Carbon Credit Markets Can Reduce the Riskiness of Bioenergy Crop Production

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Abstract

Perennial bioenergy crops have the potential to provide substantial carbon mitigation benefits through fossil fuel displacement and increasing soil carbon sequestration relative to conventional crops. However, they are likely to be less appealing to risk-averse farmers due to their long establishment periods, high upfront costs, and uncertain yields due to weather variations. Coupling an economic model with a biogeochemical model (DayCent) we examine the effect that emerging carbon markets that pay for carbon mitigation can have on the spatially varying returns and riskiness profiles of bioenergy crops (miscanthus and switchgrass) relative to conventional crops (corn and soybean) at the county level across the US rainfed region. We show that carbon mitigation payments increase mean returns and the likelihood of positive profit of bioenergy crops relative to conventional crops, but they also increase the variance of returns. However, these payments reduce the coefficient of variation, and thus the risk to return ratio, of bioenergy crops relative to conventional crops. Moreover, we find that paying for carbon expands the locations where returns from bioenergy crops are first-order and second-order stochastic dominant over conventional crops and would therefore be preferred by risk-neutral and risk-averse farmers, respectively.

1 Introduction

Since the United States has re-joined the Paris Agreement on climate change with ambitious goals for mitigating carbon emissions and the development of carbon credit markets in the U.S. has gained momentum, the potential contribution of agriculture to reaching the climate goals has attracted much attention (Bonnie, Jones, & Harrell, 2021; Elder, 2021). Perennial bioenergy crops, such as miscanthus and switchgrass have the potential to provide substantially higher carbon mitigation benefits relative to conventional row crops (Hudiburg T. , et al., 2016; Dwivedi, et al., 2015; Robertson, et al., 2017). These carbon mitigation services are provided by displacing fossil fuels as well as through higher levels of soil carbon sequestration than with conventional crops. Bioenergy crops are, however, subject to long establishment periods, high upfront costs, and risky yields, making them less appealing to risk-averse, impatient, and credit-constrained farmers (Bocquého & Jacquet, 2010; Miao & Khanna, 2017a; Alexander, et al., 2012; Yang, Paulson, & Khanna, 2016). The development of carbon credit markets or public policies that offer payments for carbon benefits provided by bioenergy crops can monetize the non-market ecosystem services and increase the returns from these crops (Feng, Zhao, & Kling, 2001; Noe, et al., 2016; Chamberlain & Miller, 2012; Bruner & Brokish, 2021; Biggs, et al., 2021).

However, carbon mitigation payments can also affect the riskiness of returns to the landowners because the amount of carbon displacement varies with biomass yield and the accompanying soil carbon sequestration and both are subject to variable weather conditions (Hudiburg T. , et al., 2016). Furthermore, the extent of soil carbon sequestration varies across time at a given location because soil carbon dynamics vary over the life of a bioenergy crop, with a soil carbon debt being created in the establishment period and carbon accumulation thereafter (Chen, et al., 2021).

Carbon mitigation payment could increase upfront costs through carbon debt in the first few years followed by positive, but random, payment for fossil fuel displacement due to uncertain yield and positive soil carbon sequestration during the mature period. The returns and risks with bioenergy crop production relative to conventional crops and their carbon mitigation services are expected to vary across the landscape that is heterogeneous in its soil and weather conditions and the expected returns from existing uses to bioenergy crop production. Carbon mitigation payments will also vary spatially and could enhance or reduce the spatial variability in bioenergy crop returns and riskiness.

Understanding the effects of carbon payments for the carbon mitigation services by bioenergy crops relative to those with conventional crops, for their relative returns and risks, is critical to assess the effects of those payments for the incentives for producing these crops for risk-neutral and risk-averse farmers. Farmers will consider the riskiness of returns when selecting whether to plant bioenergy crops over conventional crops. For example, a crop with lower returns may be preferred by risk-averse farmers over another crop that has higher but more risky returns. While risk-neutral farmers care only about the average returns to land, risk-averse farmers care not just about mean returns but also their riskiness relative to that of the current use of the land. A farmer with a utility that is weakly increasing in returns (that is, a risk-neutral farmer) will prefer the land use that gives higher net returns at every realization (this is referred to as first-order stochastic dominance). However, a farmer with a utility function that is increasing in returns but at a diminishing rate (that is, a risk-averse farmer) will prefer the land use that involves less risk and has at least as high an average return (this is referred to as second-order stochastic dominance). Formal definitions of first-order and second-order stochastic dominance can be found in Appendix A.1 and A.2 respectively As both bioenergy and conventional crops vary spatially in their returns and riskiness, the stochastic dominance ranking of bioenergy crops over conventional crops will vary spatially at any given biomass price and carbon mitigation payment level. Identification of the spatial distribution of where bioenergy crops can stochastically dominate conventional crops can identify regions where farmers that differ in their risk preferences. would be willing to grow bioenergy crops.

The objectives of this paper are three-fold. First, we examine the returns and riskiness profiles of two promising bioenergy crops, miscanthus, and switchgrass, relative to conventional crops and the spatial heterogeneity in these across counties in the rainfed region (to the east of the 100th meridian) of the United States at various levels of biomass prices. Second, we examine the effects of providing a carbon payment on the spatial pattern of returns and riskiness profiles of bioenergy crops. Third, we examine the effects of carbon payments on the stochastic dominance of bioenergy crops relative to conventional crops and the counties where bioenergy crops first-order and/or second-order stochastically dominate conventional crops.

We undertake this analysis by coupling an economic model with a biogeochemical model, DayCent, to quantify the temporally and spatially varying returns and riskiness of bioenergy crops relative to conventional crops due to yields, production costs, input requirements, and carbon intensities in 2,122 counties across the U.S. rainfed region. We use thirty years of randomized weather-related bioenergy crop and conventional crop yield data along with conventional crop price data to generate joint yield-price distributions using a copula method. We then estimate return distributions for bioenergy crops as well as conventional crops, with the option to harvest stover when profitable, using generated yields and conventional crop prices along with soil carbon sequestration rates and lifecycle carbon mitigation benefits under exogenous biomass prices and carbon mitigation payments for a fifteen-year cropping cycle for bioenergy crops.

Several studies have examined bioenergy crop profitability by calculating the minimum biomass price required for returns from producing biomass to equate the returns from the alternative use of land (this is referred to as breakeven price) (Brechbill, Tyner, & Ileleji, 2011; Perrin, Vogel, Schmer, & Mitchell, 2008; Mooney, Roberts, English, Tyler, & Larson, 2009; James, Swinton, & Thelen, 2010; Khanna, Dhungana, & Clifton-Brown, 2008; Jain, Khanna, Erickson, & Huang, 2010). However, such analyses do not take into account the riskiness of returns for either bioenergy crops or conventional crops and only a few consider spatial variability of bioenergy and conventional crop yields affecting bioenergy crop profitability. Miao and Khanna (2014) examine the risk premium needed for bioenergy crop production to break even with conventional crops. A few studies have conducted stochastic dominance analyses for bioenergy crops using data on yields from field trial data sites and/or for selected geographical areas resulting in findings that may not be representative of the entire U.S. rainfed region (Gouzaye, 2015; Griffith, Larson, English, & McLemore, 2012; Dolginow, Massey, Kitchen, Myers, & Sudduth, 2014; Skevas, Swinton, Tanner, Sanford, & Thelen, 2016). Moreover, these studies have not examined the effect of pricing the carbon mitigation services provided by bioenergy crops on their risk and return profiles. Prior work on the effect of carbon mitigation payment on bioenergy crop returns includes Mishra et al., (2021) who consider payment for switchgrass soil carbon sequestration benefits in Illinois, and Chamberlain and Miller (2012) who consider payment for switchgrass ecosystem services in the southern U.S, neither of which t consider the riskiness of returns. Additionally, Noe et al., (2016) account for the variability of prices and yield and consider prairie biomass profitability in southern Minnesota under carbon mitigation payments by using estimates from the literature. These studies are limited in their analysis to specific geographical areas, a focus on specific aspects of carbon mitigation (i.e. soil carbon sequestration mitigation), and a focus on a particular bioenergy crop.

We extend existing profitability studies of bioenergy crops by conducting stochastic dominance analysis across the entire US rainfed region using a long time series of weather-related yields for bioenergy crops and conventional crops to generate yield variability. In doing so we incorporate the riskiness of returns of the alternative use of land in addition to bioenergy crops and incorporate returns from four tillage and rotation choices for corn and soybeans with the option to harvest corn stover. We also contribute to the carbon mitigation payment literature by conducting a comprehensive lifecycle analysis of the carbon mitigation provided by bioenergy crops and conventional crops accounting for fossil fuel displacement and soil carbon sequestration for the entire rainfed US. Additionally, when compensating farmers for soil carbon sequestration benefits, we estimate soil carbon loss and the benefits of switching from more carbon-intensive to less carbon-intensive farming practices when harvesting corn stover. Furthermore, we conduct our analysis for varying levels of biomass prices and carbon mitigation payments to examine how bioenergy crop returns, riskiness, and stochastic dominance, differ at various payment levels. As carbon mitigation potential varies spatially and temporally for these crops, we can identify how farmers' returns profiles change when they are compensated for the carbon mitigation at various levels of carbon mitigation payments.

2 Methods and Data

Bioenergy and conventional crop yields

As large-scale commercial production of bioenergy crops is yet to commence in the United States, we simulate yields of bioenergy crops (miscanthus and switchgrass), conventional crops (corn and soybean), and corn stover under 30 years of randomized weather conditions using the biogeochemical model, DayCent, at the county level. DayCent selects spatially differentiating varieties of miscanthus and switchgrass that are optimally suited to each area (Hudiburg T. , et al., 2016). Conventional crop yield data are simulated under eight scenarios which are permutations of two rotation types (corn-corn and corn-soybean), two tillage types (conventional and no-tillage), and two corn stover removal scenarios (without corn stover removal and with some corn stover removal). For each rotation and tillage combination, we also simulate the quantity of corn stover that can be removed without significantly affecting yield which is set at 30% and 50% for conventional tillage and no-tillage respectively. Further details on crop yields are presented in Appendix A.3.

Geographical region

We perform our analysis for 2,122 counties that meet the following criteria: the county is on or to the east of the 100th meridian within the continental U.S, the county has available simulated bioenergy and conventional crop yields from DayCent, and the county has satellite data showing nonzero corn or soybean acreage in that county. Cropland acreage is obtained from the Cropland Data Layer by Jiang et al., (2021) and is constructed via pixel-level analysis of land-use history to identify areas that have changed in their land use from crop production to grassland or vice-versa over the past five-year period. We consider counties where corn or soybean are either permanently planted or was growing corn and soybean in 2016. Within this, we only consider corn-soybean rotations in counties where Jiang et al., (2021) show soybean crops being cultivated. Counties included are modeled to produce perennial bioenergy crops under rainfed conditions. We assume that conventional crops for all counties are rainfed, except for counties in Nebraska.

Lifecycle carbon mitigation calculations

Lifecycle carbon mitigation from fossil fuel displacement occurs when biomass from bioenergy crops is used to produce cellulosic biofuel that has lower lifecycle carbon intensity than energy equivalent fossil fuel. Carbon benefits from replacing fossil fuels are calculated as the difference in grams of CO_2 for the same amount of energy produced between cellulosic ethanol and fossil fuel production. Lifecycle carbon intensity for each source of biomass is calculated as a sum of emissions across various sectors through a life-cycle analysis of biomass production and includes material input usage, electricity, diesel, and transportation energy use, electrification co-credits, ethanol production emissions. Details of the method used to calculate lifecycle carbon emissions are presented in Appendix A.4.

Soil carbon sequestration

Annual levels of total carbon in the soil organic matter pool are simulated for all crops using the DayCent model for each year of the planting period. The data include annual soil carbon levels for conventional crops under each of the eight permutations of rotation, tillage, and corn stover removal and for each bioenergy crop. To pay for only additional soil carbon sequestration generated by biomass production, we first simulate a simplified economic model with no biomass price or carbon mitigation payment to determine the baseline conventional crop rotation and tillage choice for each county (as detailed in Appendix A.5). The difference between soil carbon levels for each crop choice and rotation and the county baseline soil carbon level is taken as the additional soil carbon sequestered for that crop choice and rotation for each year of the planting period at the county level. DayCent simulation data shows bioenergy crop production results in an initial loss of soil carbon during establishment before a linear buildup of soil carbon sequestration over the mature period of the crop. To account for the soil carbon dynamics we compute rates of soil carbon sequestration for each year in the establishment period and use an average rate of soil carbon sequestration for the mature period of the bioenergy crop. We provide details of the method used to calculate additional soil carbon sequestration are presented in Appendix A.6.

Bioenergy return calculations

The bioenergy crop (miscanthus and switchgrass) lifespan can be separated into an establishment period and a mature period. In the establishment period, the farmer incurs a cost per unit of land to establish the energy crop. In the mature period, the farmer harvests the bioenergy crop, whose yield is stochastic with a distribution known to the farmer. We assume that miscanthus reaches its mature period after two years of establishment whereas switchgrass reaches the mature period within the first year of establishment. Costs of production for bioenergy crops are constructed at the county level. Bioenergy crop costs were calculated for each year in the establishment period and the mature period with quantities from the Iowa State Extension website and input prices from NASS. Establishment period costs include costs associated with land preparation and planting such as disking, rhizomes or seed drilling, soil finishing, and chemical sprays. Mature period costs include mowing, condition, swathing, windrowing, staging, loading, baling, and storage costs. County-level fertilizer application quantities are taken from DayCent and Dwivedi et al. (2016) and input prices from NASS. Details on the spatial distribution of crop costs are provided in Appendix A.7. All bioenergy crops provide carbon mitigation services from lifecycle fossil fuel displacement and increased soil carbon sequestration relative to sequestration from current use. The former varies with biomass yield whereas the latter varies across crops and temporally over the crop's lifecycle. Farmers receive a biomass price per unit of biomass yield and a carbon mitigation payment per unit of carbon mitigated where payments are made in the year the unit of carbon is mitigated. Applied farm-gate biomass price is assumed to be constant over the period of the study and is varied exogenously from \$0 to \$100 per metric ton of biomass (Mg b^{-1}) at intervals of \$10. We select \$40 and \$60 Mg b^{-1} as two example prices to illustrate our results. Biomass price is assumed to not include transportation and other logistical costs, to not vary spatially, and to not affect other prices including conventional crop prices. Carbon mitigation payment is set exogenously at \$0 (no carbon mitigation payment), 40, and 80 per metric ton of carbon (Mg C^{-1}) and is assumed constant over time.[1] We then generate a distribution for the net present value (NPV) of returns over the life of the crop for each bioenergy crop at exogenously given biomass price and carbon mitigation payment levels. In Appendix A.8. we detail the setup and calculation of bioenergy crop returns for each year of the crop lifecycle more formally.

