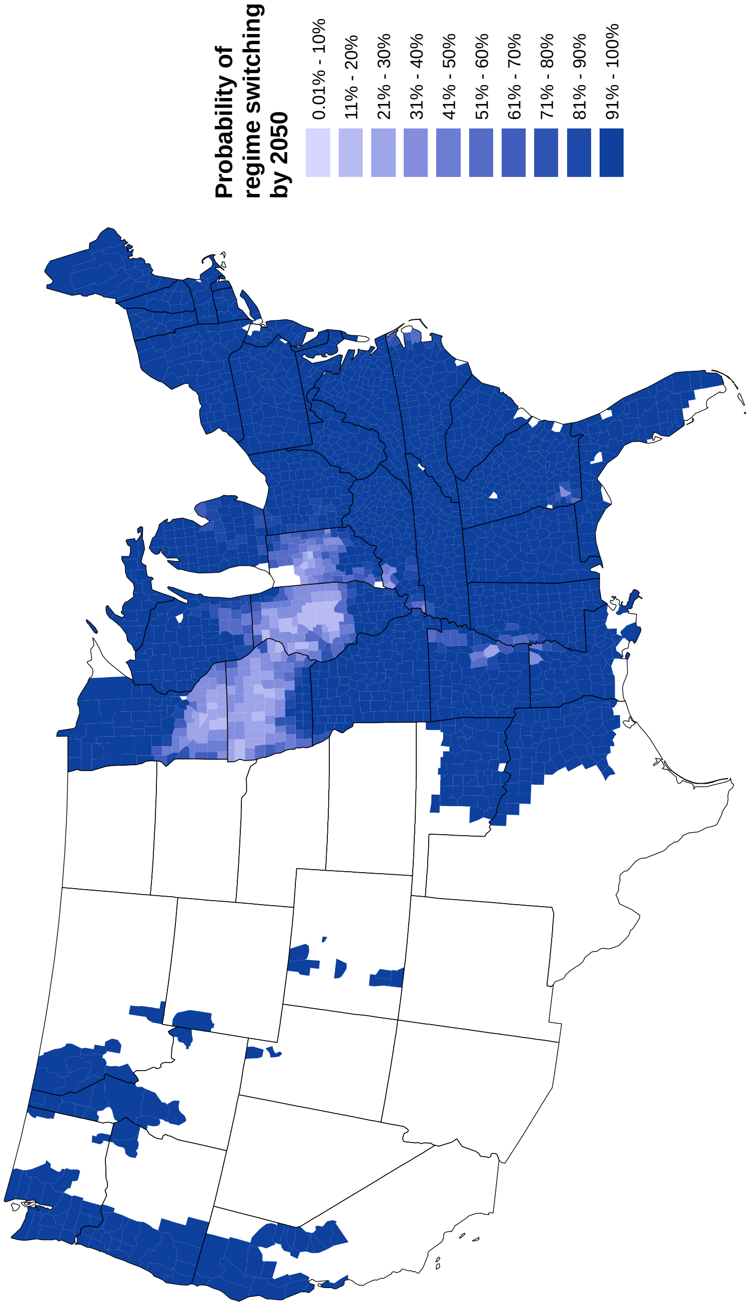


Figure 5.3 HCP Pasture: Probability of switching to forestry by 2050

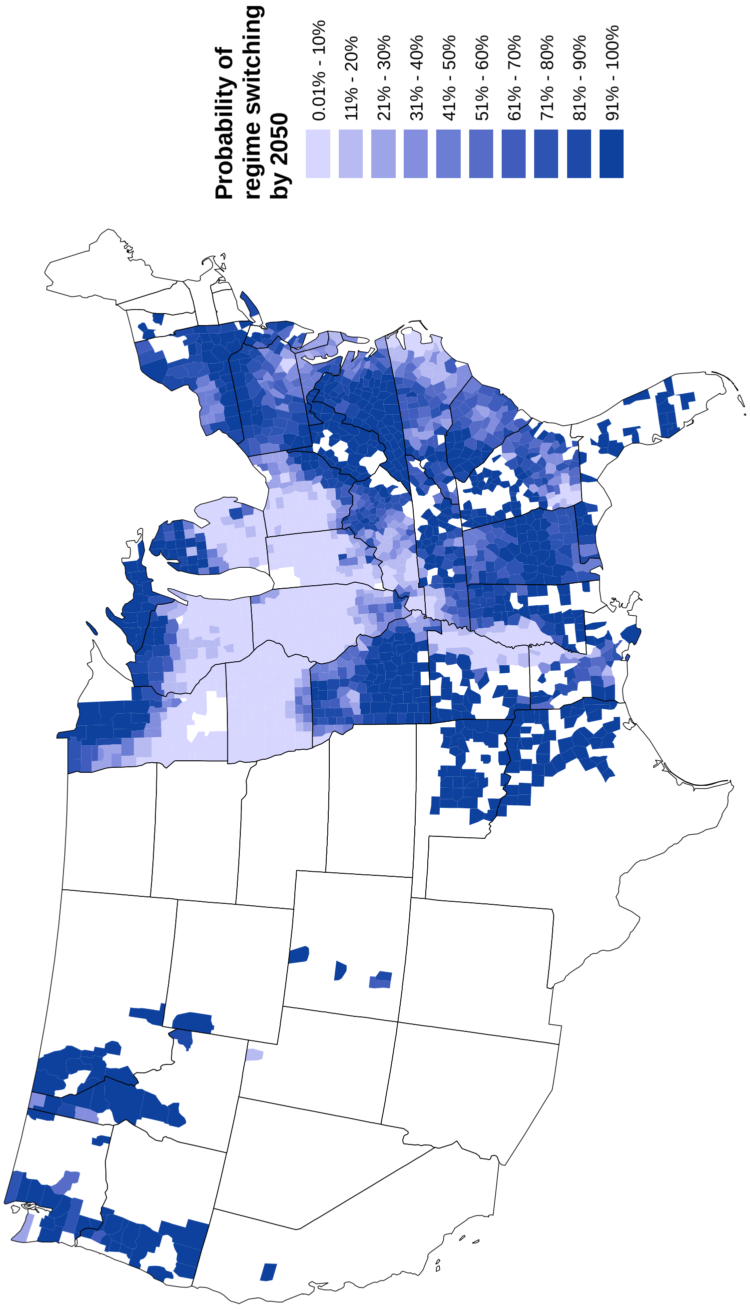


Figure 5.4 Sensitivity Analysis: Probability of switching to forestry by 2050

| | Baseline | LCP | LCP Pasture | HCP Pasture | SA |
|---|---:|---:|---:|---:|---:|
| Barley (million bu.) | 235 | 224 | 234 | 251 | 234 |
| Corn (million bu.) | 12,808 | 12,262 | 12,340 | 10,357 | 12.275 |
| Cotton (million lbs.) | 7,101 | 6,524 | 6,673 | 5,830 | 6,646 |
| Hay (million tons) | 146 | 130 | 132 | 120 | 131 |
| Oats (million bu.) | 196 | 176 | 186 | 197 | 185 |
| Rice (million cwt) | 226 | 222 | 219 | 187 | 218 |
| Soybeans (million bu.) | 3,151 | 2,931 | 2,959 | 2,204 | 2,930 |
| Sorghum (million bu.) | 262 | 202 | 252 | 322 | 252 |
| Wheat (million bu.) | 2,263 | 2,140 | 2,203 | 2,109 | 2,198 |

Table 5.3 Average scenario results: Absolute quantity impacts for the baseline (2011) and the scenarios (2050)

use the FASOM model. The option to delay afforestation and waiting 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. Replacing elm-ash-cottonwood tree planted in the Northern Plain States with high yielding oak-hickory trees in the *Sensitivity Analysis* scenario does not change the results significantly. The net revenue from agriculture in states like Illinois, Indiana, and Iowa is so high that even high yielding trees do not create an incentive to switch to forestry. As expected, the relative price impact in the *Sensitivity Analysis* scenario is strongest for corn and soybeans which are mostly grown in the region where the replacement takes place. Even in the absence of uncertainty, we believe that farmers would not switch immediately to forestry. This is similar to the finding by van 't Veld and Plantinga (2005) and is different when compared to table 2.1 which shows an effect on prices and quantity already before 2030. The waiting period for the scenario *Low Carbon Price* is visualized in figure 5.7 and analogous for quantities in figure 5.8 in which we see an increase (decrease) in prices (quantities) 25 years into the policy. In what follows, we will not report the detailed results for the sensitivity analysis because they almost coincide with the results from the scenario *LCP Pasture*.

The scenario *Low Carbon Price Pasture (LCP Pasture)* extends the previous scenario by including a significant amount of pasture in the analysis. Including pasture has two opposing effects on agricultural production. First, it reduces the net revenue from agricultural land at the county level because the net revenue from pasture is lower than from cropland as illustrated in figure 1.1. Hence counties with large amounts of pasture are more susceptible to switch which should lead to a sharper contraction in commodity supply. However, 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 counties can slightly increase their production (with a high impact because of the higher yield) into pasture when other counties pull out of crop production which leads to a lower effect on prices meaning that the second effect of crop expansion into pasture outweighs the effect of more counties switching. Pasture significantly reduces the price and quantity impact on crop production as seen in figures 5.5 and 5.6. This scenario is the most comparable with the FASOM/USDA analysis and represents a large deviation from their analysis. From a political and economic perspective, this finding is key in evaluating the impacts of a cap-and-trade policy on agriculture.

The third scenario simulates a very high carbon price with a mean of close to \$185 in 2050 and the resulting price and quantity impacts are important especially for corn and soybeans when compared with previous scenarios. The price impact for those two commodities has been moderate in the previous scenarios because the net revenues for corn and soybeans are high enough and almost no conversion takes place at a low $CO_2$ price. However, an increase of the carbon price to levels seen in the *HCP Pasture* scenario makes conversion in place profitable which did not switch in the previous scenarios. The increase in prices is fueled by the low availability of pasture in the Corn Belt and hence, the absent possibility to compensate the land lost to forests by an expansion of corn and soybeans area into pasture. The slight increase in the quantity of barley and oats in the *High Carbon Price with Pasture* scenario is likely due to the the feed demand elasticities of those crops with respect to the price of corn. Figure 5.9 shows the histograms for the scenario *LCP Pasture* in 2050.

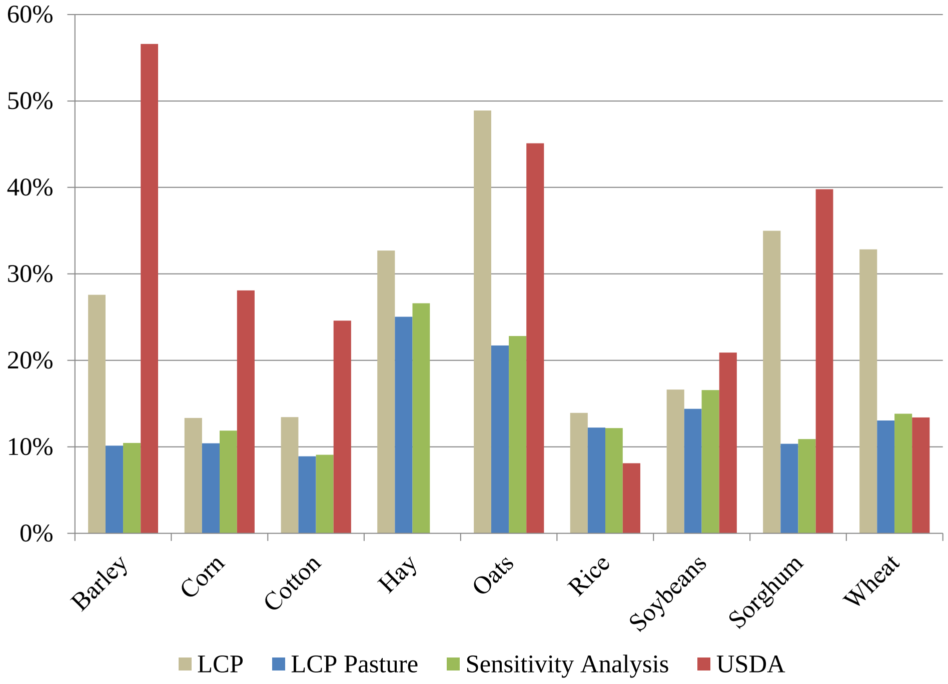


Figure 5.5 Scenario results: Relative price impacts by 2050

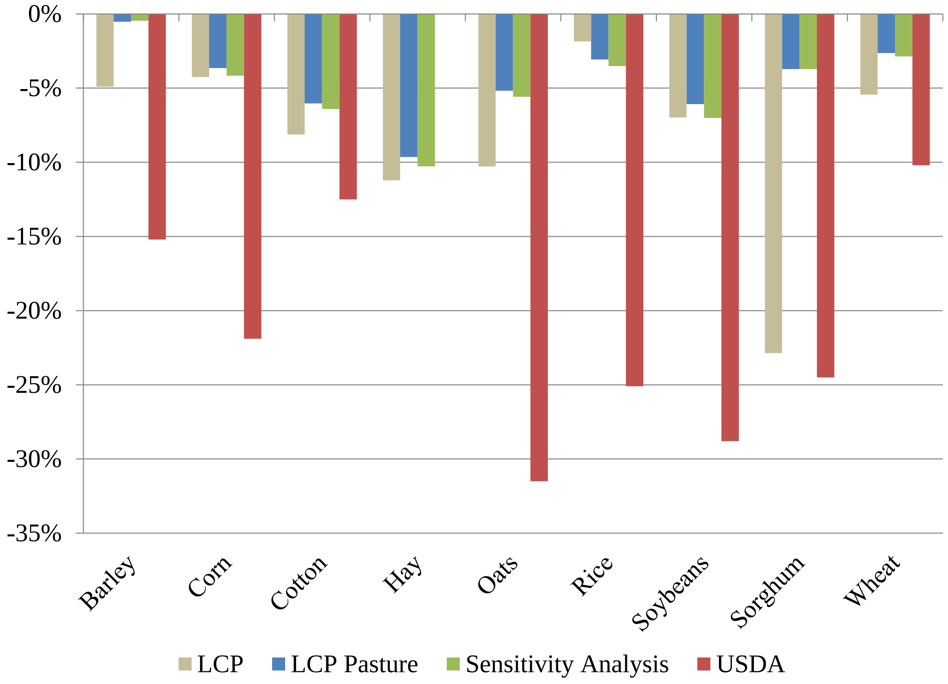


Figure 5.6 Scenario results: Relative quantity impacts by 2050

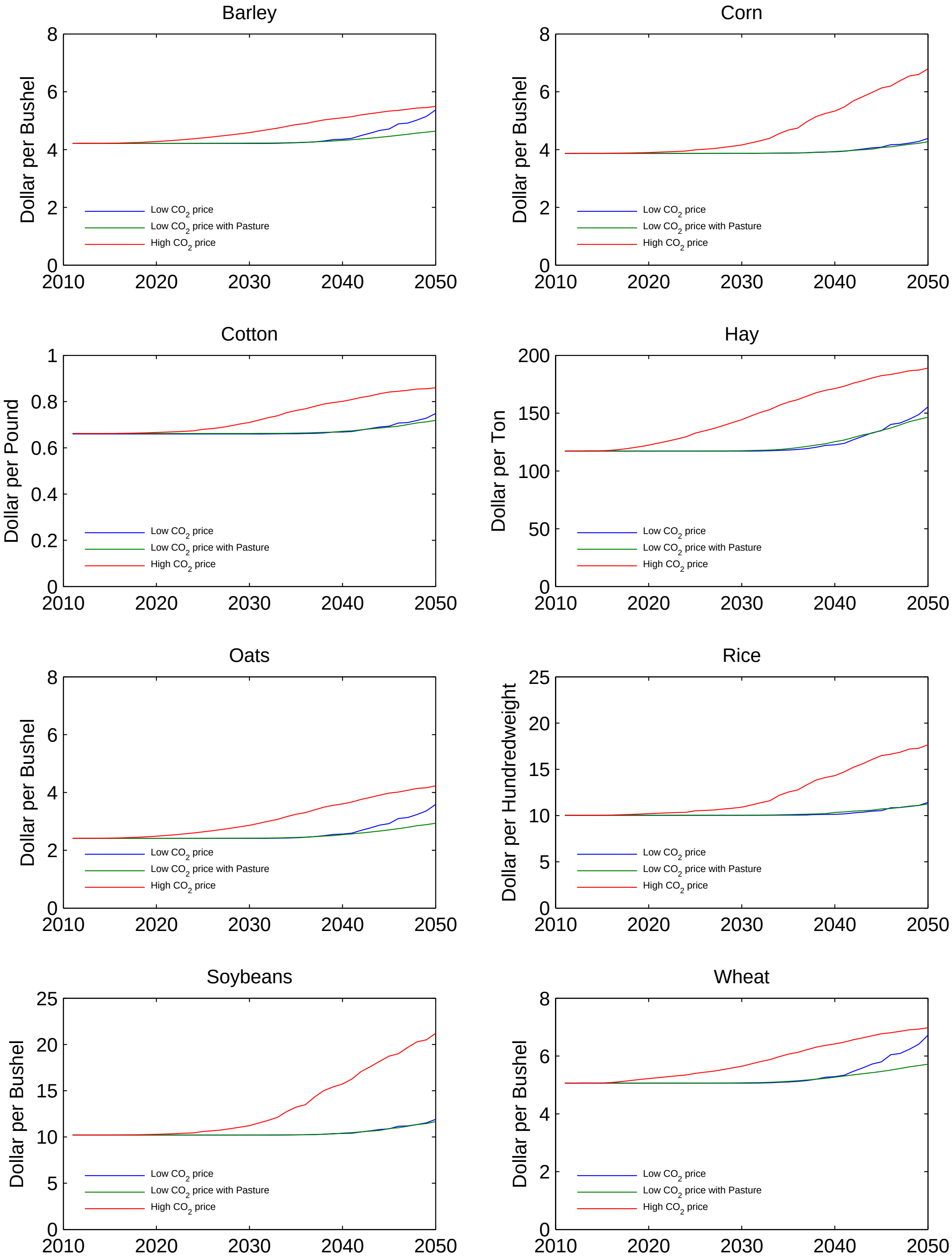


Figure 5.7 Price evolution

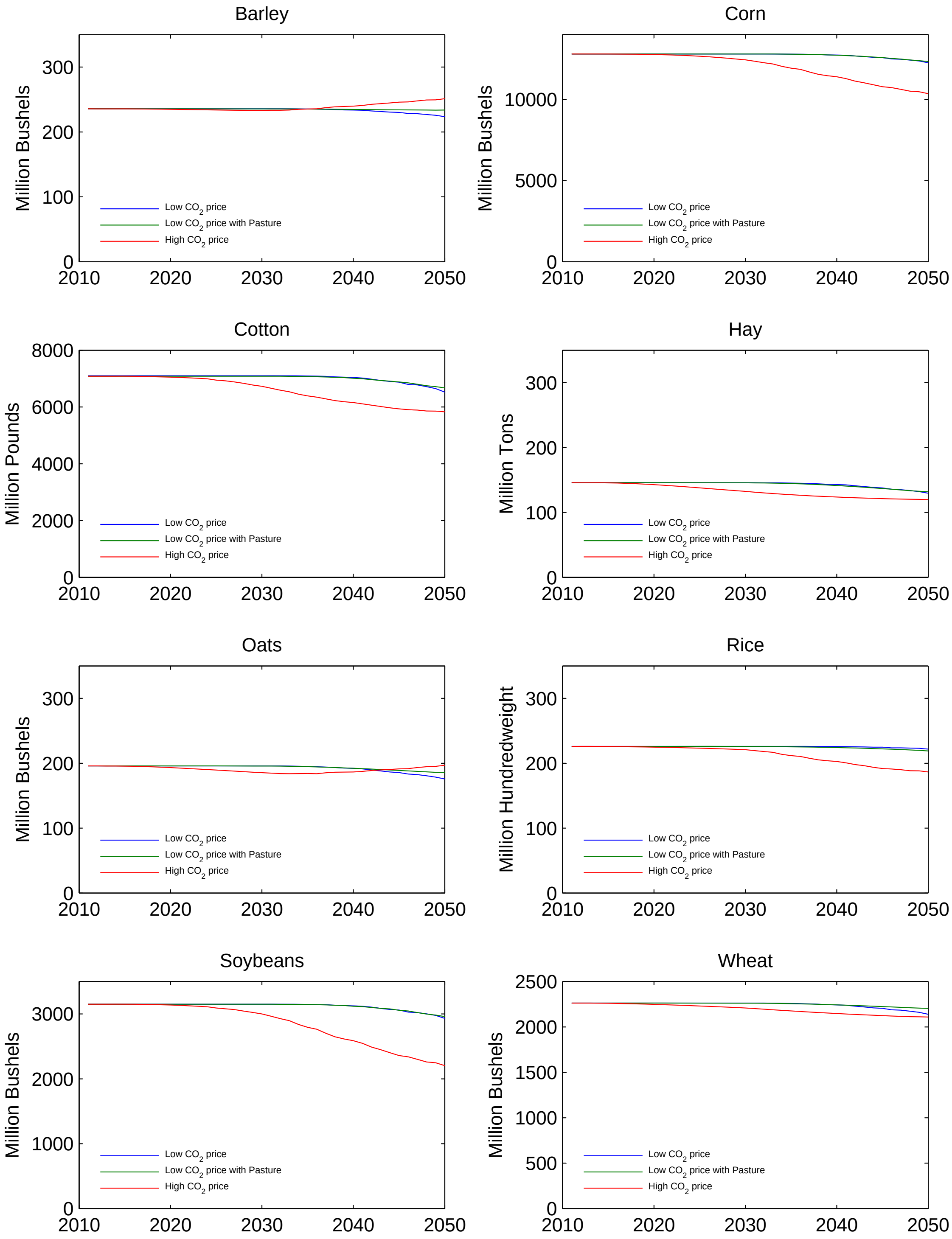


Figure 5.8 Quantity evolution

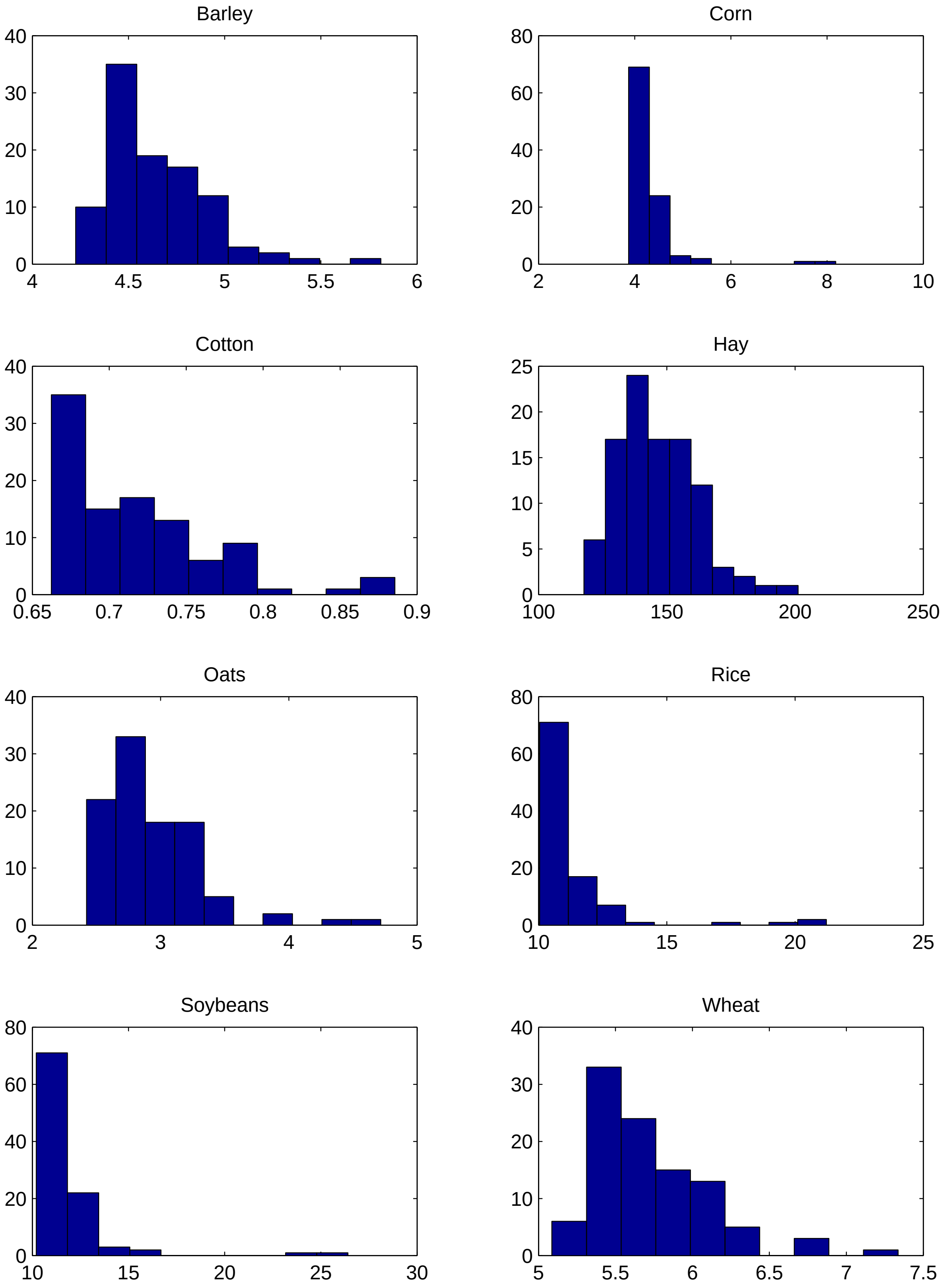


Figure 5.9 Histogram for prices by 2050 for the scenario LCP Pasture

## 5.3 Crop Area Impact

Figures 5.10-5.17 visualize the area impacts of the scenario *Low Carbon Price with Pasture* on crop area. The maps represent the average percentage change of crops between 2011 (baseline) and 2050. Three distinctive patterns can be identified in the maps. Counties in the west of the country where no afforestation is possible, crop area expands because landowners face higher output prices because of cropland contraction in the east of the country. Most counties in the east reduce their crop area because a switch to forestry occurs. This is consistent with figure 1.1 which shows that most counties in the Southeast and Northeast have low agricultural net revenue. The third important observation is the increase in corn and soybean area in the Corn Belt because of higher output prices and high net revenues which make afforestation in those area unattractive. Table 5.4 summarizes the area impacts in terms of cropland, pasture, and forests. In states where no afforestation is possible, cropland is expanded at the expense of pasture. Total cropland in the *Low Carbon Price* scenario is decreased by 27.10 million acres (which is equivalent to afforestation by the same amount). However, the big change compared to the previous analysis becomes obvious if we include pasture in the second scenario: cropland is only reduced by 19 million acres (net) but pasture is reduced by 78.71 million acres by 2050. This comes close to the afforestation activity of nearly 100 million acres in 2050. Although a large number, this is only 15% of current forest area. The important aspect is that almost 80% of the afforestation will take place on pastureland. The same can be observed in the case of the *HCP Pasture* scenario. Figure 5.5 shows the increase in forest area over time. The probabilities of counties switching to forests is illustrated in figure 5.2. Note that even in the high allowance price scenario, almost no conversion occurs in the Corn Belt. In general, afforestation activity in the U.S. would shift agricultural production more towards the west of the United States.

If we analyze the crops in more detail, we see that modeling at the county level rather than the more aggregate geographic regions is important because local differences can be observed. Figure 5.10 presents estimates from the model simulations assessing the impact of the Low Carbon Price with Pasture scenario (LCP Pasture) on barley planted acreage. Barley, which

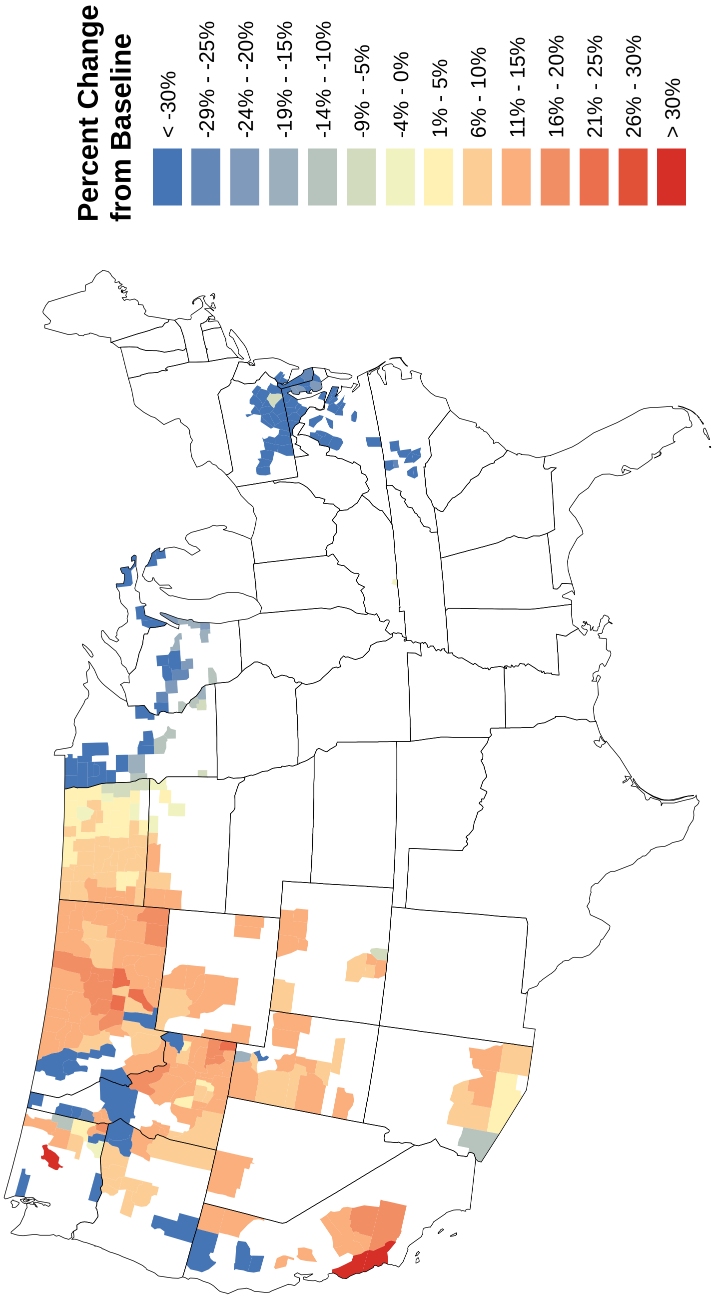


Figure 5.10 Barley: Change in the area planted compared to the base year for the scenario LCP Pasture