Conventional crop return calculations

The yields of the conventional crops (corn and soybean) are stochastic, with distributions known to the farmer. Costs of production for conventional crops are estimated at the county level. State-level production costs of conventional crops are constructed for each rotation and tillage option using crop budgets quantities and prices provided by state extension services and include chemicals, seeds, harvesting, drying, fuel, insurance, labor, machinery, and interest on capital costs. Additionally, county-level fertilizer input quantities are taken from DayCent and Dwivedi

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[1] The carbon content of one Mg of carbon is approximately 3.67 times that of one Mg of CO2. A price of \$40 Mg C^{-1} is, therefore, approximately equivalent to \$10.9 $^{-1}$ Mg b^{-1} of CO2, and a price of \$80 Mg C^{-1} is approximately equivalent to \$21.8 $^{-1}$ Mg b^{-1} of CO2. The California Carbon Allowance (CCA) Futures market has ranged between \$20 and \$35 Mg $CO2^{-1}$ since January 2021 (Live Carbon Prices Today, 2022) so we believe that carbon prices of \$40 Mg C^{-1} and \$80 Mg C^{-1} are reasonable prices in the United States.

et al., (2015), and input prices at the state level are taken from NASS. Details on the spatial distribution of crop prices are provided in Appendix A.9

The prices for conventional crops (corn and soybean) are also stochastic, with distributions known to the farmer and estimated at the state level using 30-year national-level harvest prices (USDA NASS) and futures prices (Chicago Board of Trade), and national and state-level harvest prices for 2016 (USDA NASS), The difference in harvest and futures prices are used to calculate a national level stochastic distribution. The difference in the 2016 state and national prices is used to normalize the national price distribution to the state level. Further details on conventional crop prices are provided in Appendix A.10

Corn stover costs are constructed at the state level for each corn rotation and tillage combination and include mowing, condition, raking, staging, loading, baling, and storage costs. Nitrogen application costs are computed at the county level with nitrogen quantities taken from DayCent as the additional nitrogen removed when a farmer chooses to harvest corn stover and Nitrogen application prices are taken from NASS. Details on the spatial distribution of corn stover production costs are provided in Appendix A.11. The net revenue from any given rotation and tillage choice includes the returns from conventional crops and the possible returns from harvesting corn stover. To determine the foregone returns from alternative use of the land such as returns from conventional crops (which is referred to as the opportunity cost of land), we combine distributions of net revenue of the four rotation and tillage choices for every biomass price and carbon mitigation payment to construct a distribution representing the net revenue of the alternative use of land. In Appendix A.12. we detail the setup and calculation of conventional crop returns for each rotation and tillage with the option to harvest stover more formally.

Yield and price riskiness

To simulate stochastic returns we construct a yield-price distribution using one thousand spatially varying stochastic draws for twelve crop yields (i.e., corn and corn stover (each under four rotation and tillage combinations), soybeans (under two tillage combinations), miscanthus, and switchgrass) and prices for two conventional crops corn and soybean and spatially varying input costs. Joint yield-price distributions for each county are generated by a copula approach by following Miao and Khanna (2017a), Yan (2007), and Du and Hennessy (2012). Details on how the price distribution is constructed are presented in Appendix A.13.

Annualized NPV calculations

Because bioenergy crops are perennial crops and conventional crops are annual crops, we annualize the returns from bioenergy crops for comparing the returns between the two types of crops and generate the annualized NPV. We follow Miao and Khanna (2017a), who consider two types of discount rates, a low rate of 2%, and a high rate of 10%. High discount rates indicate less willingness to wait for future returns and will lower the annualized NPV of bioenergy crops. We present results based on a 2% discount rate in the main text and results with the 10% discount rate in Appendix A.14.

3 Results

We analyze the distribution of the annualized NPV of bioenergy crops relative to conventional crop returns at various biomass prices and carbon mitigation payment levels in terms of breakeven prices, expected returns, the likelihood of positive profit, coefficient of variation (CV) of returns, and stochastic dominance. The first two give us a measure of returns without considering riskiness. The latter three allow us to quantify the riskiness of returns of bioenergy crops. Further, stochastic dominance tests allow us to order farmers' choices between distributions when farmer risk preferences are unknown.

Breakeven prices for bioenergy crops

We first estimate the breakeven price (the minimum biomass price required for returns from producing biomass to equate to the returns from the alternative use of land) for miscanthus and switchgrass as a comparison to previous literature and find that these vary substantially across the rainfed region. The median breakeven price is \$70-80 Mg b^{-1} for miscanthus (Figure A.1 (a)) and \$80-90 Mg b^{-1} for switchgrass (Figure A.1 (d)) across the rainfed region. The breakeven price for miscanthus ranges from \$50-70 Mg b^{-1} in the Midwest and is comparable to estimates in Jain et al., (2010) and Miao and Khanna (2017b). Breakeven prices for miscanthus are substantially higher in the Southern states, particularly the Mississippi delta (higher than \$100 Mg b^{-1} in some areas) due to low miscanthus yields and high corn and soybean yields. For switchgrass, the breakeven price is generally lower (\$50-70 Mg b^{-1}) in the Southern Great Plains and the Southeast and higher in counties in the Midwest (\$70-100 Mg b^{-1}). These prices are lower than Jain et al. (2010) because we consider switchgrass cultivars optimal for each region. Carbon mitigation payments at \$80 Mg C^{-1} reduce the median breakeven price to \$50-60 Mg b^{-1} for miscanthus (Figure A.1 (c)) and \$60-70 Mg b^{-1} for switchgrass (Figure A.1 (f)) across the rainfed region.

Expected bioenergy crop returns

At a biomass price of \$60 Mg b^{-1}, the expected annualized net returns for miscanthus and switchgrass in the Midwest (Figure A.2 (a)) and southern states (Figure A.2 (a)) respectively are largely positive and range from \$100-200 ha^{-1}. The addition of carbon mitigation payments increases the region with positive net returns and increases returns for miscanthus in the Midwest (Figure A.2 (b-c)) and switchgrass in the southern states (Figure A.2 (e-f)) to over \$500 ha^{-1}.

At \$80 Mg C^{-1}, carbon mitigation payments generally account for 35 to 40% of expected returns for miscanthus (Figure A.3 (c)) and switchgrass (Figure A.3 (f)) in counties with positive returns. We consider a biomass price of \$40 Mg b^{-1} to illustrate the differing effect of carbon mitigation payment at a price level where farmers would not expect positive. At \$40 Mg b^{-1}, farmers would not expect positive returns in almost any county. However, under carbon mitigation payments \$80 Mg C^{-1} returns would increase to \$100-200 ha^{-1} (annualized NPV) for miscanthus in the Upper and Central Midwest, and Switchgrass in the Southern Great Plains and Southeast.

Likelihood of positive profit

The likelihood of positive profits is the probability that the annualized NPV return distribution for a bioenergy crop is higher than the foregone returns from an alternate use of that land. The biomass and carbon price at which a farmer achieves a 50% likelihood of positive profit can serve as an *approximate* indicator for price levels at which risk-neutral farmers may consider returns from bioenergy crops profitable.[2] The median biomass price at which a county achieves a 50% probability of positive profits with zero carbon mitigation for miscanthus is \$70-80 Mg b^{-1} and is lowest in the Midwest (\$50-70 Mg b^{-1}) and highest in the great plains and the Mississippi delta region (Figure 1 (a)). With carbon mitigation payments of \$80 Mg b^{-1}, the median price of 50% probability of positive profits for miscanthus is lower at \$50-60 Mg b^{-1} (Figure 1 (c)). For switchgrass, the median price at which a county achieves a 50% probability of positive profits is \$80-90 Mg b^{-1} with the lowest prices being in the southern states (particularly southern great plains and the southeast) and the northern Midwest (Figure 1 (d)). Under carbon mitigation payments of \$80 Mg b^{-1}, the median price of 50% probability of positive profits for switchgrass

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[2] Likelihood of positive profit can serve as an indicator for price levels at which returns from bioenergy crops are profitable to risk-neutral farmers under the assumption that the return distributions are approximately symmetric.

is lower at \$60-70 Mg b^{-1} (Figure 1 (f)) across the rainfed region with counties in the southern states being between \$30-60 Mg b^{-1}.

Risk-averse farmers prefer more certainty over risk-neutral farmers for the same expected return, regions with a likelihood of positive profit higher than 50% may be regions where such farmers would prefer growing bioenergy crops. At \$60 Mg b^{-1}, even without carbon mitigation payments, many counties in the Midwest and Southern states have at least a 30% probability of positive profit from growing miscanthus (Figure 2 (a)) and switchgrass (Figure 2 (d)). Carbon mitigation payments increase both probabilities of positive profit for bioenergy crop returns and increase the number of counties achieving at least a 30% probability of positive profit. For example, at \$80 Mg C^{-1}, most counties in the Midwest and Southern achieve probabilities of profit higher than 90% for miscanthus (Figure 2 (c)) and switchgrass (Figure 2 (f)). This indicates that at \$60 Mg b^{-1}, such areas may be feasible for miscanthus even without carbon mitigation payments but that carbon payments would make miscanthus more appealing to risk-averse farmers. At a lower price of \$40 Mg b^{-1}, most counties have a near-zero probability of achieving positive profit from growing miscanthus (Figure 2 (g)) and switchgrass (Figure 2 (j)) without carbon mitigation payments. Carbon mitigation payments increase the probability of positive profit for bioenergy crop returns. For example, at \$80 Mg C^{-1}, a large number of counties in the Midwest and Southern achieve probabilities of profit higher than 50% for miscanthus (Figure 2 (i)) and switchgrass (Figure 2 (l)). These areas may be feasible for farmers to grow bioenergy crops with carbon mitigation payments even when biomass prices are low.

CV ratio of bioenergy crops relative to conventional crops

The CV of returns is the standard deviation of a distribution of returns normalized by its mean. We use a pairwise comparison of crop return CVs to compare two annualized NPV distributions in terms of relative riskiness (Hardaker, 2004). The ratio CV for bioenergy crop returns relative to those from conventional crops ranges from $(0, \infty)$ with lower numbers implying that the bioenergy crop returns are less risky in terms of their CV.[3]At a higher biomass price of $60 Mg b^{-1} and in the absence of carbon mitigation payment, returns from miscanthus (Figure 3 (a)) and switchgrass (Figure 3 (d)) are less risky than those from conventional crops in terms of CV across most of the rainfed region. Carbon mitigation payments further make these returns from miscanthus (Figure 3 (b-c)) and switchgrass (Figure 3 (e-f)) relatively less risky relative to conventional crops. At a lower biomass price ($40 Mg b^{-1}), and in the absence of carbon mitigation payment, however, bioenergy crop production is less risky in terms of CV only in a handful of counties in the central Midwest for miscanthus (Figure 3 (g)) and southern states for switchgrass (Figure 3 (j)). Although net returns for bioenergy crops are positive across many counties in the rainfed region, their returns are riskier than conventional crops in terms of CV in most counties within and surrounding the Central Midwest for miscanthus and Southern states for switchgrass. Carbon mitigation payment makes bioenergy crop returns less risky than returns from conventional crops at 40 Mg C^{-1} mostly in the Midwest for miscanthus (Figure 3 (h)) and mostly in the southern states and Midwest for switchgrass (Figure 3 (k)). At 80 Mg C^{-1}, both bioenergy crops are less risky than conventional crops in most of the rainfed regions except in parts of the Great Plains (Figure 3 (i) and Figure 3 (l)).

Stochastic dominance of bioenergy crop returns

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[3] Ratio of CV can be negative due to expected returns for bioenergy crops being negative. If returns for bioenergy crops are negative at any price level, it would imply that those bioenergy crops are not profitable even without accounting for the foregone income from alternate uses of that land. We therefore do not consider the results in this trivial case and instead simply identify where bioenergy crop returns are negative.

We perform pairwise comparisons of distributions of annualized NPV of returns using the stochastic dominance criterion to understand farmers' choices when risk preferences are unknown.

We first compare returns using a first-order Stochastic Dominance (FOSD) criteria (see Appendix A.1 for a formal definition and graphical example of FOSD). If a crop return dominates another in the FOSD sense, then a farmer who prefers higher returns to lower returns will choose it over the other regardless of her risk preferences. This is because if a crop return dominates another in the FOSD sense, then it has a larger likelihood to provide returns higher than the returns from the crop it dominates. Next, we compare crop returns using a second-order stochastic dominance (SOSD) criteria (see Appendix A.2 for a formal definition and graphical example of SOSD). If a crop return dominates in a SOSD sense, then it would be preferred by farmers who are risk-averse in addition to preferring higher returns to lower returns.[4] This is because if a crop return dominates another in the SOSD sense, then it either provides lower or equal revenue with more certainty or has a larger likelihood to provide returns higher than the returns from the crop it dominates.