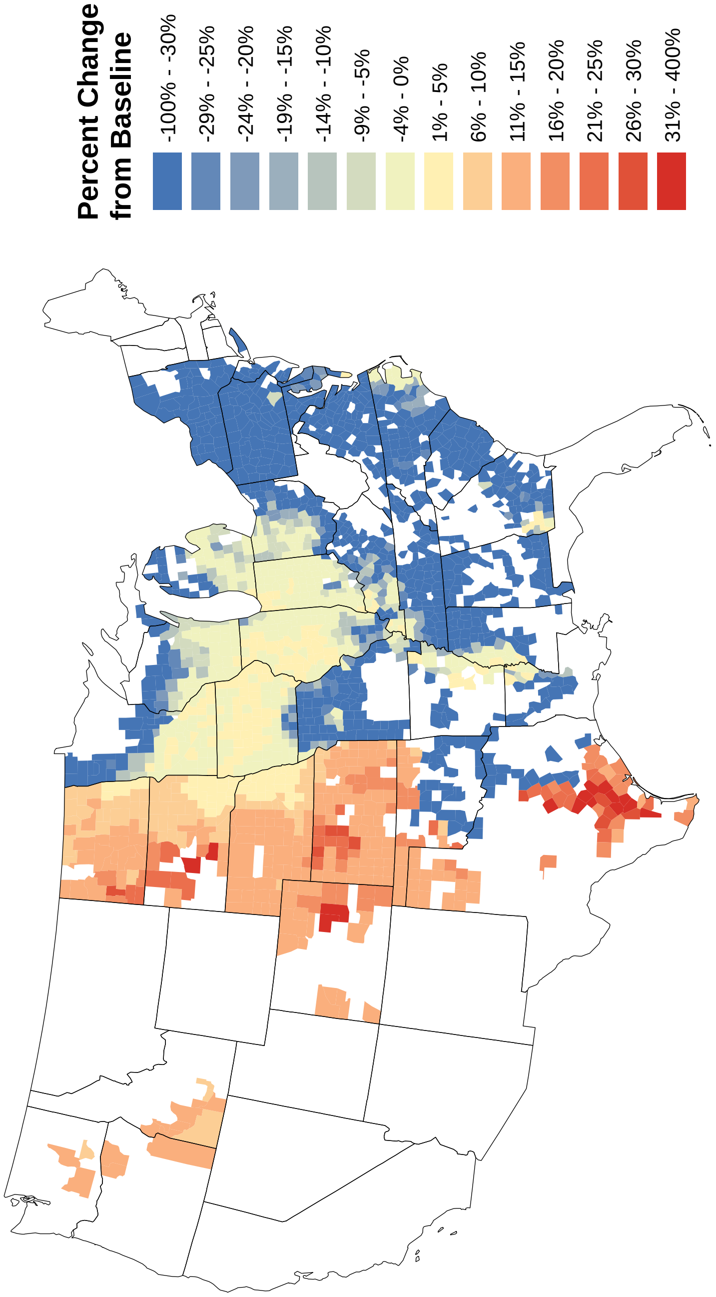


Figure 5.11 Corn: Change in the area planted compared to the base year for the scenario LCP Pasture

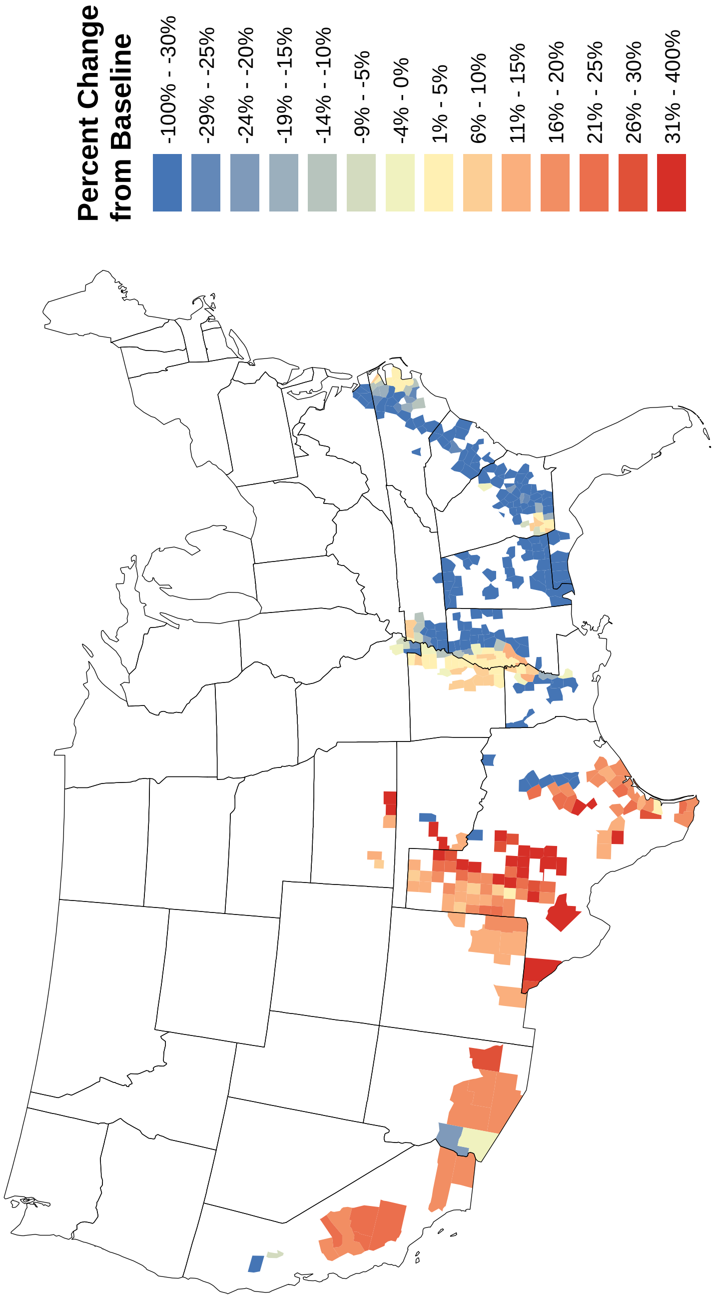


Figure 5.12 Cotton: Change in the area planted compared to the base year for the scenario LCP Pasture

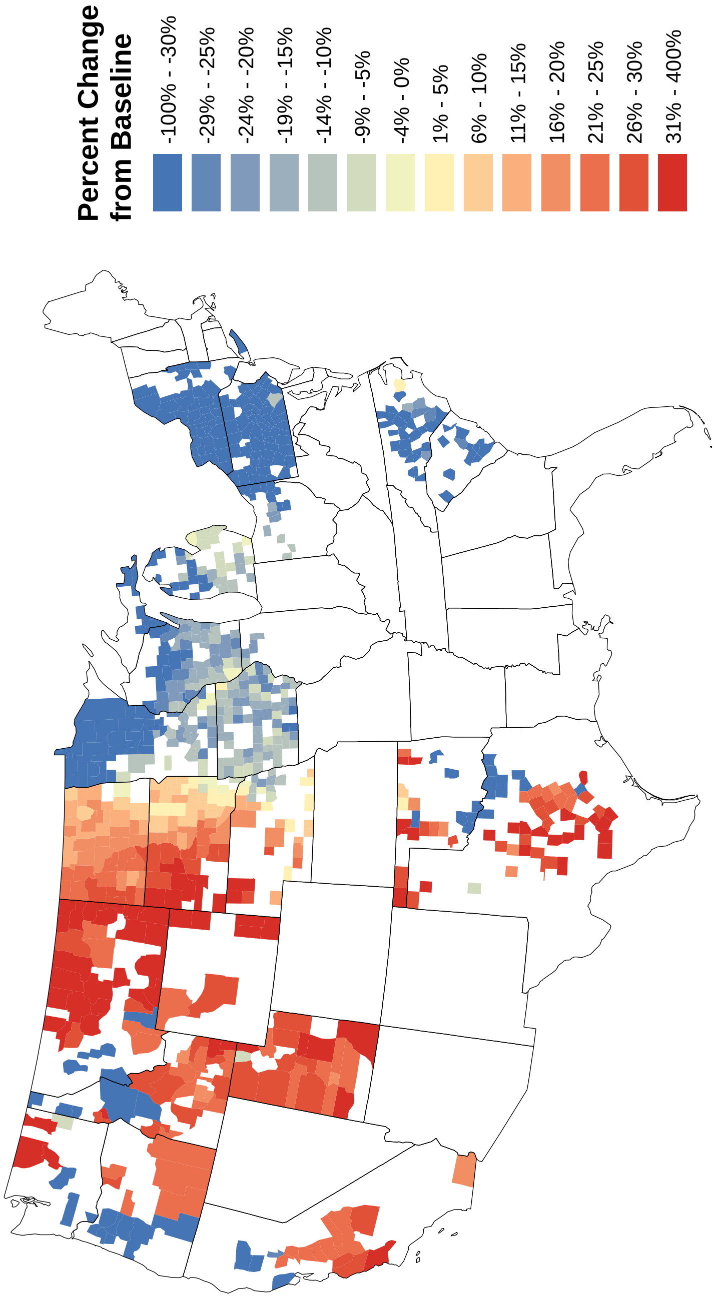


Figure 5.13 Oats: Change in the area planted compared to the base year for the scenario LCP Pasture

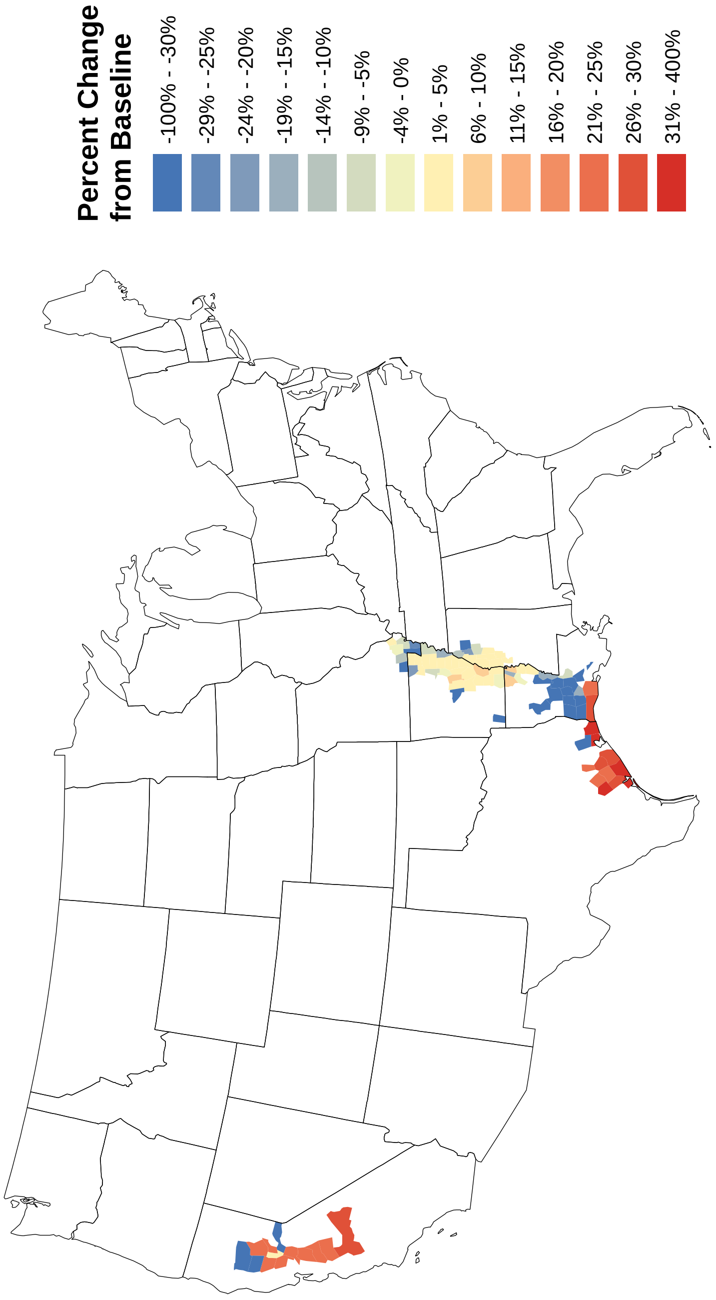


Figure 5.14 Rice: Change in the area planted compared to the base year for the scenario LCP Pasture

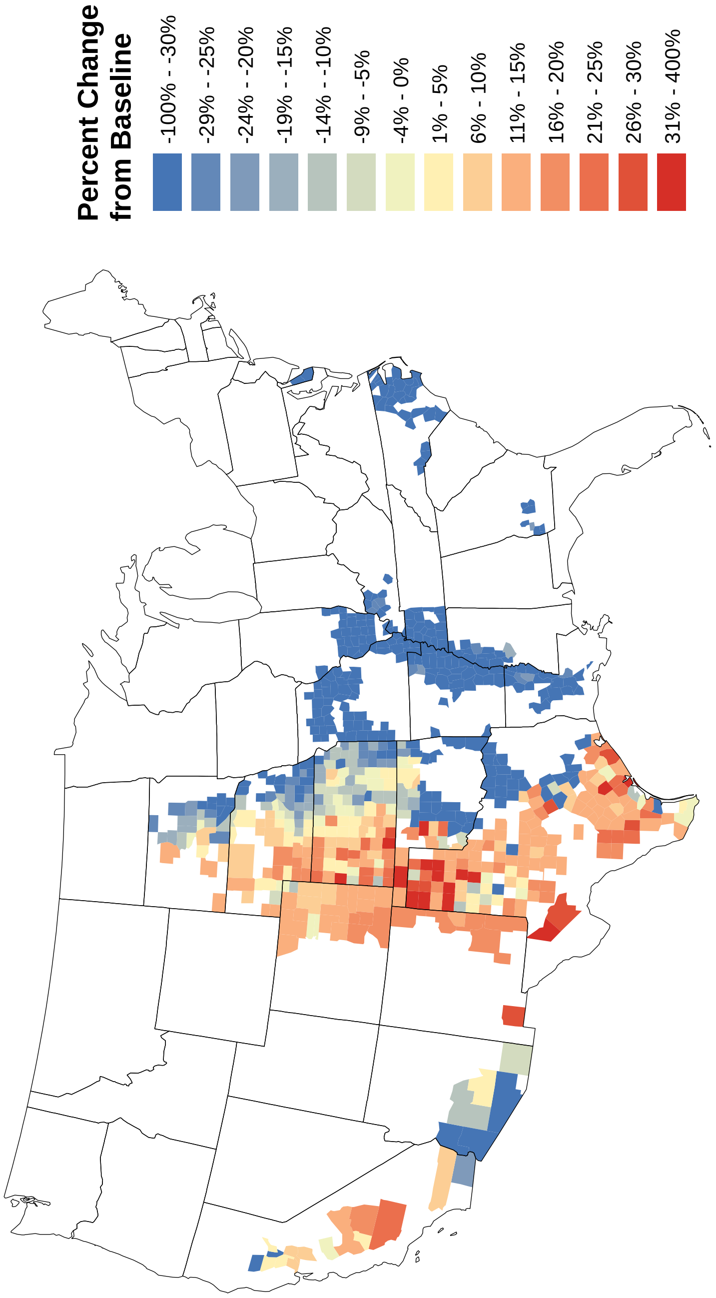


Figure 5.15 Sorghum: Change in the area planted compared to the base year for the scenario LCP Pasture

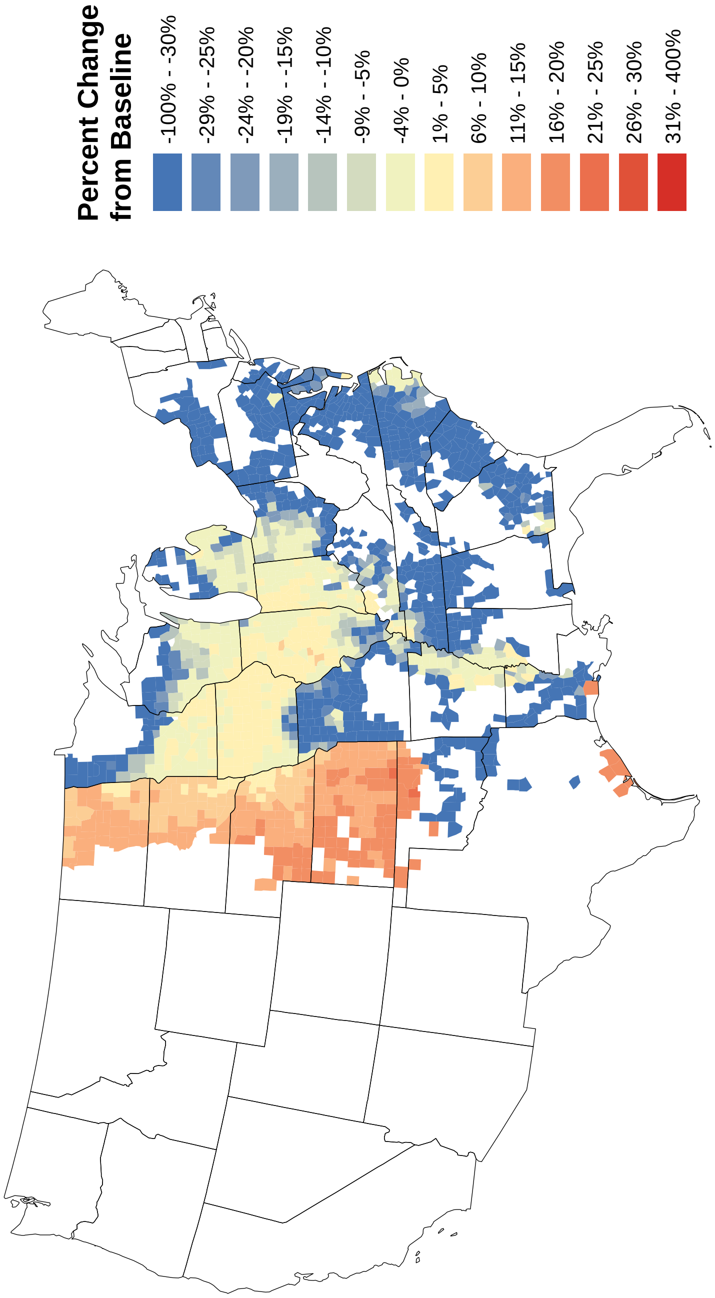


Figure 5.16 Soybeans: Change in the area planted compared to the base year for the scenario LCP Pasture

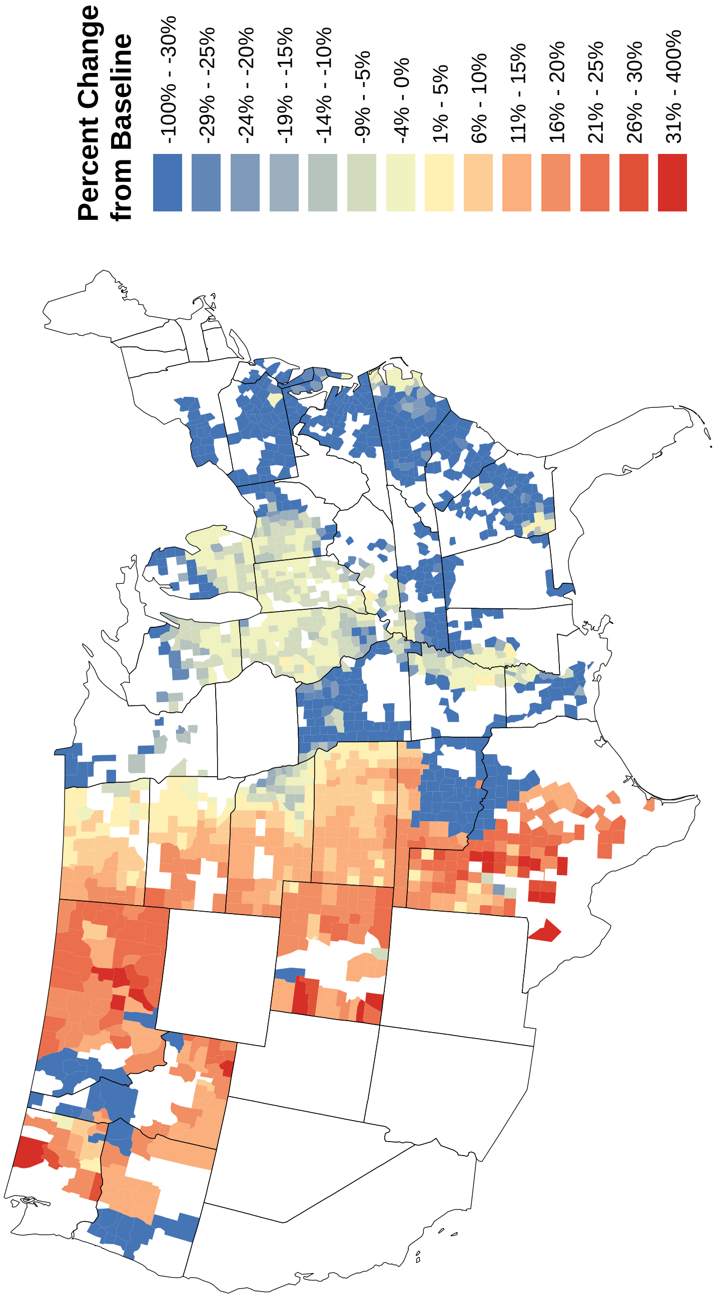


Figure 5.17 Wheat: Change in the area planted compared to the base year for the scenario LCP Pasture

is concentrated predominantly in the Northern Midwestern and Midwestern states in addition to some acreage in the Eastern Atlantic states, is predicted to experience significant declines in acreage in some areas (Eastern Atlantic, Wisconsin, Michigan, and a few counties in the West) while moderate gains in other regions, mostly in the West. However, the locations of these increases and decreases are not compactly concentrated in a specific geographic region of the country. Areas of decline over 30% from the baseline acreage include the Eastern Atlantic states including Pennsylvania, Virginia, and South Carolina as well as Minnesota, Michigan, and pockets in Western States. In contrast, areas in the Dakotas, Montana, Idaho and other Western states are predicted to increase their acreage between 1 and 20%.

In contrast to the simulations presented for barley, the predicted impact for corn and soybeans which are planted in rotation in the Corn Belt is more consistent in terms of geographic regions. Simulated results presented in figures 5.11 and 5.16 indicate that Eastern and Mid-Atlantic states stretching from New York to Georgia are predicted to have significant declines in corn and soybean acreage. The increase of corn area in eastern Nebraska and South Dakota is hindered by the lack of pasture for cropland expansion.

The results for cotton and rice are similar. The cotton region stretching from the Carolinas to Alabama drops out of production to go into forestry. The cotton as well as the rice areas in the Mississippi Valley see a slight increase in area below 10%. Rice area at the Gulf Coast, which is not included for afforestation sees an increase in rice area. For the Western part of the country, rice and cotton increase because farmers see higher prices from afforestation activity in the east.

Wheat is grown in parts of the country where we do not allow for afforestation. So the pattern is consistent with what was described before. Expansion of wheat area is observed in the West. We identify four distinct areas of afforestation. The first area comes as know surprise and is located in eastern United States. However, we also see afforestation activity in northern Missouri, at the border of Oklahoma to Missouri, and in some patches in Idaho and western Montana.

| | Baseline 2011 | | LCP 2050 | | LCP Pasture 2050 | | | LCP Pasture 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Crop | Pasture | Crop | Forest | Crop | Forest | Pasture | Crop | Forest | Pasture |
| Alabama | 2.01 | 2.02 | 1.5 | 0.5 | 0.7 | 2.9 | 0.39 | 0.00 | 4.02 | 0.00 |
| Arizona | 0.56 | 12.93 | 0.6 | 0.0 | 0.7 | 0.0 | 12.85 | 0.82 | 0.00 | 12.67 |
| Arkansas | 7.22 | 2.63 | 6.9 | 0.4 | 6.6 | 3.1 | 0.15 | 1.95 | 8.09 | 0.05 |
| California | 1.13 | 12.68 | 1.1 | 0.0 | 1.2 | 3.5 | 9.14 | 1.95 | 3.49 | 8.37 |
| Colorado | 5.99 | 17.56 | 5.9 | 0.1 | 7.1 | 0.8 | 15.66 | 10.02 | 0.79 | 12.75 |
| Delaware | 0.46 | 0.01 | 0.4 | 0.1 | 0.3 | 0.1 | 0.00 | 0.00 | 0.46 | 0.00 |
| Florida | 0.07 | 3.17 | 0.0 | 0.0 | 0.0 | 3.2 | 0.07 | 0.00 | 3.20 | 0.04 |
| Georgia | 1.97 | 1.34 | 1.4 | 0.6 | 1.1 | 2.0 | 0.21 | 0.12 | 3.18 | 0.00 |
| Idaho | 2.09 | 4.60 | 2.1 | 0.0 | 2.1 | 0.9 | 3.76 | 2.56 | 1.05 | 3.09 |
| Illinois | 24.25 | 0.89 | 23.8 | 0.4 | 23.8 | 1.0 | 0.42 | 13.55 | 12.46 | 0.08 |
| Indiana | 13.10 | 0.54 | 13.1 | 0.0 | 13.0 | 0.4 | 0.28 | 7.19 | 6.76 | 0.31 |
| Iowa | 25.86 | 1.91 | 25.8 | 0.0 | 26.0 | 0.7 | 1.15 | 17.18 | 11.71 | 0.11 |
| Kansas | 23.96 | 15.93 | 24.0 | 0.0 | 27.0 | 0.0 | 12.85 | 37.56 | 0.00 | 2.33 |
| Kentucky | 6.46 | 2.91 | 6.0 | 0.5 | 4.9 | 3.3 | 1.12 | 1.05 | 8.38 | 0.05 |
| Louisiana | 2.50 | 1.53 | 2.3 | 0.2 | 1.9 | 1.6 | 0.50 | 0.57 | 3.38 | 0.08 |
| Maryland | 1.53 | 0.16 | 1.2 | 0.4 | 1.0 | 0.6 | 0.06 | 0.02 | 1.67 | 0.00 |
| Michigan | 5.24 | 0.38 | 5.0 | 0.3 | 4.9 | 0.6 | 0.15 | 0.70 | 4.95 | 0.03 |
| Minnesota | 18.90 | 1.47 | 17.2 | 1.8 | 16.8 | 3.0 | 0.51 | 9.15 | 11.94 | 0.73 |
| Mississippi | 3.82 | 1.64 | 3.4 | 0.5 | 3.0 | 2.3 | 0.18 | 0.63 | 4.88 | 0.05 |
| Missouri | 16.06 | 6.86 | 11.3 | 4.8 | 8.7 | 12.7 | 1.53 | 0.41 | 22.51 | 0.01 |
| Montana | 9.65 | 40.00 | 9.5 | 0.1 | 11.9 | 2.3 | 35.41 | 16.34 | 2.39 | 30.93 |
| Nebraska | 19.50 | 22.62 | 19.5 | 0.0 | 21.9 | 0.0 | 20.22 | 31.65 | 0.00 | 10.47 |
| Nevada | 0.13 | 4.28 | 0.1 | 0.0 | 0.2 | 0.0 | 4.25 | 0.21 | 0.00 | 4.20 |
| New Jersey | 0.36 | 0.05 | 0.1 | 0.2 | 0.1 | 0.3 | 0.01 | 0.00 | 0.41 | 0.00 |
| New Mexico | 0.58 | 31.88 | 0.6 | 0.0 | 0.7 | 0.0 | 31.73 | 0.99 | 0.00 | 31.47 |
| New York | 3.27 | 0.71 | 1.3 | 2.1 | 1.0 | 2.9 | 0.10 | 0.01 | 3.97 | 0.00 |
| North Carolina | 4.67 | 0.94 | 3.7 | 1.0 | 3.2 | 2.1 | 0.33 | 0.23 | 5.39 | 0.00 |
| North Dakota | 19.40 | 10.42 | 19.4 | 0.0 | 21.9 | 0.0 | 7.94 | 28.50 | 0.00 | 1.32 |
| Ohio | 11.17 | 1.05 | 10.1 | 1.1 | 9.5 | 2.4 | 0.30 | 0.68 | 11.54 | 0.01 |
| Oklahoma | 10.66 | 18.71 | 6.5 | 4.3 | 6.5 | 14.2 | 8.62 | 8.55 | 14.40 | 6.42 |
| Oregon | 2.37 | 9.15 | 2.0 | 0.4 | 2.1 | 2.3 | 7.14 | 2.70 | 2.32 | 6.51 |
| Pennsylvania | 4.63 | 0.73 | 2.3 | 2.4 | 2.0 | 3.2 | 0.16 | 0.03 | 5.33 | 0.00 |
| South Carolina | 1.69 | 0.62 | 0.9 | 0.8 | 0.7 | 1.5 | 0.10 | 0.01 | 2.30 | 0.00 |
| South Dakota | 17.14 | 23.03 | 17.1 | 0.0 | 20.1 | 0.0 | 20.08 | 28.51 | 0.00 | 11.66 |
| Tennessee | 3.65 | 2.54 | 3.0 | 0.6 | 2.2 | 3.6 | 0.46 | 0.14 | 6.05 | 0.00 |
| Texas | 15.39 | 81.96 | 14.6 | 1.0 | 16.3 | 11.5 | 69.50 | 24.36 | 11.63 | 61.36 |
| Utah | 1.01 | 8.38 | 1.0 | 0.0 | 1.3 | 0.3 | 7.81 | 1.56 | 0.46 | 7.36 |
| Vermont | 0.00 | 0.14 | 0.0 | 0.0 | 0.0 | 0.1 | 0.00 | 0.00 | 0.14 | 0.00 |
| Virginia | 3.15 | 2.15 | 1.4 | 1.8 | 0.8 | 4.4 | 0.16 | 0.08 | 5.23 | 0.00 |
| Washington | 3.59 | 4.57 | 3.4 | 0.2 | 3.8 | 0.6 | 3.71 | 4.74 | 0.76 | 2.66 |
| West Virginia | 0.81 | 1.11 | 0.1 | 0.7 | 0.0 | 1.9 | 0.02 | 0.00 | 1.91 | 0.00 |
| Wisconsin | 8.78 | 1.06 | 8.2 | 0.5 | 8.2 | 1.1 | 0.55 | 1.45 | 8.42 | 0.03 |
| Wyoming | 1.54 | 27.01 | 1.5 | 0.0 | 2.3 | 0.0 | 26.20 | 3.44 | 0.05 | 25.07 |
| United States | 306.34 | 384.46 | 279.23 | 28.06 | 287.33 | 97.71 | 305.75 | 259.62 | 195.78 | 235.40 |

Table 5.4 Crop Area Impacts in Million Acres

## 5.4 Net Revenue Impacts

An important consideration for including the possibility of forest offset credits in the legislation is to improve the welfare of landowners or farmers. Figures 5.18 and 5.19 summarizes the impacts on net revenue by state. It can be seen that all states involved in agriculture can increase their net revenue due to forest offset credits. However, there is a difference in who profits the most from the carbon credits. This difference is pictured in figure 5.20 which represents the switching probability on the vertical axis and the net revenue increase on the horizontal axis. Each dot represents represents a county's average switching probability and net revenue increase over the 100 simulation runs. 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 to low carbon sequestration rates for trees. For example, the Northeast has a low agricultural productivity but the the carbon sequestration rate of 3.41 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. To illustrate the result further, we graphed the net revenue of two states, Iowa and South Carolina, in figure 5.21. Both states serve as a representation of states that mostly stay in agriculture (Iowa) or mostly switch to forestry (South Carolina) in our simulations. Note that the state with afforestation credits increases its net revenue at a higher rate than the agricultural state.

## 5.5 Forestry and Carbon Sequestration Impact

Previous analysis showed a significant impact of forestry offsets on carbon sequestration with up to 344 Mt $CO_2$-equivalent sequestered. The amount of carbon sequestered in our analysis is depicted in panel (b) of figure 5.5. In our analysis, the carbon sequestration in the scenario of interest (*LCP Pasture*) is just under 300 Mt of $CO_2$-equivalent for significant more acreage in forest. There are several important differences compared to the previous analysis.