At a higher biomass price of \$60 Mg b^{-1}, returns for bioenergy crops achieve second-order dominance over conventional crops in most counties in the Midwest for miscanthus (Figure 4 (a)) and southern states and northern Midwest for switchgrass (Figure 4 (d)) as well as first-order dominance in some counties in the same regions. With carbon mitigation payment, counties where bioenergy crop returns achieve second-order stochastic dominance expand beyond the

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[4] Note that FOSD implies SOSD, but SOSD does not imply FOSD. In other words, if returns from crop A dominate returns from crop B in the FOSD sense, then returns from crop A also dominate returns from crop B in the SOSD sense. However, the opposite does not hold. Moreover, both FOSD and SOSD offer partial rankings between returns. That is, it is possible that, neither returns from crop A first-order stochastically dominate returns from crop B nor returns from crop B first-order may stochastically dominate returns from crop A (Hardaker, 2004).

Midwest and southern states for miscanthus (Figure 4 (b-c)) and switchgrass (Figure 4 (e-f)) respectively. Additionally, biomass returns from many counties that had second-order stochastic dominance over conventional crops under no payment achieved first-order stochastic dominance over them.

We note that at a higher biomass price of \$60 Mg b^{-1} with carbon mitigation payment (for example \$80 Mg C^{-1}) returns from miscanthus and switchgrass only achieve first-order stochastic dominance over conventional crops in the Midwest (Figure 4 (c)) and in the southern states (Figure 4 (f)) respectively despite both bioenergy crops achieving second-order stochastic domination over conventional crops throughout the rainfed region. This implies that while both farmers would view both miscanthus and switchgrass returns as profitable and less risky than conventional crops but would prefer miscanthus in the northern rainfed region over switchgrass and switchgrass in the southern rainfed region over miscanthus. To test this directly, we consider areas where bioenergy crops achieve stochastic dominance over conventional crops and other bioenergy crops (miscanthus for switchgrass and vice versa). Figure 5 (a-c) shows at \$60 Mg b^{-1}, miscanthus returns achieve stochastic dominance over conventional crops and switchgrass returns only in the northern half of the rainfed region. The same is true for switchgrass in the southern states (Figure 4 (d-f)). The implication from Figure 4 and Figure 5 is that while carbon mitigation payments make both miscanthus and switchgrass less risky across the entire rainfed region, miscanthus may only be appealing to risk-averse farmers in the Midwest and switchgrass may only be appealing to risk-averse farmers in the Southern states.

At a lower biomass price of \$40 Mg b^{-1}, no county achieves stochastic dominance of bioenergy crop returns over conventional crops returns (Figure 4 (g) and Figure 4 (j) for miscanthus and switchgrass respectively) or other bioenergy crops (Figure 5 (g) and Figure 5 (j) for miscanthus and switchgrass respectively) without carbon mitigation payments. With carbon mitigation payments, some counties can achieve second-order stochastic dominance of bioenergy crop returns over conventional crops and bioenergy crop returns but only a handful achieve first-order stochastic dominance. For example, at \$80 Mg C^{-1}, miscanthus and switchgrass returns achieve second-order stochastic dominance over conventional crop and bioenergy crop returns in counties in the Midwest (Figure 5 (i)) and southern states (Figure 5 (l)) respectively. The implication here is that at lower biomass prices, carbon mitigation payments make miscanthus and switchgrass more profitable and less risky in northern and southern parts of the rainfed region respectively, however, the increase in returns and reduction in riskiness may not be enough to appeal to significantly risk-averse farmers.

Sensitivity analysis

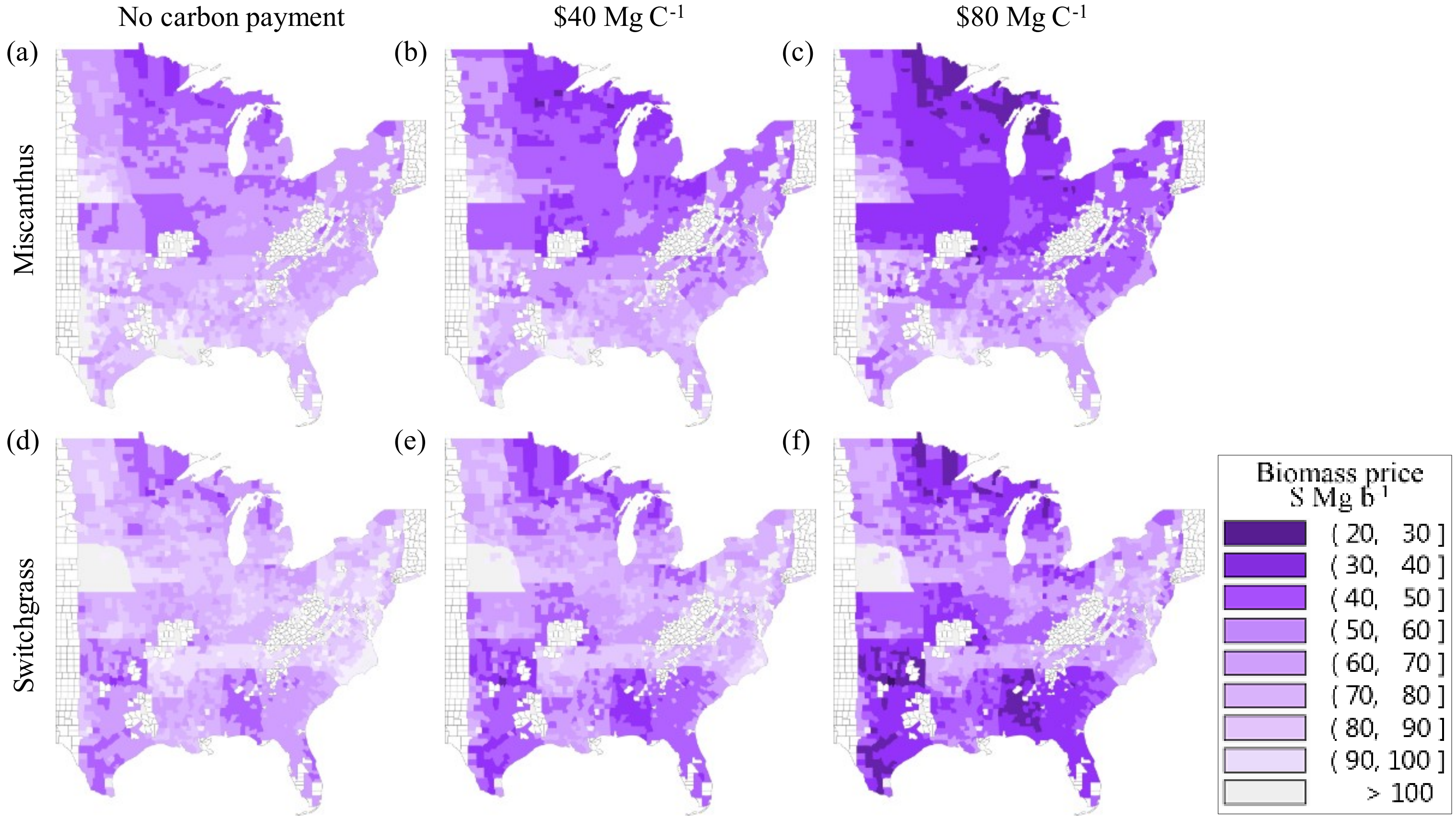
We conduct four types of sensitivity analyses on our results and present results in detail in Appendix A.14-17. First, following Miao and Khanna (2017a), we consider a case where the farmer has a higher discount rate. We set discount rates higher at 10% and find that both bioenergy crops can achieve similar patterns of stochastic domination over conventional crops as under the low discount rate scenario (Appendix A.14 and Figure A.4). Second, following Clifton-Brown et al., (2000), and Kucharik (2013) we consider survival risk in miscanthus crops. We first note that DayCent accounts for the climatic variability and potential impact of extreme weather events such as cold winters on yield and soil carbon sequestration and the likelihood of 100% crop failure are very low (Figure A.5 (a) shows that in the upper Midwest where the risk of extreme winters is high, the expected miscanthus yields to be around 20-22.5 Mg ha^{-1} and Figure A.6 (a) shows that the yield risk of miscanthus relative to switchgrass in the upper Midwest is consistent with the rest of the northern rainfed region). Nevertheless, consider a scenario where there is 100% establishment failure in the form of mortality losses after establishment followed by reestablishment in the second year. We find that under 100% crop failure and replanting, miscanthus achieves neither first-order nor second-order stochastic domination over conventional crops and switchgrass in the Midwest (at \$60 Mg b^{-1} and \$80 Mg C^{-1}) where instead switchgrass achieves second-order stochastic dominance over conventional crops and miscanthus crops. Further, Chen et al. (2021), who use similar DayCent data, implement a sensitivity analysis under assumptions of up to 20% crop failure rates and show negligible impact on carbon mitigation through soil carbon sequestration (sensitivity analysis results and further discussion are in Appendix A.15 and Figure A.7). Third, following Skevas et at., (2016) we consider the case of maturation risk, where miscanthus crops do not reach maturity till the fifth year and produce a lower yield of similar magnitude to the second year up till the fourth year. We find that delayed maturity has only a small effect on overall returns due to the long life of the bioenergy crops (Appendix A.16 and Figure A.8). Fourth, Chen, Gramig, & Yun (2021) show that yield under conservation tillage is not statistically different from conventional tillage, however, they point out that a yield penalty could arise when farmers adopt conservation tillage but do not change other management practices accordingly, We, therefore, reduce no-till corn yields by 10%. We consider the case where corn yields under conservation tillage are not lower than those under conventional tillage as shown by Chen, Gramig, & Yun (2021), and find there are no significant differences in returns and riskiness for bioenergy crops (Appendix A.17 and Figure A.9).

4 Discussion

We make several simplifying assumptions in our analysis. We assume that soil carbon will permanently be sequestered in the ground and therefore we value one unit of carbon sequestered in the soil as one unit of carbon mitigation. We assume that the entirety of the carbon mitigation payment will go to the farmer and not to other agents in the value chain such as the processing plants or transporters. There is extensive literature that has looked at conditions in which policy payments get capitalized in the value of the rent, which comes under certain assumptions about inelasticity of demand for output, the elasticity of supply of land, and changes to input prices, etc. (Alston, 2007). It is reasonable to assume some of these criteria might be true under certain market conditions, however, assuming that the entirety of the carbon mitigation payment will go to the farmer at best provides an upper bound to the payment a farmer can expect to receive from such policies. Moreover, we assume that farmers will not change their behavior in later years after choosing cropping decisions. We additionally assume that all farmers in each county have the same time discounting factor. We do not include other conventional crop choices beyond corn and soybean; however, other crops may be more profitable in some parts of the rainfed region. We do not take into account that yield for energy crops may be lower at the end of the fifteen-year land tenure. We also assume that all crop productivity and yield variability depend only on factors captured by the DayCent model. Furthermore, we do not take into account that farmers may change their input usage to increase profits, such as changing fertilizer application which may result in higher yield but lower carbon mitigation. However, we expect the insights provided by our analysis of the effects of carbon mitigation payment to hold. We leave it to future research to go beyond our analysis and simulate how carbon mitigation payment would affect farmer adoption of bioenergy crops and consider the cost-effectiveness of carbon mitigation policies for bioenergy crops compared to other methods of carbon mitigation.

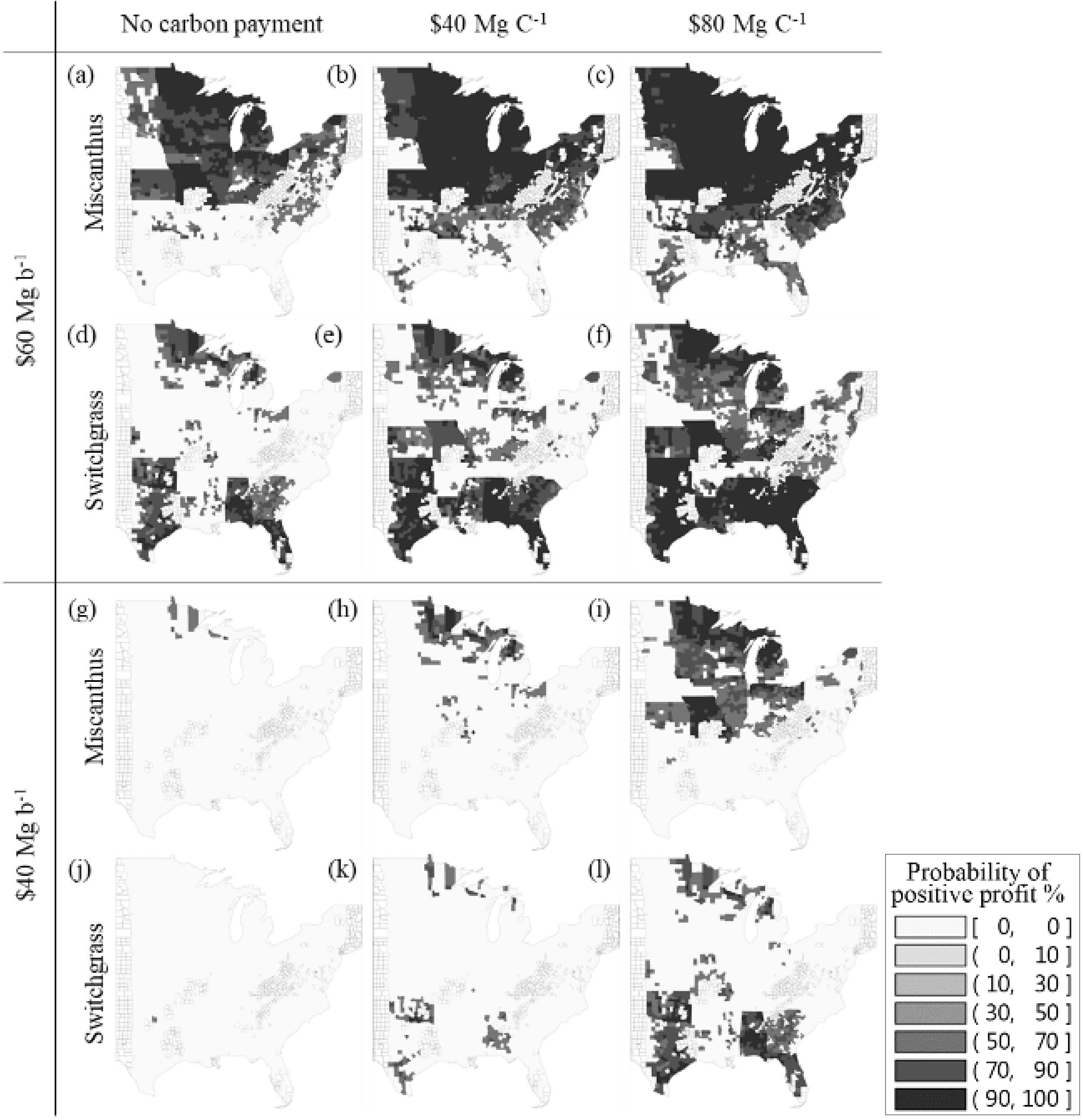
Tables and Figures

Figure 1. Biomass price at which county attains 50% likelihood of positive profit under Error! Reference source not found.