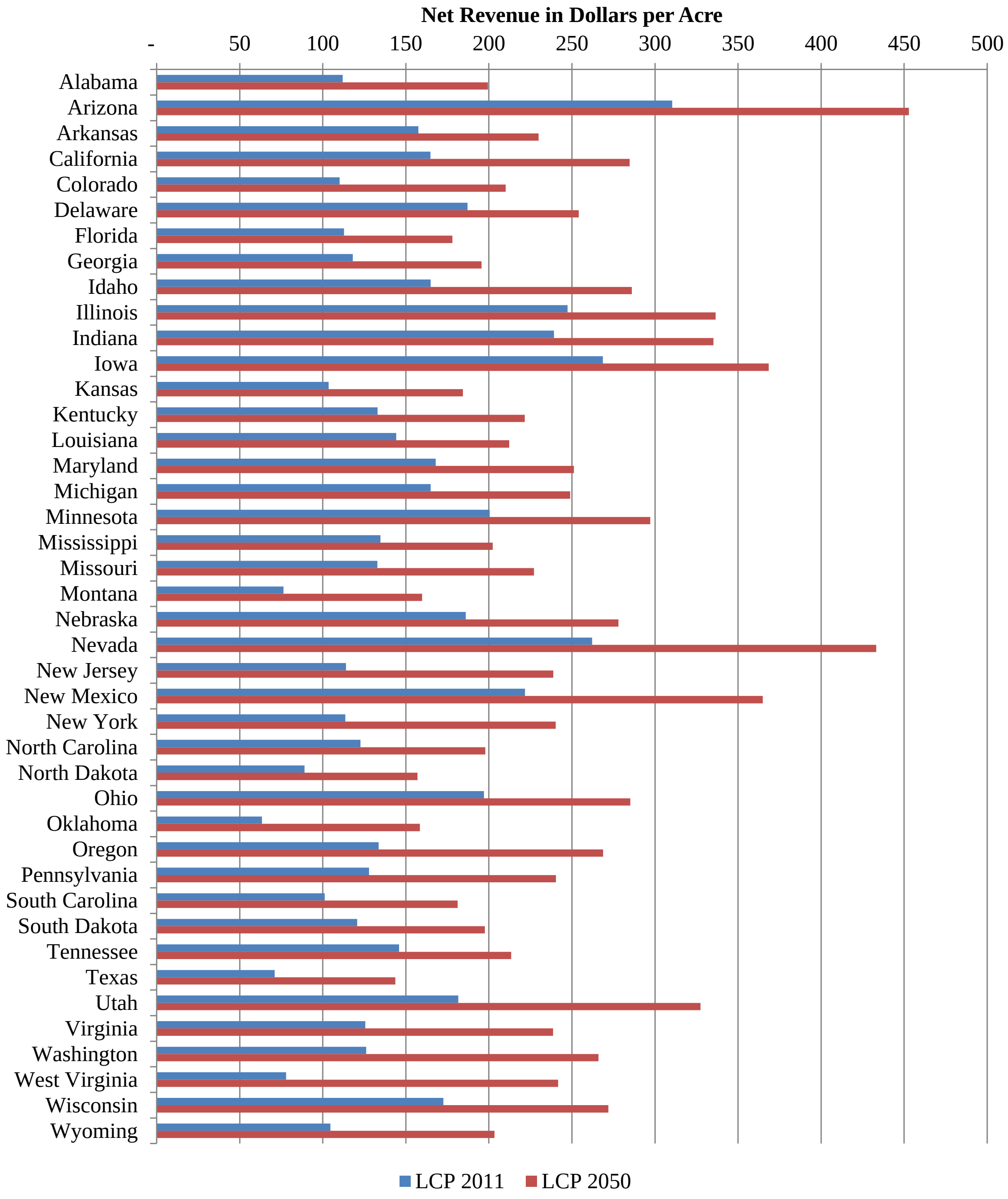


Figure 5.18 Net Revenue Impact for LCP Scenario

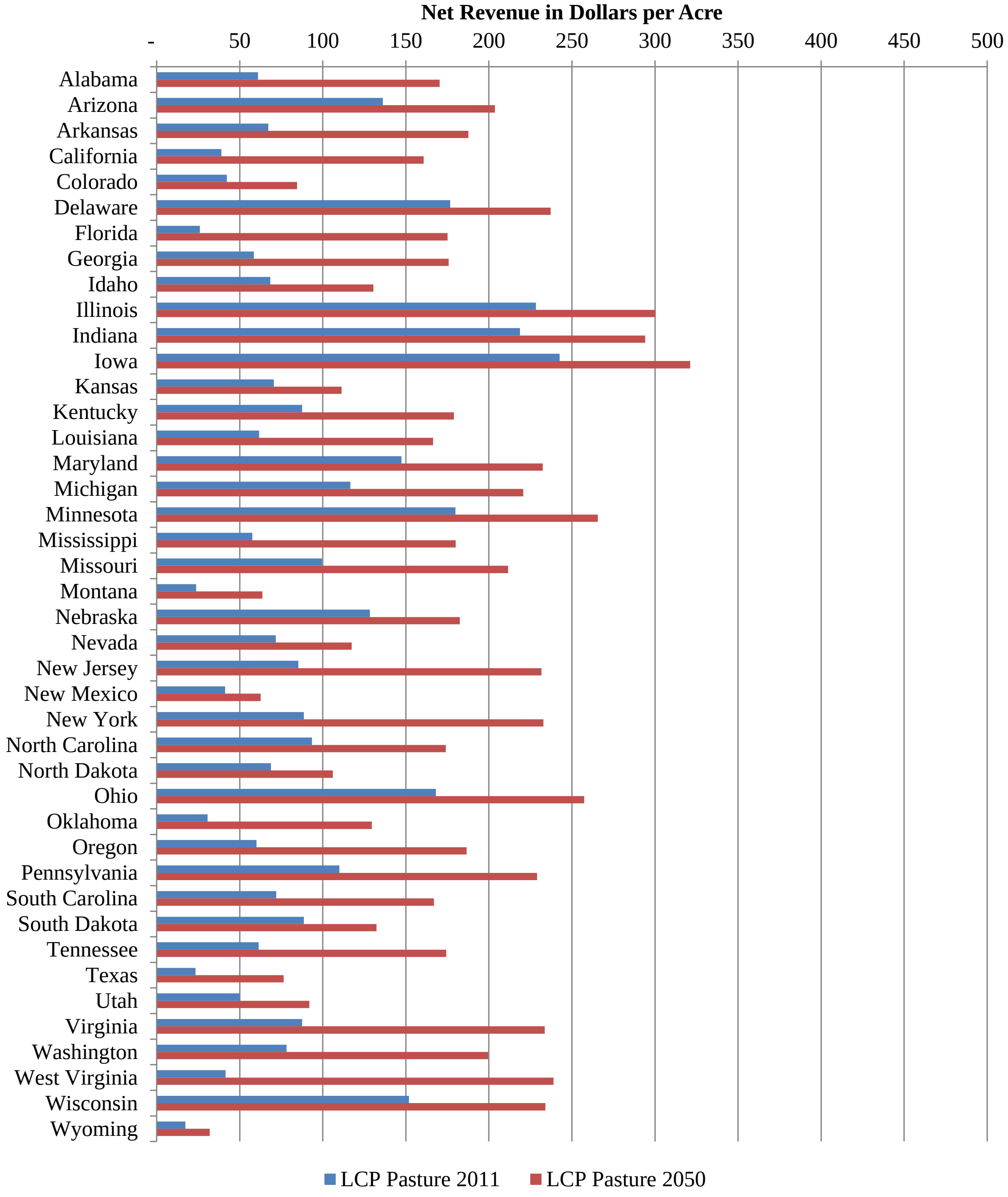


Figure 5.19 Net Revenue Impact for LCP Pasture Scenario

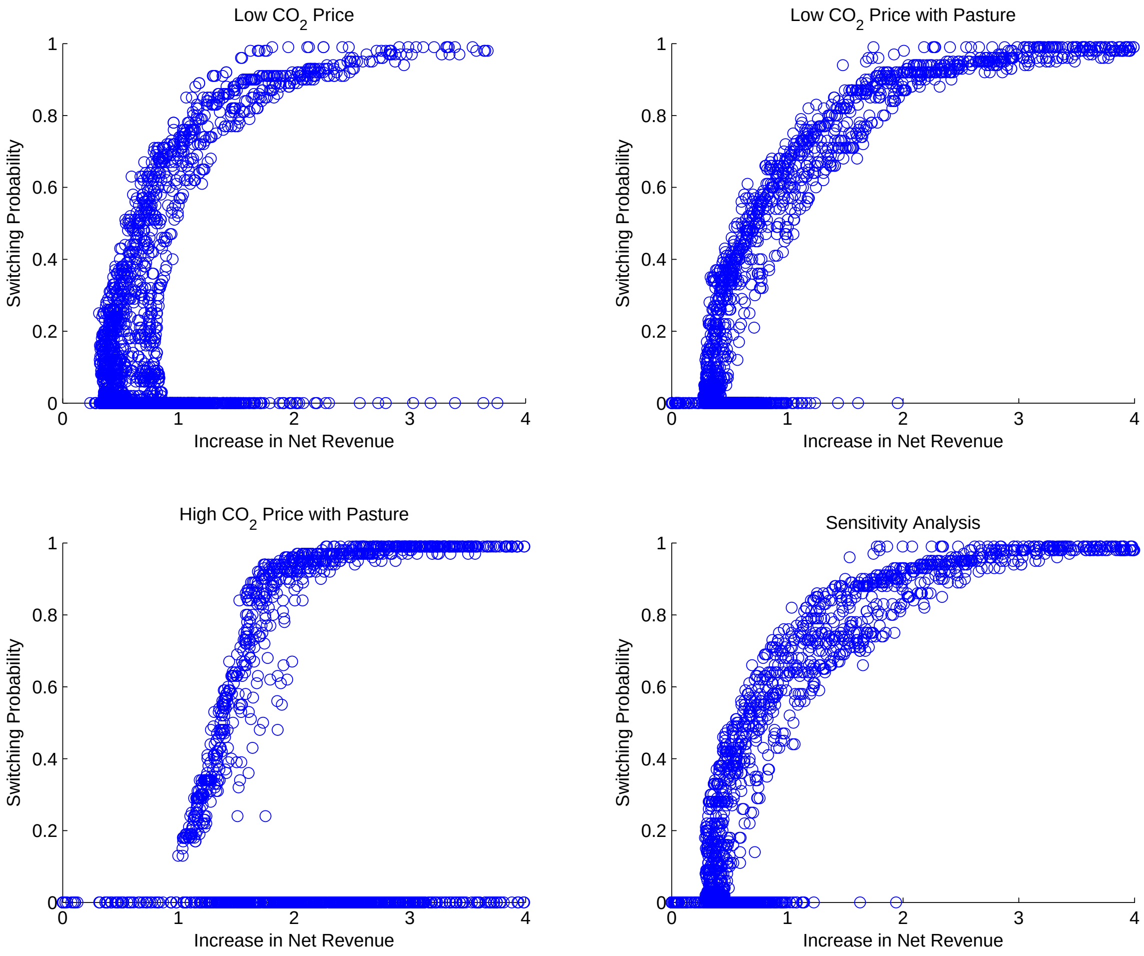


Figure 5.20 Correlation of net revenue increase and switching probability

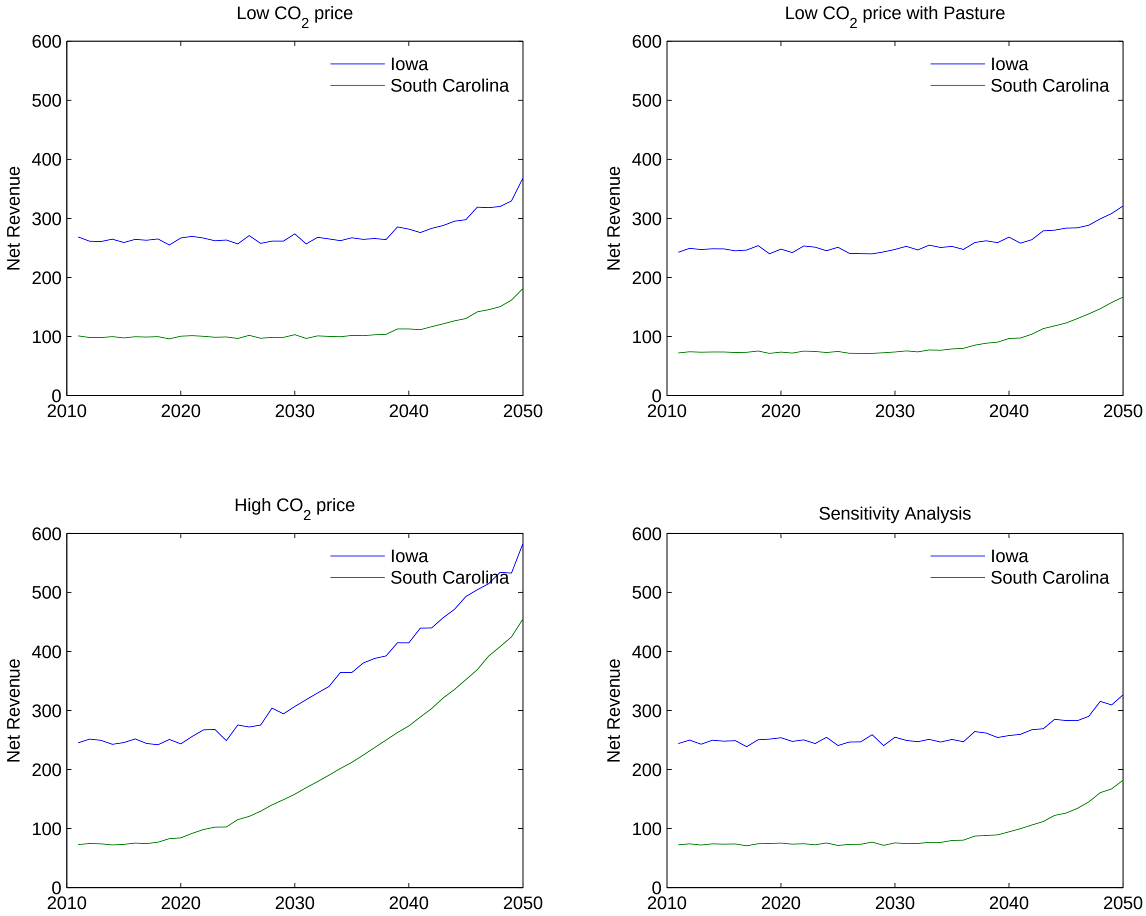
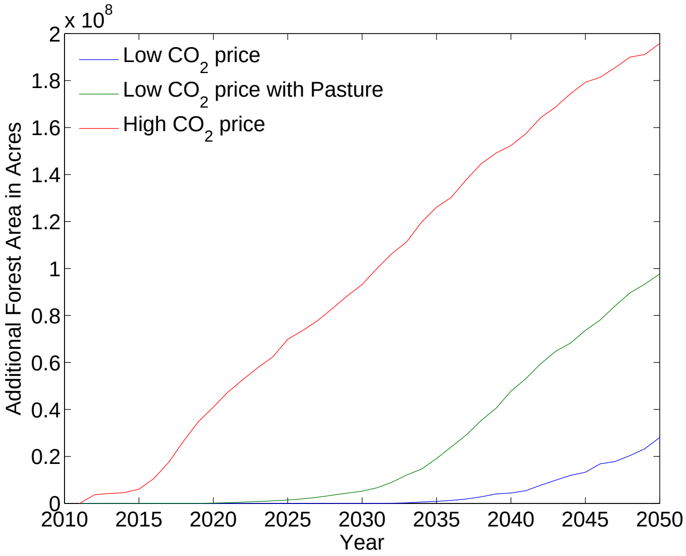
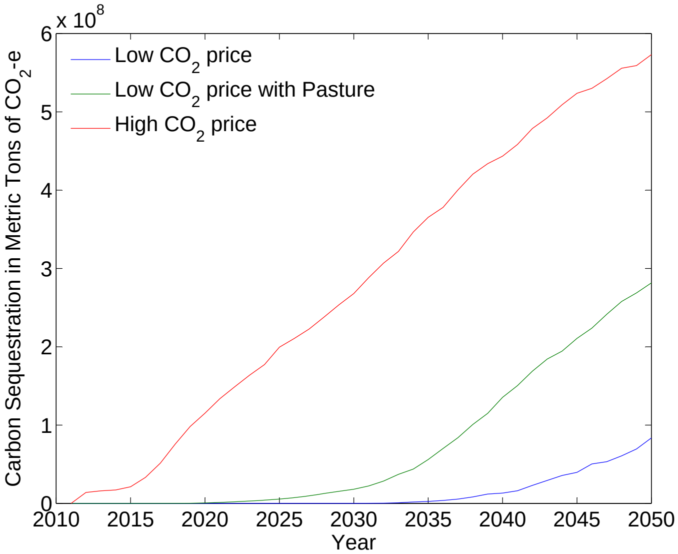


Figure 5.21 Net revenue increase



(a) Forest Area



(b) Carbon Sequestration

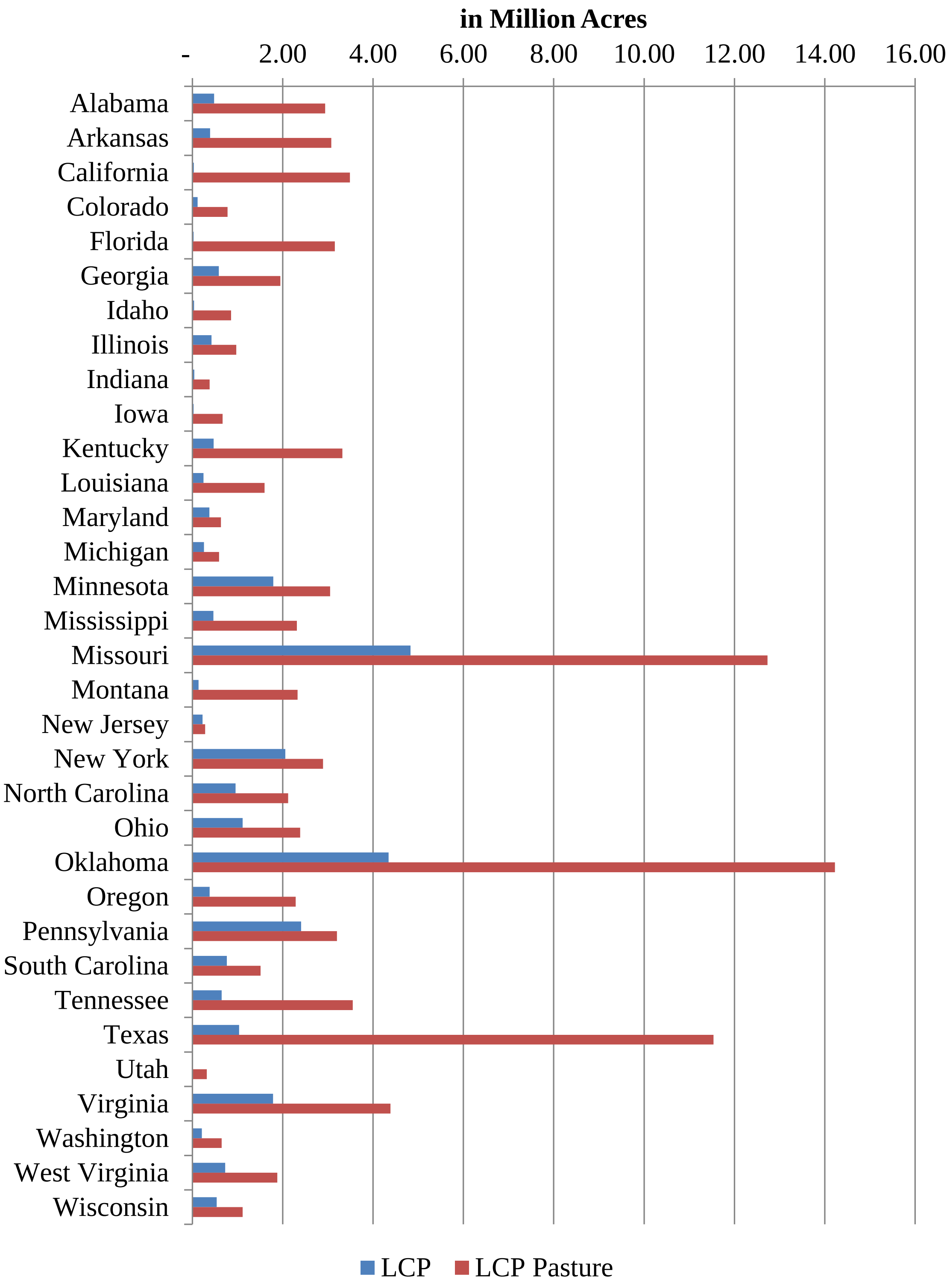


Figure 5.22 Forest Area by 2050 in Million Acres

First, the forest area converted in our simulation is higher than in the FASOM/McCarl analysis (97 versus 59 million acres in the *LCP Pasture* scenario) but with lower impacts on commodity prices. Most of the afforestation in our model is done on pasture and not on cropland. Pasture is reduced significantly because of (a) afforestation and (b) cropland expansion because of higher commodity prices. Although we have more forest area than FASOM/McCarl, total carbon sequestration is lower. The FASOM/McCarl analysis use sequestration rates which are too high. Hence, using more realistic sequestration rates, we find less carbon sequestration.

The allowance price is not endogenously modeled but in general we would expect a low impact on the allowance price from afforestation activity alone.

# CHAPTER 6. CONCLUSION

Concerns about climate change led to the introduction of two cap-and-trade bills 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. Shortly after the introduction of the bills, concerns surfaced about the effects of cropland to forestland conversion and the resulting increase in commodity prices. This dissertation revisits the issue of land conversion and crop price increases and extends the previous literature by adopting a real options framework to model the decision of U.S. landowners to switch from agricultural land-use to forestry.

The previous analysis are based on the FASOM model and result in considerable cropland conversion in areas such as the Corn Belt which seem unlikely places of land conversion due to very high net returns in agriculture. In addition, the FASOM analysis does not include uncertainty as a component in the net revenue analysis. From the investment under uncertainty literature, it is well known that certainty leads to a lower investment threshold, i.e., an earlier switch, than under uncertainty. We incorporate the uncertainty by applying a real option switching model where the key decision variable of the landowner is switching or not.

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.

The real option switching model is calibrated to nine major U.S. crops and pasture. The three scenarios analyzed differ in the level and growth rate of the emission allowance price and the availability of pasture. The first scenario assumes a low carbon price and evaluates the location and conversion rate of cropland (excluding pasture). This is a very restrictive scenario as it only covers cropland and does not consider the possibility of expanding cropland onto pasture. We show that even under those assumptions, almost no land conversion takes place in the Corn Belt and the price impact are comparable to what was found under certainty and by including pasture. The intuition behind this result is the landowner looses the flexibility to adapt land to market conditions. Planting a forest is a commitment which is difficult and costly to reverse. The second scenario allows for pasture to be converted and to serve as a reserve pool for cropland expansion, i.e., pasture can be used to offset the crop production which is lost in parts of the country due to afforestation. This reduces the commodity price impact further. The last scenario can be thought of as a worst case scenario from the perspective of high crop prices because it assumes a very high carbon price which was included in some previous analysis and follows the price ceiling established in the cap-and-trade literature.

The afforestation area in the model is restricted to areas which have seen forest cover historically or which have sufficient precipitation. There are four major findings: First, 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. Second, the incentive to wait for further information about the evolution of net revenues in agriculture and forestry leads to a significant delay of 25 years before an increase in commodity prices is observed in the low carbon price scenarios. Third, 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.

Several implications arise from these results. First, commodity price increases are not as high as previously estimated and thus, the decision to include carbon offsets from afforestation or not in any legislation should include this perspective. Second, offset revenue from afforestation is lower than previously estimated leading likely to lower total welfare for the farm sector. And third, one argument for the offset provision is that it 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.

Predicting the evolution of commodity or carbon prices over a period of 40 years is an impossible task. To put the time frame into perspective, this is similar to attempting a prediction of what the world will look like in 2011 in 1971. 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 dissertation, 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 dissertation, 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. A second issue which is not addressed in the dissertation is the possibility of a "natural attrition" of cropland. Over the past decades, we have seen cropland dropping out of crop production and put into non-agricultural land-use such as CRP and urbanization. It might very well be that this trend continues in the future if crop productivity advances such that yield improvements grow faster than demand. This would free up land which could then be used as forestland.

The application of our model is not limited to the United States but can be applied anywhere. It shows that in the presence of carbon payments, a clear relationship between carbon/energy, forest, and agricultural markets exist. Carbon presents an additional and important source of revenue for forest owners and thus increasing the competition for land.

Although climate change policy is not on top of the political to-do list, we believe that this dissertation contributes to the discussion on the effects of carbon offsets on agricultural markets.

# APPENDIX A. AGRICULTURE IN THE UNITED STATES

The data presented on the following pages is obtained from the 2007 Agricultural Census conducted by the U.S. Department of Agriculture. The county specific raw data can be downloaded under http://quickstats.nass.usda.gov/.