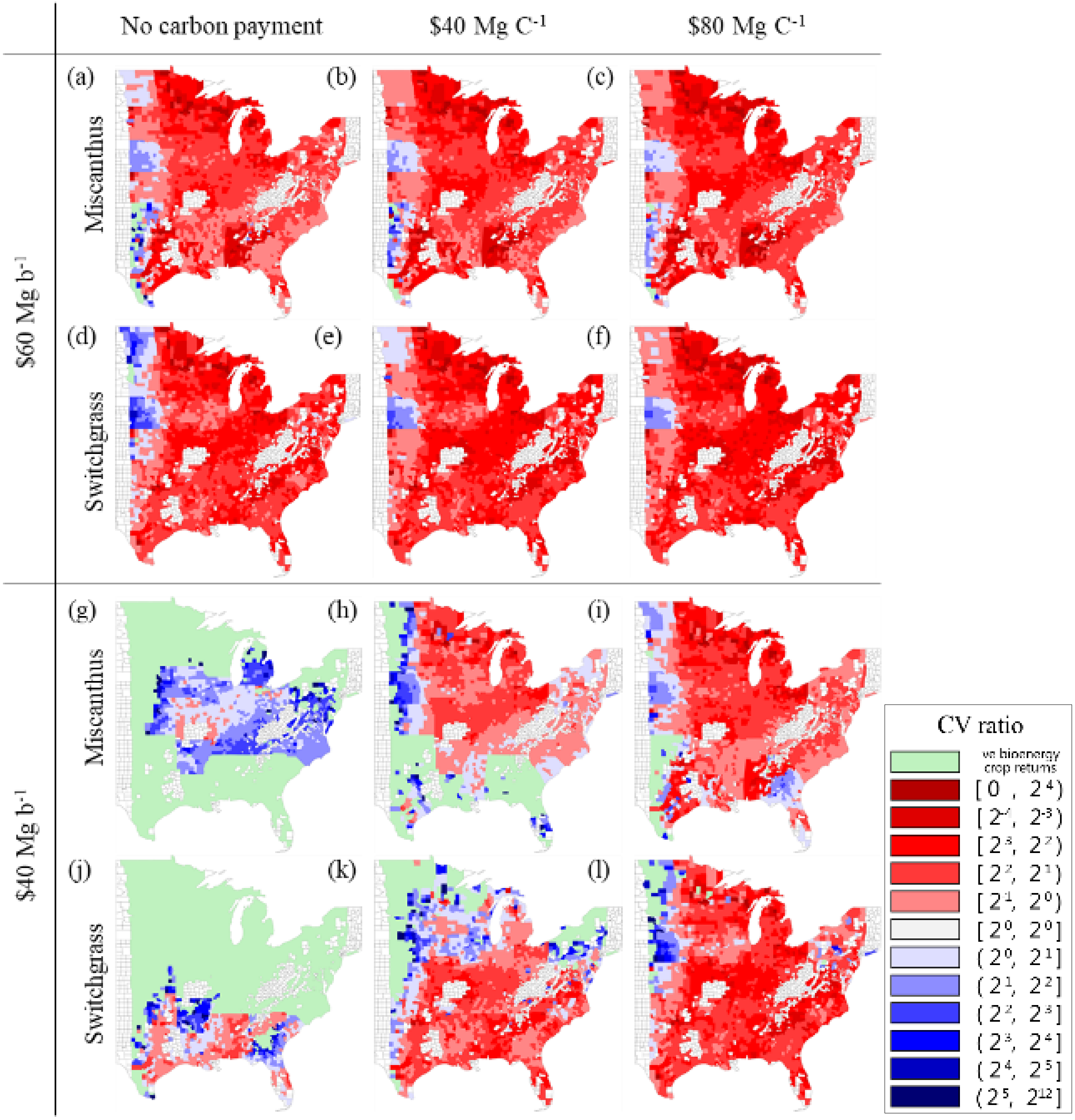
These graphs show the lowest biomass price at which each county achieves a 50% likelihood of positive profit for miscanthus after including carbon mitigation payment. For miscanthus, counties in the Central Midwest have the lowest price where farmers achieve 50% positive profit. For switchgrass, the Southern Great Plains and the Southeast states have the lowest price where farmers achieve 50% positive profit. Carbon mitigation payment lowers the price where farmers achieve 50% positive profit and expands the region where farmers achieve at least 50% positive profit at low biomass prices.

Figure 2. Probability of Positive Profit at \$40 Mg b^{-1} biomass price



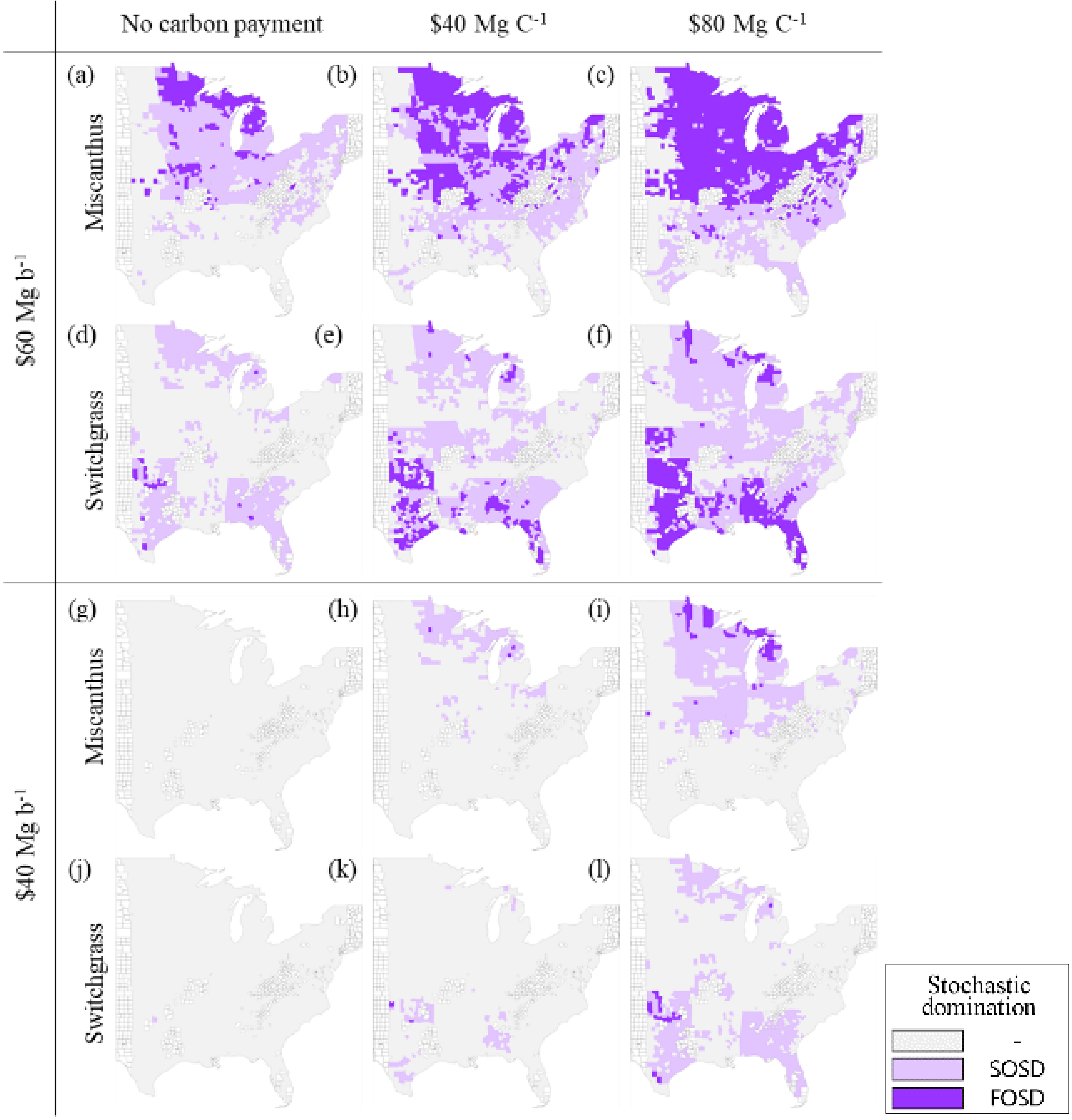
Breakeven prices for miscanthus are lowest in the Midwest around \$50 Mg b$^{-1,}$ breakeven prices for switchgrass are lowest in the southern states as well as some counties in the Midwest around \$50 Mg b$^{-1.}$

Figure 3. The ratio of bioenergy and conventional crop CV at $60 and 40 Mg b^{-1} biomass under Error! Reference source not found.



CV is the stochastic domination of a return distribution normalized by its mean; CV ratio is the ratio of bioenergy crop CV relative to that of conventional crops. Red areas depict counties where bioenergy crops are less risky (in terms of **Error! Reference source not found.**) than conventional crops, and blue areas depict where they are riskier. Green areas are those where bioenergy crop returns are negative.

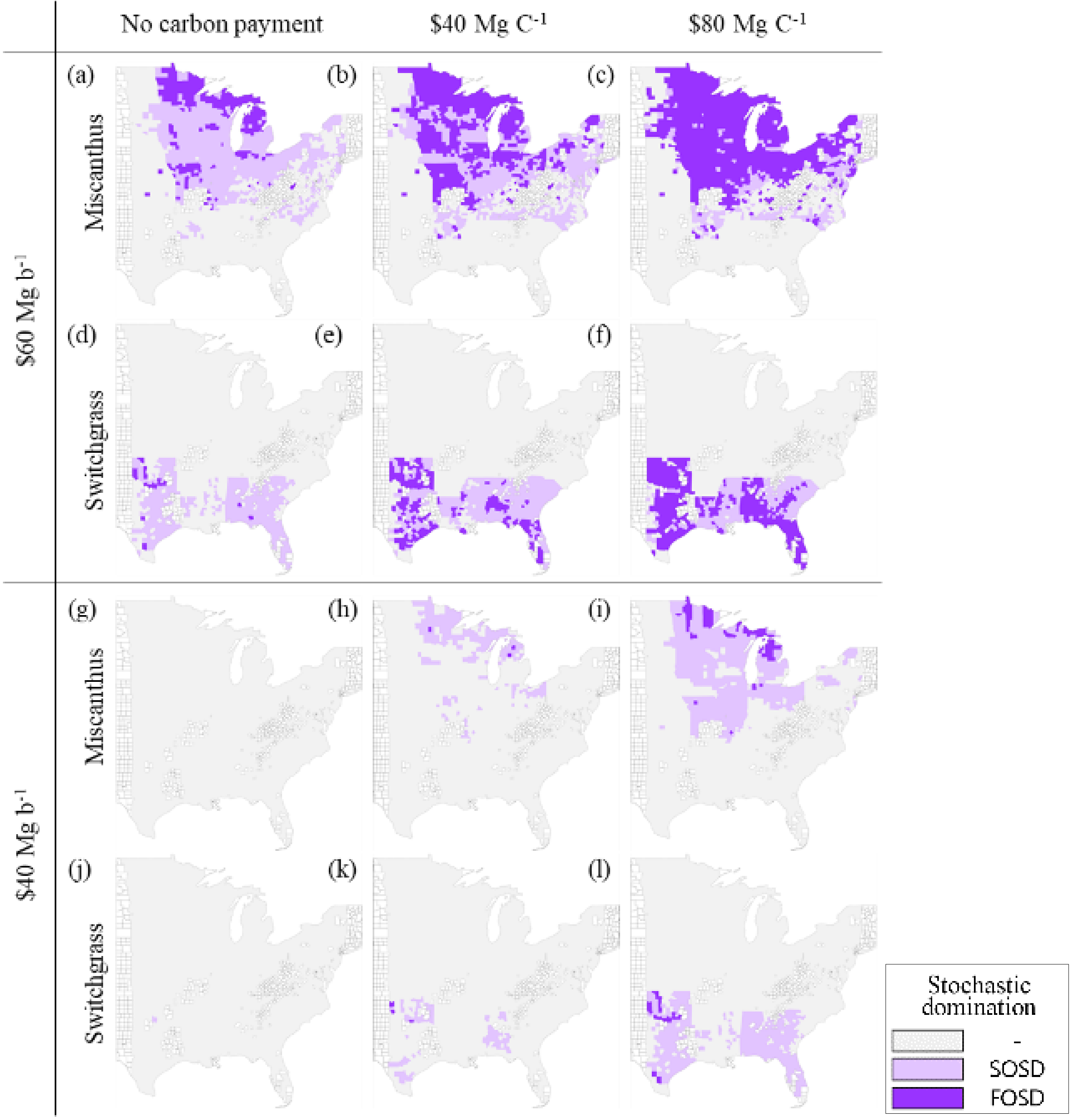
Figure 4. Stochastic dominance of bioenergy over conventional crop returns at \$60 and 40 Mg b^{-1} under Error! Reference source not found.