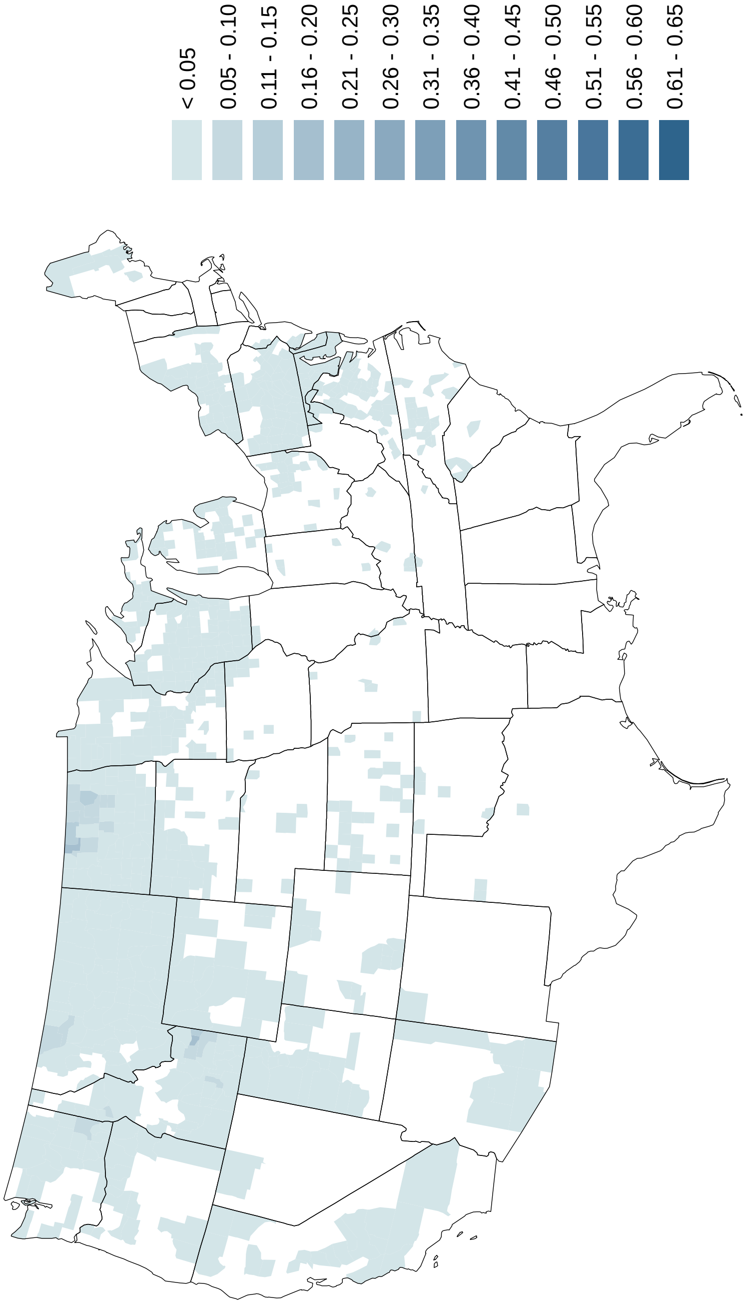


Figure A.1 Barley area harvested as a fraction of total county area in 2007

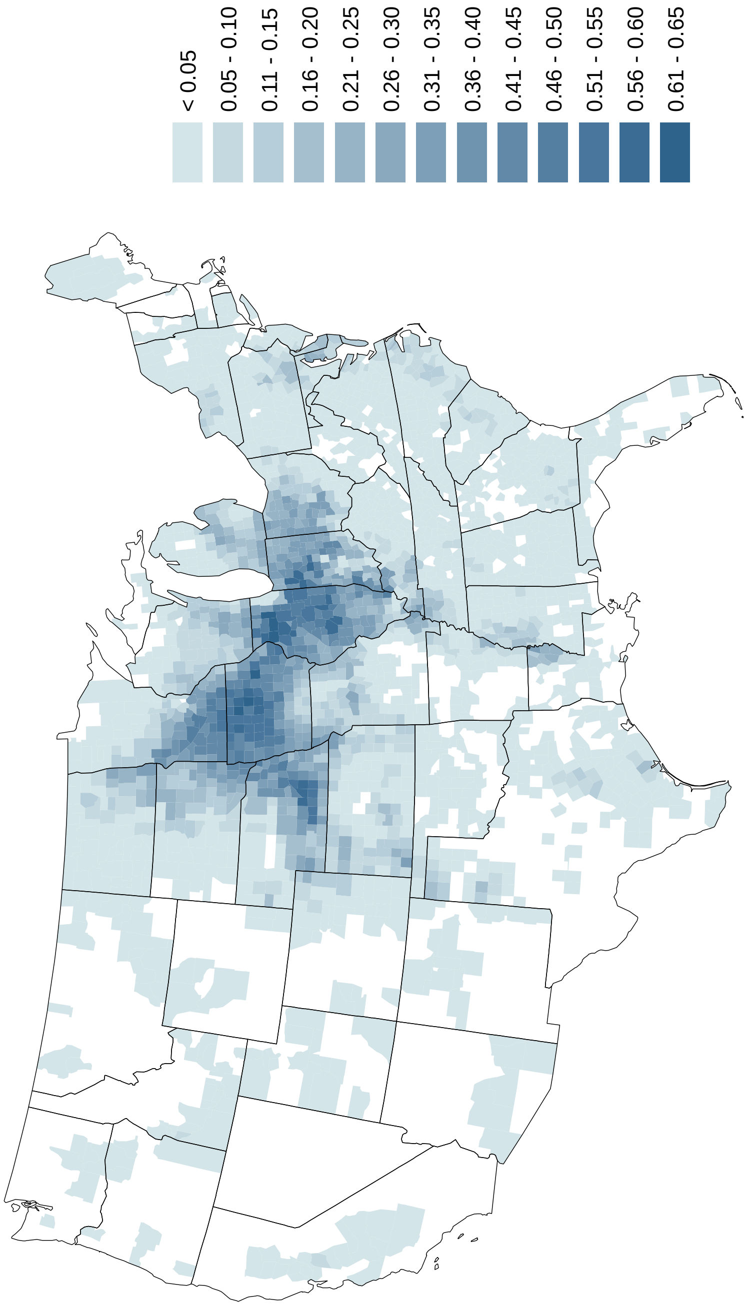


Figure A.2 Corn area harvested as a fraction of total county area in 2007

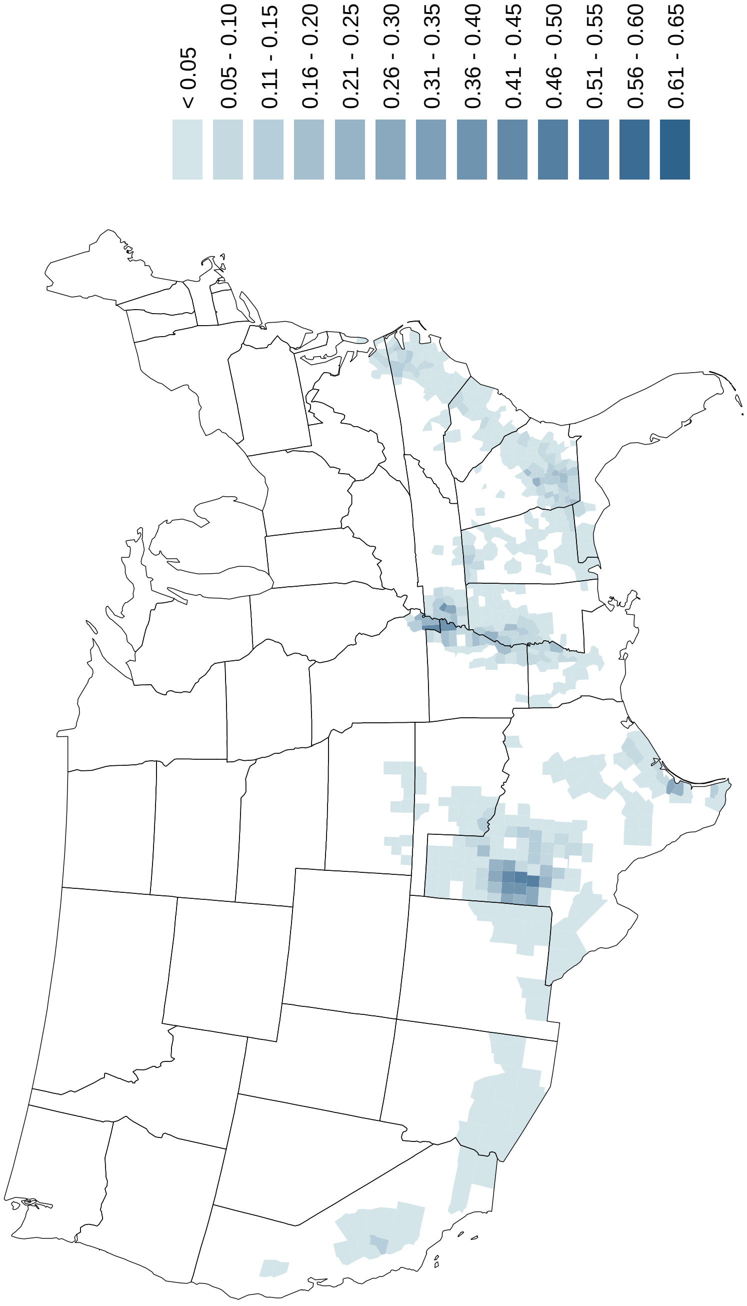


Figure A.3 Cotton area harvested as a fraction of total county area in 2007

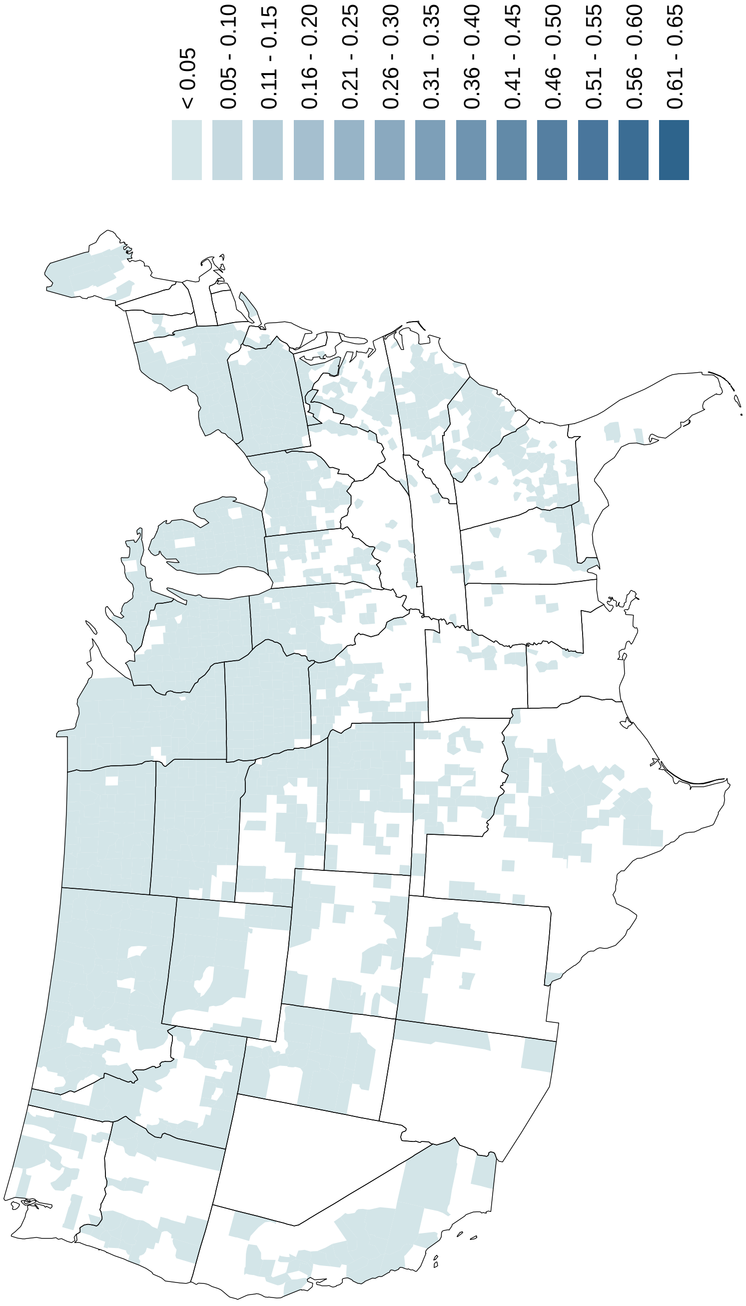


Figure A.4 Oats area harvested as a fraction of total county area in 2007

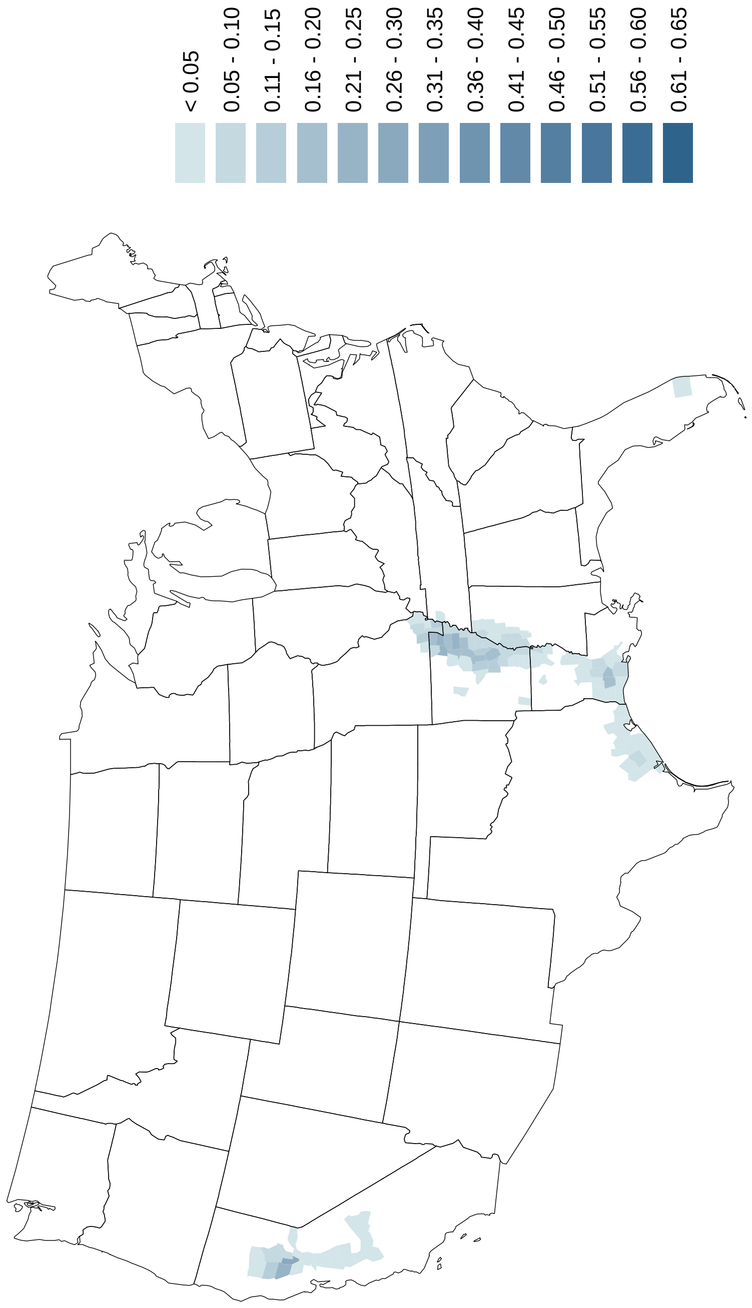


Figure A.5 Rice area harvested as a fraction of total county area in 2007

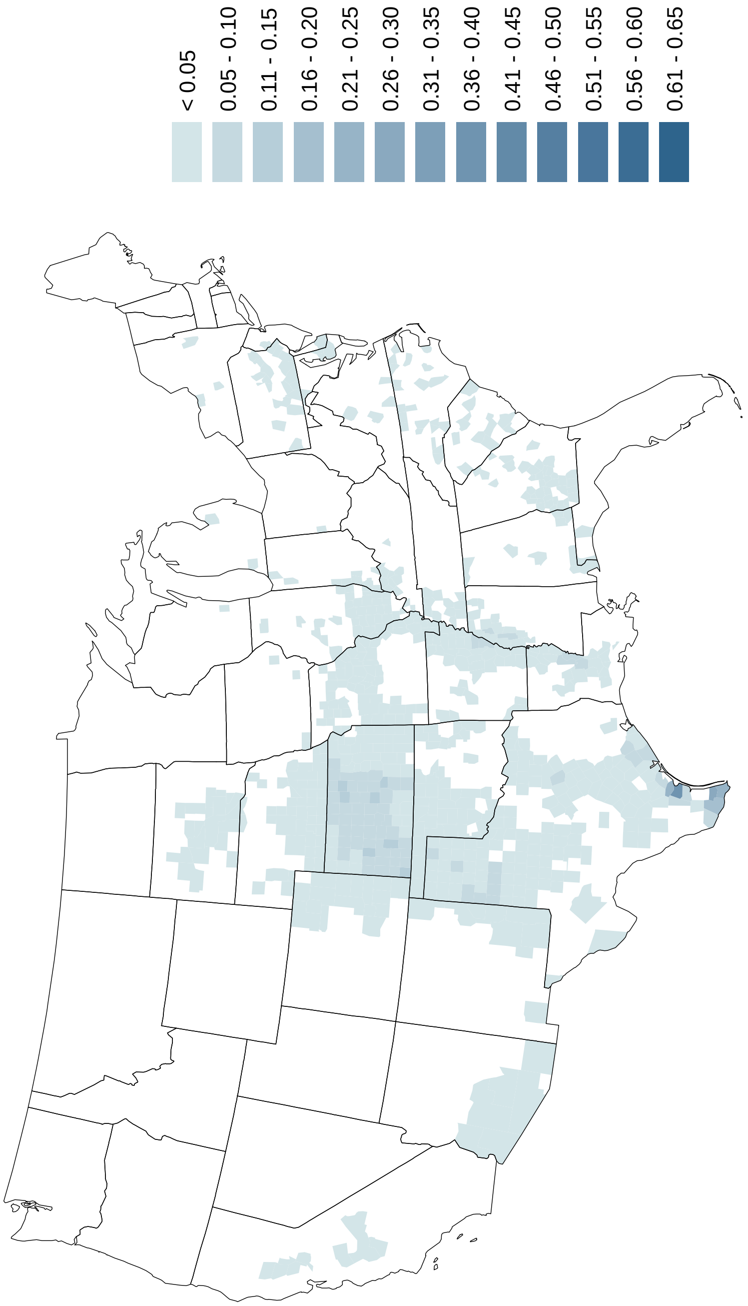


Figure A.6 Sorghum area harvested as a fraction of total county area in 2007

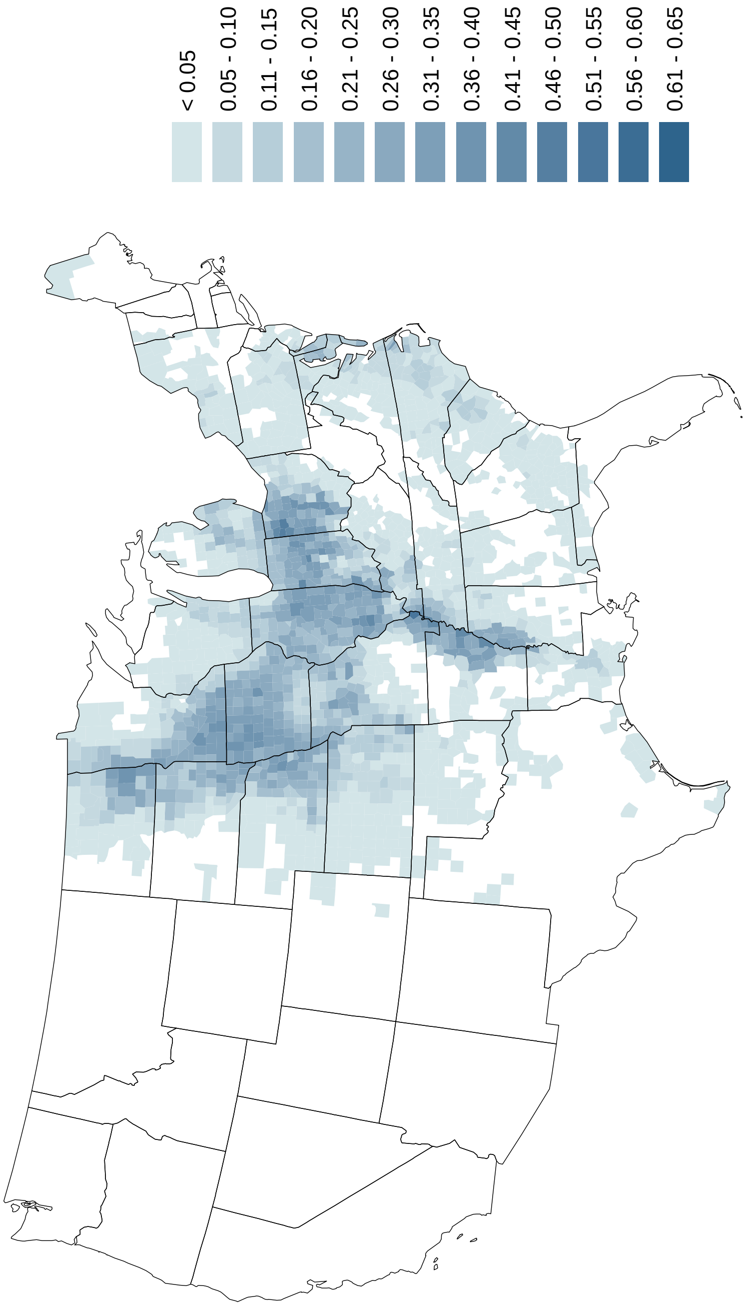


Figure A.7 Soybeans area harvested as a fraction of total county area in 2007

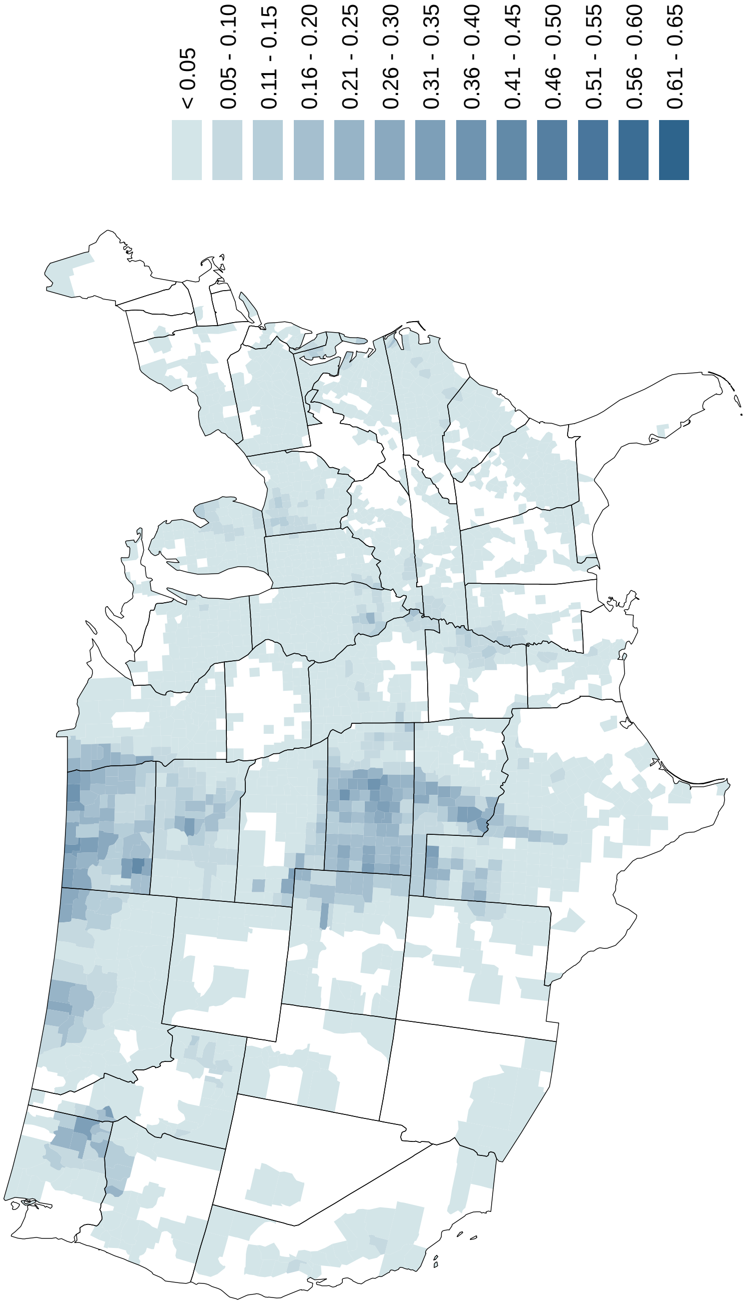


Figure A.8 Wheat area harvested as a fraction of total county area in 2007

# APPENDIX B. FORESTRY IN THE UNITED STATES

The data for the forest model calibration is taken from Smith et al. (2006) who subdivides the United States into nine major forestry regions depicted in figure B.1. The regions are the Northeast (NE), the Northern Lake States (NLS), the Northern Plain States (NPS), the Pacific Southwest (PSW), the Pacific Northwest (PWE), the Rocky Mountains North (RMN), the Rocky Mountains South (RMS), South Central (SC), and the Southeast (SE). In addition, the region PWE is subdivided into West and East.