"SOSD" represents counties with second-order stochastic dominance only. "FOSD" represents counties with first-order stochastic dominance and second-order stochastic dominance. "-" represents counties where neither dominance criteria are met. At \$60 Mg $b^{-1,}$ under no carbon mitigation payment, most counties in the Midwest achieve second-order stochastic dominance over conventional crop returns. For switchgrass, large parts of the southern states, as well as some counties in the northern Midwest, achieve second-order stochastic dominance over conventional crop returns. Carbon mitigation payment for miscanthus allows counties in the

Central Midwest and Upper Midwest to achieve first-order stochastic dominance and expands the region where farmers achieve second-order stochastic dominance. Carbon mitigation payment for switchgrass allows for some counties in the southern states to achieve first-order stochastic dominance and expands the region where farmers achieve second-order stochastic dominance to span much of the Central Midwest and Upper Midwest.

Figure 5. Stochastic dominance of bioenergy over other bioenergy crops and conventional crops returns at \$60 and 40 Mg b^{-1} under Error! Reference source not found.



"SOSD" represents counties with second-order stochastic dominance only. "FOSD" represents counties with first-order stochastic dominance and second-order stochastic dominance. "-" represents counties where neither dominance criteria are met. At \$60 Mg b^{-1}, under no carbon mitigation payment, most counties in the Central Midwest and Upper Midwest achieve second-order stochastic dominance over conventional crop returns. For switchgrass, the Southern Great Plains, and the Southeast states as well as some counties in the Central Midwest and Upper Midwest achieve second-order stochastic dominance over conventional crop returns. Carbon mitigation payment for miscanthus allows counties in the Central Midwest and Upper Midwest to achieve first-order stochastic dominance and expands the region where farmers achieve second-order stochastic dominance. Carbon mitigation payment for switchgrass allows for counties in the Southern Great Plains and the Southeast states to achieve first-order stochastic dominance and expands the region where farmers achieve second-order stochastic dominance to span much of the Central Midwest and Upper Midwest.

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Appendices

Appendix A: Metrics construction

A.1 Stochastic domination: first-order stochastic domination

First-order stochastic dominance criteria is that for portfolio A to dominate portfolio B, and $F_A(x) \leq F_B(x)\ \forall x$ where x denotes revenue and $F_A(x)$ and $F_B(x)$ are the cumulative distribution function values for portfolio A and B at point x respectively. If bioenergy crop returns dominate conventional crop returns in the FOSD sense, then a farmer will prefer the bioenergy crop to the conventional crop, regardless of her risk preferences (Hardaker, 2004)., This indicates that a decision-maker only prefers higher returns over lower returns from any particular investment option and makes no assumption about decision maker risk preferences. Graphically, if the cumulative distribution of returns for a bioenergy crop is always below and on the right of the cumulative distribution for conventional crops. For example, Figure A.10 (a) which displays the cumulative distributions of NPVs, shows that the red line has first-order stochastic dominance over the black line in the FOSD sense. Additionally, in the example, the blue line does not have first-order stochastic dominance over the black line. If the cumulative distributions of returns for the two investments cross at any point, then the two returns cannot be ranked by FOSD.

A.2 Stochastic domination: second-order stochastic domination

Second-order stochastic dominance criteria is that for portfolio A to dominate portfolio B, $\int_{-\infty}^{x} F_A(x) \leq \int_{-\infty}^{x} F_B(x)\ \forall x$ where x denotes revenue and $F_A(x)$ and $F_B(x)$ are the cumulative distribution function values for portfolios A and B at point x respectively. If returns from a bioenergy crop dominate returns from conventional crops, then a risk-averse farmer will prefer the bioenergy crop to the conventional crop if they are willing to accept lower revenue with certainty than higher but more variable revenue (and generally prefer higher returns over lower returns). SOSD criteria are analyzed by looking at the area underneath the cumulative distribution curve. If the area under the cumulative distribution function curve for a bioenergy crop is always smaller than that for a conventional crop, then the returns from the bioenergy crop dominate the returns from the conventional crops in the SOSD sense. For example, in Figure A.10 (b) which shows the difference in the area underneath cumulative distributions of NPVs, shows that the red line has second-order stochastic dominance over the black line. If the difference is negative at any point, then the SOSD criteria are unable to determine whether the risk-averse farmer would invest in bioenergy crops over conventional crops.

A.3 Yields

Simulated yields of corn, corn stover, soybean, miscanthus, and switchgrass are taken from the biogeochemical model, DayCent using output mass and conversion rates provided by DayCent. For conventional crops, yield data is used for corn-soybean and corn-corn rotations, and conventional and no-tillage, as well as with corn stover removed and not removed. DayCent is the daily version of the CENTURY model (Parton, Schimel, Ojima, & Cole, 1994), and simulates changes in carbon and nitrogen in the ecosystem including simulation of plant production and changes in soil organic matter where plant production is a function of genetic potential, phenology, nutrient availability, water/temperature stress, and solar radiation.

As large-scale commercial production of bioenergy crops is yet to commence in the **Error! Reference source not found.**, data from field experiments with miscanthus and switchgrass across the **Error! Reference source not found. Error! Reference source not found.** are used to calibrate the productivity parameters in the DayCent model that relate soil attributes and weather with yields (Hudiburg T. W., et al., 2016). DayCent is then used to obtain simulated yields of miscanthus and switchgrass with the assumption that the previous thirty years of historical weather conditions for each county cycle are in a randomly distributed order.

In DayCent, Miscanthus takes two years to reach maturity and has crop cycles for two cycles of fifteen years, while Switchgrass reaches maturity in the second year and spans three cycles of ten years. For both bioenergy crops, yields are at mature levels without any aging effect. Corn, Soybean, and Stover are annual crops that reach maturity, are harvested, and are replanted each year. As we cannot disentangle the weatherization effect and crops growing before reaching maturity, we only have years where we have mature level yields for all crops, so only the 24 years of yields with randomized weather data are used where all yields are mature. **Error! Reference source not found.** presents the summary statistics of the average mature yields and standard deviation across and within counties for both bioenergy crops and land types. Yields for all crops are considered dry yields with 13 percent moisture and no storage, transportation, or harvest loss. There is a slight difference in the DayCent yields of the four rotation/tillage options for corn. Additionally, switchgrass yields have a higher variation, making it possible to have higher switchgrass yields in certain counties.

Figure A.5 shows the geographical distribution of the three sources of biomass. Switchgrass is productive throughout the eastern United States with a higher yield in the Southern states. Miscanthus is more productive in the northern United States, but its productivity drops off significantly in the Southern states. Miscanthus has an overall higher yield, reaching up to 28 Mg ha^{-1} (with 13% moisture) in the Central Midwest and South-Central areas and switchgrass has the highest yields in the Southeast and Delta region, reaching up to 16 Mg ha$^{-1.}$ It should also be noted that miscanthus has a higher yield in many counties in the Southern states where switchgrass yields are the highest.

For bioenergy crops, we assume that the crop lifespan for both switchgrass and miscanthus is fifteen years or longer and use the first fifteen years of data for our analysis. Miscanthus is assumed to have no harvestable yield in the first year, a half the mature yield in the second year, and a fully mature yield from the third year onward. Switchgrass is assumed to reach mature yield in the first year and does not show a significant reduction in yield beyond its regular lifespan of ten years. Bioenergy crops, therefore, mature no later than their third year so the yields between years three and fifteen for either bioenergy crop are assumed independent of previous years.

As there is no consensus on the optimal removal rate of corn stover and whether to maintain soil carbon levels or corn yields, corn stover removal rates are dependent on the DayCent model parameters which are set at 0% and 50% for no-till and 30% for till yields, as no-till cropping disturbs the soil nutrients less, as shown below, and allows for greater removal of corn stover. corn yields for when corn stover is removed and when it is not removed do not differ significantly so only the corn yield when corn stover is removed is considered for each rotation/tillage for both corn stover removal and non-removal.

For corn-soybean rotations, the DayCent simulated two scenarios for each tillage option, corn-soybean, and soybean-corn with the base year starting with corn and soybeans, respectively. As yields are independent by year-by-year but each year shares the same weather draw, we assume that for planting a mixed rotation conventional crop, half planted corn, and the other half soybeans.

A.4 Carbon emissions calculations

Carbon intensity calculations in $g\ CO_2eq\ Mj^{-1}$ are computed for each feedstock by county and land type for the establishment and full yield years using the methodology as highlighted in

Dwivedi et al., (2015). Application rates of inputs that are not available in the DayCent model are taken as specified in Dwivedi et al., (2015). Lifecycle carbon intensity is calculated as a sum of emissions across various sectors through life-cycle analysis. The major components included are material input usage, electricity, diesel, and transportation bioenergy use, electrification co-credits, and ethanol production emissions resulting over the lifecycle of the various cellulosic ethanol feedstocks.

Lifecycle emission intensities are calculated as follows. First, we calculate the bioenergy content per hectare for each feedstock, which is tied to the yield of the crops.

$$MJ\ ha^{-1} = [Mg\ ha^{-1} yield] \times [Gallons\ of\ ethanol\ produced\ \ Mg\ b^{-1}\ biomass] \\ \times\ [MJ\ Gallon^{-1}\ energy\ content]$$

Next, for material input usage, we consider nitrogen, potassium, phosphorus, insecticide, lime, and herbicide application rates. Sources of application rates are detailed in previous sections and are applied as either Kg Input ha^{-1} or Kg Mg b^{-1} and multiplied by the gCO_2 emitted per g of input used. Emissions related to electricity, diesel, and transportation usage are taken as parameters of the global warming intensity of the service used. The electricity co-product credit is applied as a constant parameter per MJ produced used and is negative. Ethanol production emissions are applied as constant parameters by feedstock related to the emissions produced while converting a feedstock to ethanol.

Data for carbon emission factors of gCO_2 per MJ energy, electricity co-credit, and calorific values of fuels are taken from the GREET model. Nitrogen application rates for bioenergy crops are taken from the DayCent model, while corn stover application rates are taken from Dwivedi et al., (2015). Table A.13 and Table A.14 provide an overview of the data used to compute carbon emissions with factors used to calculate emissions in the first table and application rates in the second.

Presented in Table A.15 are the estimated lifecycle material input carbon intensities of the various sources of cellulosic feedstocks. For miscanthus, the lowest carbon intensity is in the Midwest and Central East, followed by the Northeast.

Due to the higher fertilizer requirements for feedstock, switchgrass is more carbon-intensive than miscanthus. As corn stover fertilizer requirement is less compared to other feedstocks, requiring only replacement nitrogen material intensity is lower than switchgrass for No-till corn-soybean rotation where the replacement fertilizer requirement is minimal as crop rotation reduces the material use demand on corn stover production, thereby leading to a lower carbon intensity for corn-soybean rotations.

Total lifecycle emission mitigated calculated relative to gasoline as follows for each feedstock.

$$GHG\ mitigation_{lifecycle} = GHG\ intensity_{gasoline} - GHG\ intensity_{biomass}$$

Finally, we convert the total carbon mitigated lifecycle back to a carbon saved per hectare to incentivize the total carbon saved lifecycle and use the carbon sequestered per hectare as the carbon saved belowground.

A.5 Calculation of baseline sequestration rate

Please see Appendix A.7 for the setup of general numerical simulation. For belowground soil carbon emissions reduction, we consider the additional sequestration that occurs due to the harvest of energy crops and corn stover denoted by b_t^e and b^k respectively. From the data, we have the change in absolute sequestration from energy crops for each time period $r_{d,t}^e$ and change in absolute sequestration for conventional crops with and without corn stover harvest, r_1^c and r_0^k

respectively. The baseline rate $r_{d,0}$, is calculated using a simplified numerical simulation to elicit which conventional crop the farmer will plant when they receive no carbon mitigation payment. The expected utility is for any rotation and tillage option is given by

$$V_k^0 = \sum_{t=1}^{\overline{T}} \beta^{t-1} E\left[\, u\left(\left[\pi^c + h_k \pi_k^{A,s}\right] \mid \beta, \lambda\right)\right], \tag{A.3.1}$$

from which the farmer chooses the conventional crop, c_0^*, with the highest expected utility, V_k^0, from all four possible conventional crop choices where $k \in C$ so

$$r_{cropland,0} = \begin{cases} r_0^c, \; h_k = 0 \\ r_1^c, \; h_k = 1. \end{cases} \tag{A.3.2}$$

Additional sequestration for each crop choice is calculated as the sequestration that occurs over the baseline sequestration rate such that $b_{d,t}^e = r_{d,t}^e - r_{d,0}, \forall e, d, t$ for all energy crops and $b^k = r_1^k - r_{cropland,0}, \forall k$ with all conventional crops. Note that soil carbon change from the end of the final year of the planting cycle is not considered for any crop as it is dependent on the farmers' future planting choices.

A.6 Soil Carbon Sequestration Calculations

Annual levels of total carbon in the soil organic matter pool are provided for all crops through the DayCent model for each year of the planting period. This data includes annual soil carbon levels for all rotations and tillage as well as corn stover harvest combinations for conventional crops and all choices of bioenergy crops. The difference between soil carbon levels over the planting period is used to calculate the annual rate of soil carbon sequestration during the planting period. For bioenergy crops, the soil carbon change in each year of the establishment period is calculated independently and the rates during the mature period are calculated independently.

Carbon mitigation payments are intended to pay for the additional carbon sequestered relative to a baseline level that the farmer would have planted without being incentivized. We conduct a simplified numerical simulation detailed in Appendix A.5 to simulate farmer conventional crop rotation and tillage choices with no corn stover harvested under a no carbon mitigation payment scenario at each level of biomass price. Annual rates of additional soil carbon sequestration under biomass production, through corn stover harvest or bioenergy crop production, are calculated as the difference in the annual rate of sequestration of each crop choice from the baseline rate of sequestration.