Figure B.2 shows the average annual precipitation between 1960 and 2008 for the United States. The input data was obtained from the PRISM Climate Group at Oregon State University[1]. Although states like Iowa, Illinois, parts of Missouri and Minnesota did not have forest cover historically, we include those regions in our analysis because there is sufficient precipitation for afforestation to be possible.

For computational tractability, we assume constant volume growth and carbon sequestration for trees in this dissertation. Adding nonlinear growth functions to the model is possible but would significantly increase the computational time with little additional insight. Figure B.3 shows the growth rate for biomass and carbon (Smith et al., 2006) for the trees selected in this dissertation and figure B.4 depicts the spatial distribution of selected tree species in the United States.

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[1] Data accessed on April 9th, 2011 from http://www.prism.oregonstate.edu

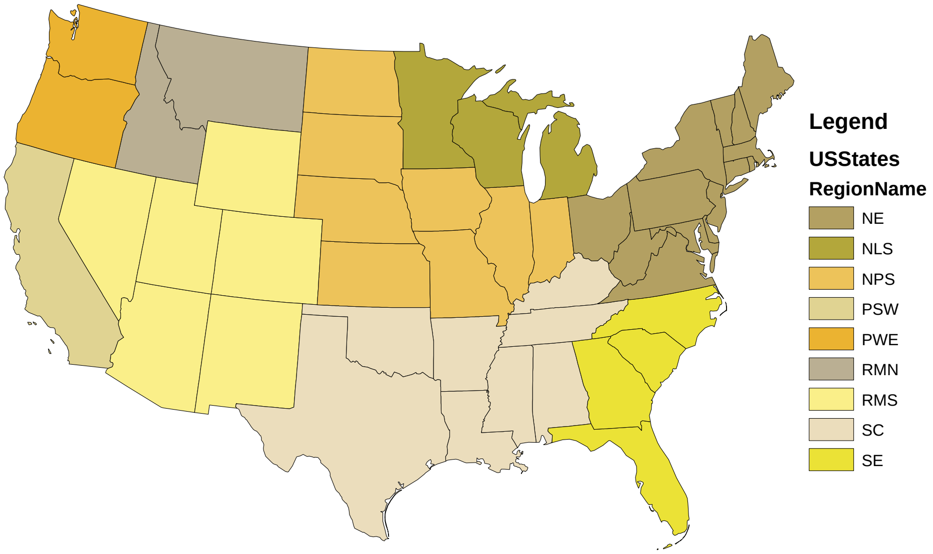


Figure B.1 Forest regions in the United States

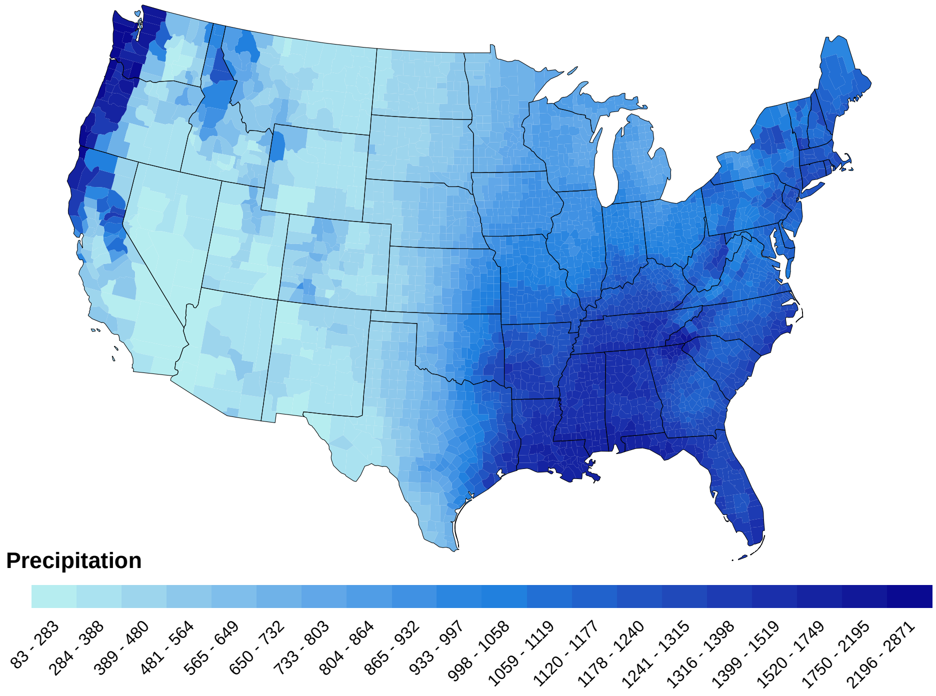
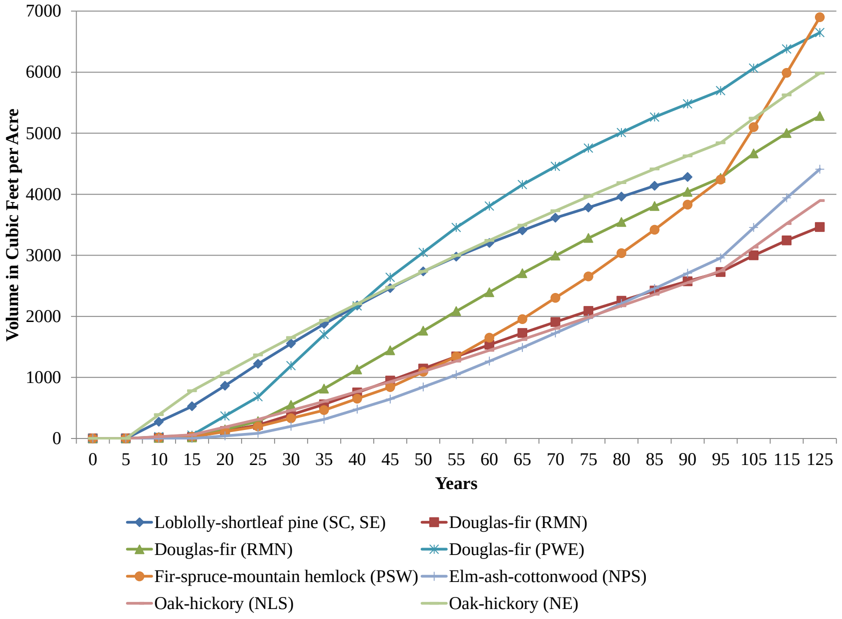
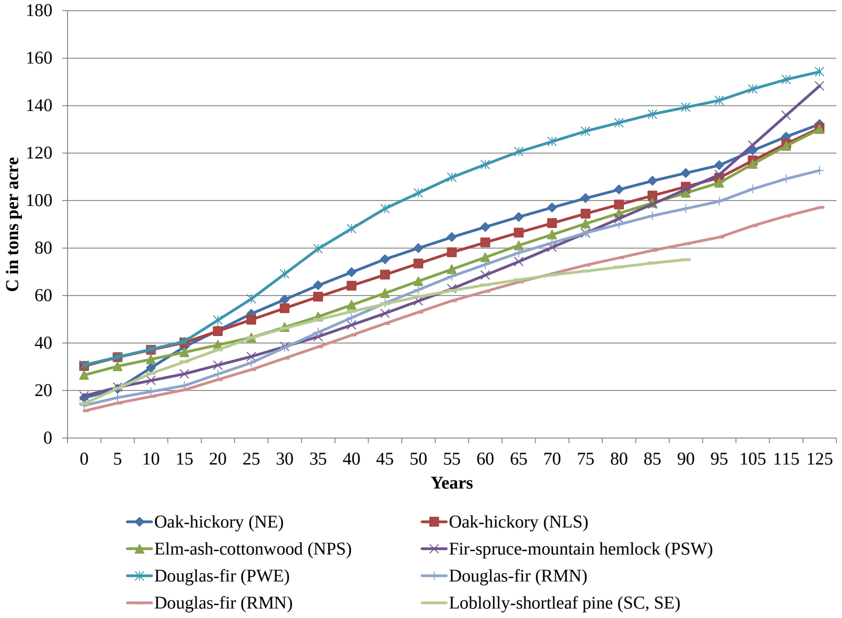


Figure B.2 Average precipitation in millimeters (1960-2008)

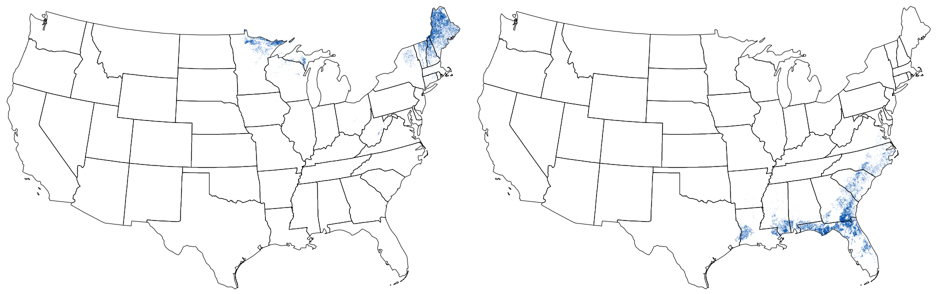


(a) Biomass Volume

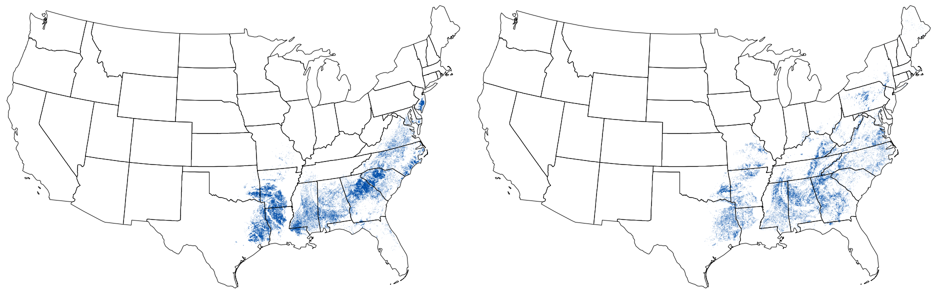


(b) Biomass and Soil Carbon

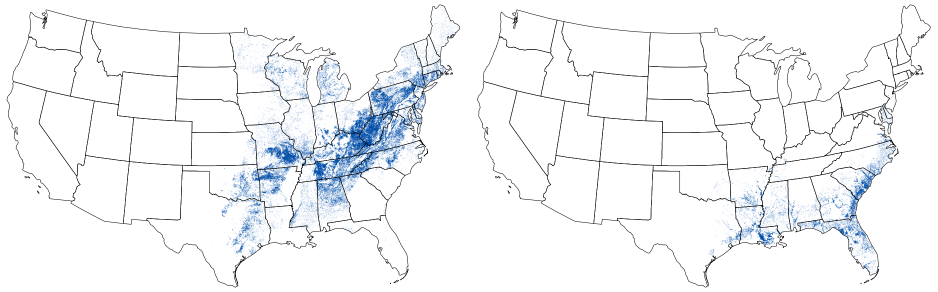
Figure B.3 Volume and Carbon Content by Forest Type in the United States



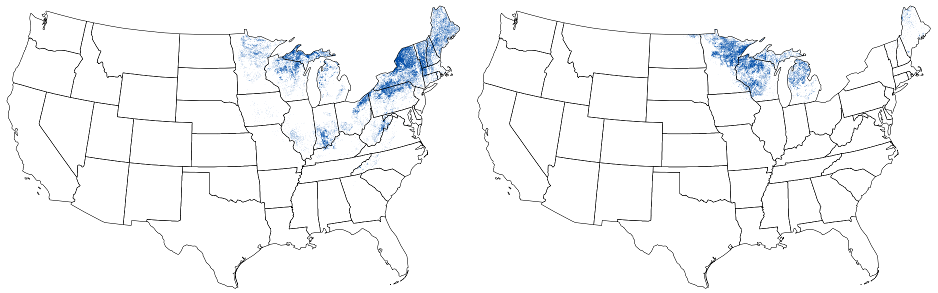
(a) Spruce-fir (b) Longleaf-slash pine



(c) Loblolly-shortleaf pine (d) Oak-pine



(e) Oak-hickory (f) Oak-gum-cypress



(g) Maple-beech-birch (h) Aspen-birch

Figure B.4 Forest Type Cover in the United States

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