Additional sequestration rates (i.e., sequestration rates in addition to baseline rates) will depend on the difference between the sequestration rate of a biomass crop and the baseline sequestration rates. If for example, the alternative use of land is corn-soybean under conventional tillage, which results in soil carbon loss, switching to miscanthus will result in the soil carbon benefits of adopting miscanthus as well as switching away from corn-soybean under conventional tillage. Similarly, switching from continuous corn no-tillage, which already has positive sequestration benefits, to miscanthus will result in a lower sequestration rate as continuous corn-no tillage already sequesters some amount of carbon.

Soil carbon sequestration in the case of harvesting corn stover is also composed of two parts. First, there may be soil carbon loss when harvesting corn stover, as corn stover removal results in lower additional sequestration rates after corn stover removal than their respective baselines. Second, farmers may change rotation and tillage practices due to higher biomass prices or soil carbon sequestration payment. Incentivizing soil carbon sequestration may therefore encourage farmers to switch from cropping practices that have low or negative sequestration rates, such as corn-soybean under conventional tillage, to those that have a higher sequestration rate after corn stover removal, such as continuous corn under no-tillage. Details of the calculation of the net soil carbon sequestration are presented in Appendix A.6.

Table A.11 shows regional averages for the baseline county-level sequestration rates. Figure A.11 shows the change in total soil organic carbon over 15 years for three selected counties, Champaign, IL, Talladega, AL, and Harper, OK to illustrate additional soil organic accumulation potential for feedstock at locations with varying ecological compositions. For baseline bioenergy crop sequestration, Figure A.11 (a-b), we note that in the establishment period of bioenergy crops, there is a release of soil carbon that continues to the second or third year, and only after the plant reaches maturity does the sequestration rate start to increase and substantially high levels that are much larger than row crop rates. Bioenergy crop sequestration rates used in the model are divided into sequestration in the first year, the second year, and an average sequestration rate for subsequent years per county while row crops sequestration rates used is an average value over the life of the crop.

A.7 Bioenergy crop cost calculations

As can be seen in Table A.9, which shows the fixed cost per hectare over the life of the crop, the largest expense the farmers face is the high establishment and fixed costs in the first few years before bioenergy crops produce yield at a mature level.

For miscanthus, the establishment cost per hectare is above $2,200, while switchgrass is cheaper at around 690 per hectare, however, the fixed cost after the establishment period for miscanthus is lower. A uniform payment would therefore subsidize all bioenergy crops similarly over the region and land type rather than favoring those that produce larger carbon mitigation through high yields and gasoline displacement or below ground sequestration.

There is also a larger variance in cost by county for switchgrass than miscanthus.

presents the operating cost per ton of biomass produced, where we use the farmer's expected yield in each county, we can see that it is cheapest to produce miscanthus in the Midwest, South Central, or Central East regions with the Southern states being substantially more expensive. For switchgrass, the cheapest places to produce are in the Southern states, all areas that are more costly to produce miscanthus. Additionally, the Northern Great Plains are expensive for both bioenergy crops.

A.8 Numerical Analysis setup and Bioenergy crop returns

We assume that the farmer chooses to plant a perennial energy crop (e) in place of a conventional annual crop rotation and tillage (c). $\bar{T}$ is land tenure and t depicts the discrete years during this period such that $t \in \{1,2.\bar{T}\}$. Conventional crops complete one lifecycle each year while energy crops complete one lifecycle during the fifteen-year cycle.

The energy crop lifecycle can be separated into an establishment period and a maturity period with $\hat{t}$ being the number of years in the establishment period. The foregone returns of using cropland for energy crop production are the returns from conventional crops on that land. All bioenergy crops provide carbon mitigation services from lifecycle gasoline displacement, l, which varies with feedstock yield as well as from belowground soil carbon sequestration, b, which varies temporally over the fifteen-year cycle. Farmers receive a biomass price p^b per unit of biomass yield and a carbon mitigation payment p^g per unit of carbon mitigated where payment is made annually.

Bioenergy Crop Returns

We consider two energy crops, miscanthus, and switchgrass. Let *me* denote the energy crop, so we have $e \in E \equiv \{miscanthus, switchgrass\}$. In the bioenergy crop establishment period, the farmer incurs a cost, w_t^e, per unit of land to establish the energy crop for each year. The farmer harvests the bioenergy crop, where the yield y_t^e differs temporally and is stochastic with distributions known to the farmer and yields realized at harvesting. Miscanthus is not harvested in the establishment period and produces a lower yield until it reaches the mature period while switchgrass produces harvestable yield in the establishment period as well. Following Miao & Khanna., (2017a), we assume that miscanthus has no yield in the first year, half the mature level yield in the second year, and mature yield from the third year onward. Similarly, following Miao & Khanna., (2017a), we assume that switchgrass has full yield throughout the land tenure. The farmer receives the value of carbon mitigated in the year it was mitigated. For energy crops, profit per unit of land in year t is

$$\pi_t^e = \begin{cases} -w_t^e + p^g b_t^e, & t \leq \hat{t}, e = misc \\ -w_t^e + (p^b - v^e) y_{y_t^e}^e + p^g b_t^e - f^e, & t \leq \hat{t}, e = swit \\ (p^g l^e + p^b - v^e) y_{y_t^e}^e + p^g b_t^e - f^e, & t > \hat{t}, \end{cases} \quad \text{(A.1.1)}$$

where f^e is the fixed cost, v^e a variable cost, and p^b the payment per unit of biomass, p^g is the payment per unit of carbon mitigated, l^e is the lifecycle carbon mitigated in a year per unit of biomass, b_t^e is the total belowground. We detail the construction of b_t^e in Appendix A.5.

The NPV of bioenergy crop $\boldsymbol{e}$ is given as

$$\boldsymbol{NPV_{e,full}} = \sum_{\boldsymbol{t=1}}^{\boldsymbol{\bar{T}}} \boldsymbol{\beta^{t-1}} [\boldsymbol{\pi_t^e}], \quad \text{(A.1.2)}$$

where the farmer's discount rate is $\boldsymbol{\gamma} \in [\mathbf{0}, \mathbf{1}]$ such that the discount factor $\boldsymbol{\beta} = \mathbf{1}/(\mathbf{1} + \boldsymbol{\gamma})$.

To compare revenues between bioenergy crops, which are perennial, and conventional annual crops, we present all results as annualized values. To compare revenues between bioenergy crops, which are perennial, and conventional annual crops, we present all results as annualized values. We, therefore, convert all NPV calculations to annualized equivalents following Weston & Copeland, (1986). The annualized NPV for energy crop e is calculated as

$$ANPV_e = \frac{\gamma \, NPV_e}{1 - \frac{1}{(1+\gamma)^T}}, \qquad \text{(A.1.3)}$$

where $ANPV_e$ is the annualized NPV of bioenergy crop e, γ is the discount rate, and T is the lifespan of the bioenergy crop.

A.9 Conventional crop production cost calculations

Presented below in Table A.7 are the total cost per bushel of corn and soybean divided by regions and rotation and tillage. On average, soybean is cheapest to produce in the Midwest while corn costs vary by tillage and rotation but is cheapest in the Northern States and cheaper to produce under no-till practices. For corn, the revenues needed are close to the market price, which reflects the position of corn as a narrow margin crop. Soybeans follow a similar pattern but have wider profit margins. In both cases, there is a high standard deviation showing the variation in prices across regions.

A.10 Conventional crop price calculations

We use four price inputs for soybean and corn to generate prices for the numerical analysis; a national level realized price, state-level realized farm gate prices, a national-level historical harvest price, and a country level historical futures price to generate a price distribution for the model, and exogenously sets a biomass and carbon mitigation payment. State-level and national received prices for corn and soybean are obtained from the USDA National Agricultural Statistics Service and averaged for the 2016 harvest period of available states, Sept, Oct, and Nov with the marketing year used for states where monthly data is not available. National prices over this period at \$3.71 per bushel for corn and \$9.41 for soybean. Annual national-level historical prices are taken for the past thirty years from 1987 to 2016 from NASS. Country-level historical futures prices for corn and soybeans are derived from the Chicago Board of Trade futures prices for the same years with prices being averaged from Sept to Nov taken from https://www.macrotrends.net/. Both historical prices are then converted to 2016 dollars using Gross Domestic Product: Implicit Price Deflator obtained from the St Louis Federal Reserve with third-quarter values being used to adjust historical prices. As prices are considered to be stochastic along with yields, the difference in state-level prices and national-level prices is used to calculate a price basis, while the log difference in realized and futures prices are used to calculate the distribution in risk, which is used using a Copula method to generate a distribution of prices and yields for the model. Table A.6 shows the distribution of the three prices for corn and soybeans.

A.11 Stover harvest cost calculations

As there is no significant difference in harvesting and storage costs between tillage choices and rotations, the major difference in costs is due to replacement nitrogen application rates which differ over the four tillage and rotation. Potassium and Phosphorus applications are applied as a variable cost as given by Dwivedi et al., (2015). It should be noted that while corn stover production costs matter on their own, a farmer's willingness to harvest corn stover also depends in part on the profitability and riskiness of corn and soybean. Presented in are the total cost per bushel of corn and soybean divided by regions and rotation and tillage. On average, the no-till harvest is more expensive as it requires a higher replacement rate for nitrogen loss, however, no-till also and the great plains and Midwest region are the cheapest places to harvest corn stover.

Corn stover offer requirement is similar to or slightly higher than the cost of producing bioenergy crops as it has a similar harvest cost structure to bioenergy crops with the addition of raking and storage requirements, however low yields mean that per Mg of corn stover harvested, fixed costs have a greater impact on the costs. Corn stover cost requirements also show low variation both spatially and minimal variations within counties as its yield closely follows that of corn making corn stover both less risky and similar in cost to bioenergy crops as a source of biomass. Additionally, with corn stover harvests, farmers do not need to forgo their row crop harvests, something they will have to do in the case of bioenergy crops. Interventions based solely on payment for biomass yield will encourage farmers to harvest more corn stover, which may have a net negative effect through the removal of soil organic carbon.

A.12 Conventional Crop Return

We consider two types of rotation for conventional crops, corn-corn (cc) or corn-soybean (cs) rotation, under conventional tillage (ct) or reduced/no-tillage (nt). Let *c* denote the conventional crop rotation and tillage combination and we have $k \in C \equiv \{(cc, ct), (cc, nt), (cs, ct), (cs, nt)\}$. The yields and prices of corn grain and soybeans are denoted by y_k^{corn}, $y_k^{soybean}$, p^{corn}, and $p^{soybean}$, respectively. The yields and prices of the conventional crops are stochastic, with distributions known to the farmer and the yields and prices realized at harvesting. The fixed and variable costs of producing corn, soybeans, and corn stover are represented by f_k^{corn}, $f_k^{soybean}$, v_k^{corn}, $v_k^{soybean}$ respectively where fixed costs (denoted by f_k^{corn}, and $f_k^{soybean}$) are per unit of land and variable costs (denoted by v_k^{corn}, and $v_k^{soybean}$) are per unit of yield produced. Conventional crop profit per unit of land for corn grain and soybeans without corn stover harvest under rotation-tillage combination in set *C* can then be written as $\pi_{\mathrm{k}}^{\mathrm{corn}} = (p^{corn} - v_k^{corn})y_k^{corn} - f_k^{corn}$ and $\pi_{\mathrm{k}}^{\mathrm{soybean}} = \left(p^{soybean} - v_k^{soybean}\right)y_k^{soybean} - f_k^{soybean}$. For corn-soybean rotation, we assume that half of the land is used for corn and half for soybeans. Overall conventional crop profit without corn stover harvest or carbon mitigation payment is

$$\pi^k = \begin{cases} \frac{1}{2}\pi_{\mathrm{c}}^{\mathrm{corn}} + \frac{1}{2}\pi_{\mathrm{c}}^{\mathrm{soybean}}, c \in \{(cs, ct), (cs, nt)\} \\ \pi_{\mathrm{c}}^{\mathrm{corn}}, c \in \{(cc, ct), (cc, nt)\}. \end{cases} \tag{A.2.1}$$

Additionally, corn stover is produced as a by-product of corn from any conventional crop choice and may be harvested for biomass only if the farmer deems it profitable to do so. The farmer receives a biomass price, p^b per unit of biomass produced through corn stover. The fixed and variable costs of producing corn stover for crop c are represented by f_k^s and v_k^s respectively, where fixed costs are per unit of land and variable costs are per unit of yield produced. We assume that one-unit corn stover yield generates l^c units of lifecycle carbon mitigation. We also assume that one unit of land harvesting corn stover will produce b^c units of carbon mitigation through soil carbon sequestration. As corn-soybean rotations will only produce half the corn. Profit from harvesting corn stover from corn from a rotation-tillage combination is denoted as

$$\pi_k^{\mathrm{s}} = \begin{cases} \frac{1}{2}((p^b - v_c^s + p^g l^k)y^k + p^g b^k - f_k^s), k \in \{(cs, ct), (cs, nt)\} \\ (p^b - v_k^s + p^g l^k)y^k + p^g b^k - f_k^s, k \in \{(cc, ct), (cc, nt)\}. \end{cases} \tag{A.2.2}$$

For simplicity, we assume that corn stover is harvested if and only if the expected gains from doing so are positive. The condition to harvest, (h_k = 1) or not (h_k = 0) is calculated as the expected profit such that

$$h_k = \begin{cases} 1, & E[\pi_k^s] \geq 0 \\ 0, & E[\pi_k^s] < 0. \end{cases} \tag{A.2.3}$$

The net revenue from conventional crop c for one unit of land is given as

$$\Pi_k = \pi^k + h_k \pi_k^s. \tag{A.2.4}$$

Conventional crop profit distribution

Farmer choice of conventional crop rotation, tillage, and corn stover harvest choice determine the value of returns from the current use of the land and could vary according to expected yields and prices. Using the yield and conventional price distributions generated as described in Section C.4, net revenue for each rotation and tillage is calculated as described above for each exogenous price p^b and p^g. For each element i of this distribution, the highest net revenue is chosen as the current use net return. This is done as farmers be expected to react differently at different expected yield and conventional crop price levels, which vary for each i, and choose different rotation and tillage for each one. Farmer net returns for conventional crop net revenue are given by

$$\Pi_{CC,i} = max\left(\Pi_{cc,ct,i}, \Pi_{cc,nt,i}, \Pi_{cs,ct,i}, \Pi_{cs,nt,i}\right) \forall i. \tag{A.2.5}$$

The NPV of current use for one unit of land is then given as

$$NPV_{CC,full} = \sum_{t=1}^{\overline{T}} \beta^{t-1} \left[\Pi_{CC}\right], \tag{A.2.6}$$

where the farmer's discount rate is $\gamma \in [0,1]$ such that the discount factor $\beta = 1/(1 + \gamma)$.

Similarly, we generate the annualized NPV from current use as

$$ANPV_C = \frac{\gamma \, NPV_{CC}}{1 - \frac{1}{(1+\gamma)^T}}, \tag{A.2.7}$$

where $ANPV_C$ is the annualized NPV of the current use of the land and NPV_{CC} is the NPV of the same. For ease of discussion, we will write $ANPV_C$ and $ANPV_e$ evaluated at p^b and p^g as $ANPV_C(p^b, p^g)$ and $ANPV_e(p^b, p^g)$ going forward.

A.13 The riskiness of yields and prices

A joint yield-price distribution is assumed where the farmer knows the distribution of prices and yields estimated for their county to reflect the stochastic nature of crop yields and prices. Stochastic crop yields are modeled for corn grain, corn stover, soybean grain on cropland for all rotation and tillage options, and miscanthus and switchgrass along with corn and soybean prices. Biomass and carbon mitigation payments are adjusted exogenously within the analysis and assumed to not affect other yields and prices. The joint distributions are modeled using the copula approach following Miao and Khanna (2017a), Yan (2007), and Du & Hennessy (2012).

Similar to Du & Hennessy (2012), yields are assumed to have beta distributions and price lognormal distributions. Once joint distributions are estimated, draws are taken to conduct a Monte Carlo simulation from which draws are obtained from the joint distributions to conduct Monte Carlo simulations. Next, a linear detrending approach is applied to remove the systematic components of yield variation for each county, which is then added to the county-level yield trend for 2016.

Table A.3 shows the mean distributions of the generated yields. Corn yields stay consistent over rotations and tillage choices except for in the Southeast and Central East regions, with the Central Midwest, South Central, Delta region, and Southeast showing the highest corn yields. Soybean yields are highest in the Central Midwest, South Central, and Delta regions. Stover yields are highest in areas where corn yield is highest. Miscanthus yields vary spatially with the Midwest and South-Central states having the highest yields and the Southeast has the lowest.

Additionally, in regions such as the Southeast where Miscanthus yield is low on cropland. For Switchgrass, the highest yield areas are the Delta region and the Southeast.

Table A.6 shows the average CV by region for all yields. Figure A.6 (a) shows the CV ratio of miscanthus to switchgrass. There is lower yield riskiness in terms of CV for crops in areas where yield itself is lower, in these areas farmers can expect low yields and can achieve them with more certainty. Some areas, however, such as the Southern Great Plains tend to have high CVs and low yields which are both risky and low yielding. This implies that switchgrass yields are less risky in the Northern States, and miscanthus yields are less risky in the Southern states. Figure A.6 (b) shows the CV ratio of miscanthus to continuous corn with conventional tillage. We use Figure A.6 (b) as a stand-in for all energy crops to conventional crops as CV ratio maps of switchgrass to other conventional crops with and without corn stover removal look similar. Corn and corn stover CV are lowest in areas such as the Northeast, Delta region, and Northern Great Plains – all areas where yield itself is lower for corn and corn stover, and the same is true for soybeans. Switchgrass and Miscanthus are less risky than row crops except for Nebraska and some counties in the Delta region.

Next, Table A.5 shows an averaged Rho Hat matrix of all draws for miscanthus and switchgrass showing the linear correlation coefficient of parameters for a Gaussian copula method, where each element has been normalized to include numbers from all draws. We can see that corn grain, corn stover, and soybeans yields are highly correlated with each other. Conventional crop yields are highly correlated with various tillage options. Stover production is however not completely correlated over various tillage and rotation options, so farmers, therefore, could choose a mixture of rotation and tillage options to lower their risk of corn stover yield. Additionally, the correlation between bioenergy crops and corn stover as well as conventional crops is low, a risk-averse farmer may, therefore, choose a mixture of cellulosic feedstock to reduce the yield risk. Miscanthus and Switchgrass yields are minimally correlated with conventional crops and corn stover yield. This indicates that for farmers, a crop mix of conventional crop rotations and tillage, as well as a mixture of bioenergy crops, may generate a large diversification benefit.

A.14 Sensitivity analysis: high discount rates

Following Miao and Khanna (2017a), we consider a case where the farmer is less patient and values future returns less. We conduct sensitivity analysis with discount rates set at 10%. We find that both bioenergy crops can achieve similar patterns of stochastic domination over conventional crops under the low discount rate scenario. At \$60 Mg b^{-1} (Figure A.4 (a-f)), carbon mitigation payments enable miscanthus to achieve first-order stochastic domination over conventional crops and switchgrass in many counties in Central Midwest, and the same for switchgrass in the Southern states similar to our main results (Figure 5 (a-f)). Additionally, at \$40 Mg b^{-1} (Figure A.4 (g-l)), carbon mitigation payments enable miscanthus to achieve second-order stochastic domination over conventional crops and switchgrass in the Upper and Central Midwest similar to our main results (Figure 5 (g-l)). The same conclusion holds for switchgrass in the Southern states.

A.15 Sensitivity analysis: miscanthus establishment failure

We consider survival risk in miscanthus crops, where there is establishment failure in the form of mortality losses after planting (Clifton-Brown & Lewandowski, 2000; Kucharik, VanLoocke, Lenters, & Motew, 2013). Evidence suggests that the rate of establishment failure is determined by the minimum air and soil temperature and can vary by location and across genotypes of miscanthus. As the DayCent model generates yield and soil dynamics based on thirty years of climate conditions at the county level, it accounts for the climatic variability and potential impact of extreme weather events such as cold winters on yield and soil carbon sequestration. Figure A.2 (a) shows that in the northern rainfed region where the risk of extreme winters is high, the expected miscanthus yields are around 20-22.5 Mg ha^{-1} and Figure A.3 (a) shows that the yield risk of miscanthus relative to switchgrass in the upper Midwest is consistent with the rest of the northern rainfed region. Further, Chen et al. (2021), who use similar DayCent data, implement a sensitivity analysis under assumptions of up to 20% crop failure rates and show negligible impact on carbon mitigation through soil carbon sequestration. Nevertheless, below we consider the case where 100% crop failure occurs for miscanthus crops in the first year and therefore needs to be replanted the next year, incurring both economic and soil carbon loss. We assume that when the miscanthus crop fails to establish, it is replanted again in the second year. So, in the first year, the farmer incurs the cost of establishment and incurs soil carbon loss. In the second year, the farmer again incurs the cost of establishment and incurs further soil carbon loss associated with bioenergy feedstock establishment. Returns from the third year onward are calculated with yields, applications, and soil carbon dynamics that would normally have occurred in the second year onward. The crop reaches maturity in the fourth year and the total land tenure is still calculated at overall 15 years.

We find that under 100% crop failure, miscanthus achieves neither first-order nor second-order stochastic domination over conventional crops and switchgrass in the Midwest even under carbon mitigation payments of \$80 Mg C^{-1} (Figure A7 (c) and Figure A.7 (i) at biomass prices of \$60 and \$40 Mg b^{-1} respectively). Additionally, switchgrass achieves first-order stochastic dominance in the south and second-order stochastic dominance over conventional crops and miscanthus crops in the Midwest under carbon mitigation payments of \$80 Mg C^{-1} (Figure A.7 (f) and Figure A.7 (l) at prices of \$60 and \$40 Mg b^{-1} respectively).

A.16 Sensitivity analysis: miscanthus delayed maturity

We consider the case of maturation risk in miscanthus crops, where the bioenergy crop is delayed in reaching maturity (Skevas, Swinton, Tanner, Sanford, & Thelen, 2016). A meta-analysis of field trials by Sharma et al. (2022) shows that the risk of delayed maturity is low. Additionally, we perform a sensitivity analysis where miscanthus yields reach maturity two years later than expected. We assume that when there is delayed maturation in the miscanthus crop, the crop produces low yields for two additional years. So, in the first year, the farmer incurs the cost of establishment and incurs soil carbon loss. From the second year to the fourth year, the farmer produces low yields, applies inputs, experiences soil carbon dynamics incurs the costs that would normally have occurred in the second year. The crop reaches maturity in the fifth year and the total land tenure is still calculated at 15 years.

We find that delayed maturity has a small effect on overall returns due to the long life of the bioenergy crops. Figure A.10 shows that at \$60 and 40 Mg b^{-1} biomass, both miscanthus and switchgrass crops achieve second-order stochastic domination over other bioenergy crops and conventional crops in a similar pattern to Figure 5, however, at a lower biomass price of \$40 Mg b^{-1} (Figure A.8 (g-l)), fewer counties achieve second-order stochastic domination in comparison to (Figure 5 (g-l)).

A.17 Sensitivity analysis: no-till yield adjustment

Lastly, We consider the case where corn yields under conservation tillage are not lower than those under conventional tillage as shown by Chen, Gramig, & Yun (2021). They also note that conservation tillage could reduce production costs by reducing fuel and labor costs and have carbon mitigation benefits by reducing soil erosion. In our analysis, we had reduced no-till corn yields by 10% to reflect a yield penalty that could arise when farmers adopt conservation tillage but do not change other management practices optimally. We consider a sensitivity analysis without applying a yield penalty for no-till practices below.

We find that more counties adopt no-till practices without biomass and carbon mitigation payment and that conventional crop returns may be slightly higher in some counties. However, there are no significant differences in returns and riskiness for bioenergy crops. Figure A.9 (a-l) shows that bioenergy crops achieve similar spatial patterns of stochastic domination to Figure 5 (a-l).

Appendix Tables and Figures

Table A.1 DayCent Yields

		min	max	mean	std of county means	mean of std within county
CT	Corn CS	65.27	224.95	149.09	25.12	29.42
	Corn CC	63.16	227.41	149.22	25.58	29.62
	Stover CS	1.04	3.48	2.46	0.42	0.48
	Stover CC	1.13	3.48	2.46	0.40	0.47
	Soybean	13.51	80.90	40.76	9.32	8.91
NT	Corn CS	65.33	220.34	149.23	25.08	29.27
	Corn CC	63.37	220.69	149.32	25.48	29.33
	Stover CS	1.83	5.59	3.99	0.64	0.75
	Stover CC	1.83	5.58	3.96	0.64	0.74
	Soybean	13.55	80.85	40.70	9.28	8.91
	Miscanthus	6.73	28.94	22.09	4.87	2.10
	Switchgrass	5.60	22.05	14.55	3.35	1.22

Computed from DayCent (2019)

Miscanthus, Switchgrass, and Stover yields are Mg ha$^{-1.}$ (Thirteen percent moisture), Corn and Soybean yields are bu ac^{-1} (13% moisture)

Table A.3 Generated Yield Distributions (average for regions)

Crop	Rot.	Tillage	Unit	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.
Corn	**Cont.**	**Conv. Till**	bu ac^{-1}	145.64	134.25	127.83	159.19	167.17	172.78	138.22
		No-Till		145.94	133.02	127.87	159.97	167.24	171.29	137.59
	CS rot	**Conv. Till**		145.70	137.02	127.90	159.17	166.34	172.26	138.34
		No-Till		145.90	136.44	127.97	159.51	166.40	172.14	138.52
Stover	**Cont.**	**Conv. Till**	Mg ha^{-1}	2.48	2.30	2.16	2.73	2.74	2.65	2.36
		No-Till		3.99	3.66	3.48	4.40	4.41	4.22	3.78
	CS rot	**Conv. Till**		2.48	2.32	2.16	2.73	2.76	2.71	2.37
		No-Till		4.00	3.71	3.49	4.40	4.43	4.33	3.81
Soybean	**CS rot**	**Conv. Till**	bu ac^{-1}	42.63	30.94	42.38	46.43	43.41	45.32	42.55
		No-Till		42.58	30.83	42.24	46.36	43.42	45.20	42.50
Miscanthus	**-**	**-**	Mg ha^{-1}	20.00	14.71	22.01	26.71	27.05	20.60	23.55
Switchgrass	**-**	**-**	Mg ha^{-1}	10.53	16.84	11.31	13.89	15.34	20.55	12.87

Generated data

Table A.4 Generated Yield Distribution CV (average for regions)

Crop	**Rot.**	**Tillage**	**Unit**	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Referenc source no found.
Corn	Cont.	Conv. Till	bu ac^{-1}	0.18	0.31	0.20	0.20	0.20	0.17	0.14	0.2
		No-Till		0.18	0.31	0.20	0.20	0.20	0.17	0.14	0.1
	CS rot	Conv. Till		0.18	0.30	0.20	0.21	0.20	0.17	0.14	0.1
		No-Till		0.18	0.30	0.20	0.21	0.20	0.17	0.14	0.1
Stover	Cont.	Conv. Till	Mg ha^{-1}	0.16	0.22	0.19	0.18	0.17	0.15	0.13	0.1
		No-Till		0.16	0.22	0.19	0.18	0.17	0.14	0.13	0.1
	CS rot	Conv. Till		0.16	0.23	0.19	0.18	0.17	0.15	0.13	0.1
		No-Till		0.16	0.23	0.19	0.18	0.17	0.14	0.13	0.1
Soybean	CS rot	Conv. Till	bu ac^{-1}	0.20	0.36	0.22	0.22	0.22	0.20	0.15	0.2
		No-Till		0.20	0.36	0.22	0.22	0.22	0.20	0.15	0.2
Miscanthus	-	-	Mg ha^{-1}	0.18	0.12	0.08	0.07	0.10	0.07	0.09	0.1
Switchgrass	-	-	Mg ha^{-1}	0.15	0.14	0.06	0.05	0.05	0.06	0.05	0.0

Generated data

[a] Biomass yields are in Mg ha$^{-1,}$ row crops are in bu ac$^{-1,}$ and prices are in \$ bu$^{-1,}$ all at 13% moisture

Table A.5 Average Correlation Coefficients Matrix for Miscanthus Draws

		Corn				Stover				Soybean		Misc.	Swit.	Row Pr
		CC_CT	CC_NT	CS_CT	CS_NT	CC_CT	CC_NT	CS_CT	CS_NT	CS_CT	CS_NT	C.land	C.land	Corn
Corn	**CC_CT**	1.00												
	CC_NT	1.00	1.00											
	CS_CT	0.99	0.99	1.00										
	CS_NT	0.99	0.99	1.00	1.00									
Stover	**CC_CT**	0.93	0.93	0.93	0.93	1.00								
	CC_NT	0.93	0.93	0.93	0.93	1.00	1.00							
	CS_CT	0.82	0.81	0.82	0.82	0.84	0.84	1.00						
	CS_NT	0.84	0.84	0.84	0.84	0.86	0.86	0.89	1.00					
Soybean	**CS_CT**	0.93	0.93	0.93	0.93	0.92	0.91	0.92	0.92	1.00				
	CS_NT	0.93	0.93	0.93	0.93	0.92	0.91	0.92	0.92	1.00	1.00			
Misc.		0.38	0.38	0.38	0.37	0.39	0.39	0.39	0.39	0.40	0.40	1.00		
Swit.		0.44	0.44	0.43	0.43	0.45	0.45	0.45	0.45	0.43	0.43	0.52	1.00	
Row Prices	**Corn**	-0.10	-0.10	-0.10	-0.10	-0.09	-0.08	-0.11	-0.07	-0.08	-0.08	-0.18	-0.04	1.00
	Soybean	-0.07	-0.07	-0.07	-0.07	-0.05	-0.05	-0.08	-0.06	-0.06	-0.06	-0.22	-0.09	0.65

Computed Values

Table A.6 Conventional Crop Prices

Conventional Crop Prices	Unit	Mean	Std Dev	Min	Max
Corn - expected price over period [ac]	\$ bushel^{-1}	3.98	1.27	2.49	8.09
Corn - realized price over period [bc]	\$ bushel^{-1}	3.71	1.16	2.21	7.29
Corn - farm gate price over state [b]	\$ bushel^{-1}	4.17	0.46	3.45	5.19
Soybeans - expected price over period [ac]	\$ bushel^{-1}	9.73	2.61	5.99	16.94
Soybeans - realized price over period [bc]	\$ bushel^{-1}	9.41	2.35	5.65	15.09
Soybeans - farm gate over states [b]	\$ bushel^{-1}	9.50	0.30	8.77	10.12

[a] NASS (2019) – marketing year realized prices

[b] Chicago Board of Trade (2019) – Corn and Soybean Futures prices

[c] St Louis Federal Reserve – Implicit GDP deflator

Table A.7 Conventional Crop Costs (average for regions)

$ Mg b^{-1}	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	**All Counties**	**All Counties SD**
Corn											
CC_CT	2.91	3.39	3.13	3.47	3.60	2.72	3.50	3.20	3.71	3.35	0.50
CC_NT	2.91	3.36	2.95	3.40	3.54	2.63	3.21	3.17	3.67	3.26	0.50
CS_CT	2.91	3.41	3.13	3.40	3.60	2.72	3.05	3.20	3.73	3.30	0.49
CS_NT	2.91	3.37	2.95	3.33	3.55	2.63	2.80	3.17	3.69	3.23	0.50
Soybean											
CT	6.63	9.21	6.16	6.68	10.52	9.66	8.34	7.40	8.86	7.97	1.81
NT	6.64	9.22	6.16	6.69	10.52	9.66	8.34	7.39	8.86	7.97	1.81

Price per bushel of corn and soybean - Computed using crop budgets from state extension services and expected model yields

Costs per bushel based on expected yields by county

Table A.8 Stover Production Costs (average for regions)

\$ Mg b^{-1}	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	**All Counties**	**All Countie SD**
CC_CT	50.39	51.73	53.37	48.93	50.88	50.65	56.90	53.21	52.11	51.53	3.
CC_NT	44.28	45.44	46.22	43.31	44.96	44.48	48.92	46.63	45.91	45.23	2.
CS_CT	57.31	58.69	60.50	55.54	57.66	56.57	65.01	60.05	60.46	58.60	5.
CS_NT	61.61	62.63	64.56	60.32	63.12	62.19	68.79	66.25	67.50	63.66	5.

Price per ton of corn stover - Computed using crop budgets from state extension services and expected model yields
Costs per ton based on expected yields by county

Table A.9 Bioenergy Crop Fixed Costs per Hectare (average for regions)

\$ ha^{-1}	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	**All Counties**	**All Counties SD**
Miscanthus											
Est Cost yr1	2209.85	2223.48	2215.01	2228.16	2244.01	2242.34	2226.70	2238.65	2238.67	**2227.49**	12.55
Est Cost yr2	540.26	545.07	547.36	560.50	573.35	563.93	560.29	570.17	566.43	**557.73**	12.51
Fixed cost yr3^{-1} 5	153.85	158.66	160.95	174.09	186.94	177.52	173.88	183.76	180.03	**171.32**	12.51
Switchgrass											
Est Cost yr1	659.05	662.04	659.20	670.73	684.23	677.93	675.15	697.04	695.42	**673.12**	14.62
Est Cost yr2	301.20	301.13	309.30	336.26	346.35	331.26	342.09	361.63	347.54	**329.96**	22.43
Fixed cost yr3^{-1} 5	228.99	228.93	237.10	264.06	274.14	259.06	269.88	289.42	275.33	**257.75**	22.43

Cost \$ per Hectare of a bioenergy crop - Computed using Iowa State Extension

Table A.10 Operating costs for bioenergy crops (average for regions)

\$ Mg b^{-1}	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	**All Counties**	**All Counties SD**
Miscanthus											
total operating cost	42.09	51.14	40.02	37.53	37.51	42.60	39.37	37.38	46.50	**41.33**	4.20
Switchgrass											
total operating cost	47.61	37.92	45.55	42.97	41.19	35.08	45.52	42.34	37.60	**41.92**	5.76

Price per ton of bioenergy crop - Computed using crop budgets from state extension services and expected model yields
Costs per ton based on expected yields by county

Table A.11 Baseline Soil Carbon Sequestration Rates (average for regions)

Baseline Sequestration Mg C ha^{-1}	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	**All Counties**
Row Baseline										
CC_CT Base	0.15	0.03	0.11	0.15	0.07	0.01	0.11	0.01	-0.01	0.08
CS_CT Base	-0.04	-0.08	-0.03	-0.04	-0.05	-0.08	-0.04	-0.07	-0.05	-0.05
CC_NT Base	0.42	0.30	0.34	0.47	0.38	0.26	0.38	0.25	0.17	0.35
CS_NT Base	0.15	0.10	0.13	0.18	0.15	0.10	0.14	0.08	0.06	0.13
Miscanthus										
CL - y1	-0.47	-0.28	-0.58	-0.62	-0.58	-0.54	-0.70	-0.57	-0.38	-0.52
CL - y2	0.52	0.34	0.60	0.68	0.48	0.41	0.27	0.48	0.39	0.50
CL - y3-end	1.13	0.45	1.18	1.41	1.35	0.63	1.20	1.21	0.48	1.04
Switchgrass										
CL - y1	-0.15	0.60	-0.53	-0.33	0.27	0.49	-0.56	0.22	0.53	0.03
CL - y2	0.35	1.22	-0.03	0.28	1.12	1.45	-0.12	1.01	1.26	0.68
CL - y3-end	0.46	0.90	0.29	0.52	1.05	0.96	0.35	0.94	0.89	0.69
Stover										
CC_CT	0.03	-0.03	0.00	0.03	-0.02	-0.05	0.00	-0.06	-0.06	-0.01
CS_CT	-0.09	-0.11	-0.08	-0.09	-0.10	-0.11	-0.09	-0.10	-0.08	-0.09
CC_NT	0.18	0.16	0.13	0.22	0.18	0.13	0.16	0.09	0.06	0.15
CS_NT	0.04	0.03	0.03	0.06	0.05	0.03	0.04	0.00	0.01	0.04

Computed from DayCent (2019)

Table A.12 Factors Used for carbon Emission Calculations

Calorific Values	**Unit**	**Value**
Ethanol	MJ US Gal^{-1}	80.63
Gasoline	MJ US Gal^{-1}	120.00
Carbon Emission Factors		
Nitrogen manufacturing	g CO2e g of N^{-1}	3.52
Denitrification	g CO2e g of N^{-1}	7.14
Phosphorus	g CO2e g of P^{-1}	0.67
Potassium	g CO2e g of K^{-1}	0.65
Herbicides	g CO2e g of H^{-1}	21.19
Relative carbon intensities		
Gasoline	g CO2e MJ^{-1}	94.00
Other		
Gallons of ethanol Mg b^{-1}	US Gal Mg $biomass^{-1}$	63.20[a]
Electricity co-product credit	g CO2e MJ^{-1}	$^{-1}$ 6.00[b]

All values from GREET unless specified

[a] Jain et al., (2010), [b] Dwivedi et al., (2015)

Table A.13 Input Application Rates

Input	Unit	Miscanthus	Switchgrass	Corn Stover
Nitrogen	Kg N ha^{-1}	50[a]	58.3[a], 86^{-1} 15[a]	Replacement Rate [a]
Phosphorus	g P Kg b^{-1}	2.20	0.60	1.90
Potassium	g K Kg b^{-1}	6.30	0.60	11.30
Herbicide	Kg H ha^{-1}	8.42[b]	8.20[b]	0.00

All values from Dwivedi et al., (2015) unless specified

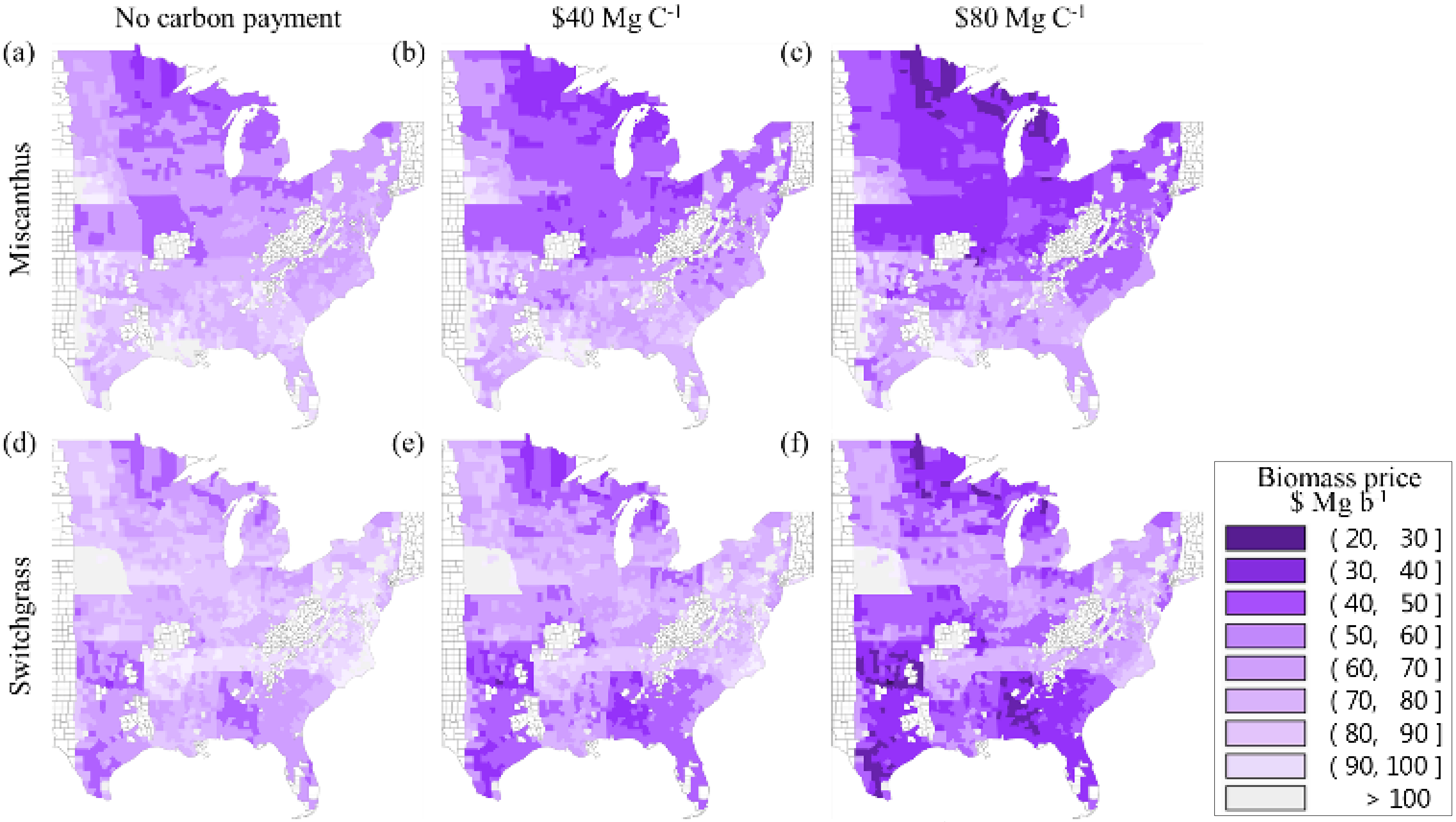
[a] DayCent nitrogen application rates (2019) for the second and continuing years only

[b] Dwivedi et al., (2015), herbicide applied for the first two years only

Table A.14 Material Input carbon intensity rates (estimated mean)

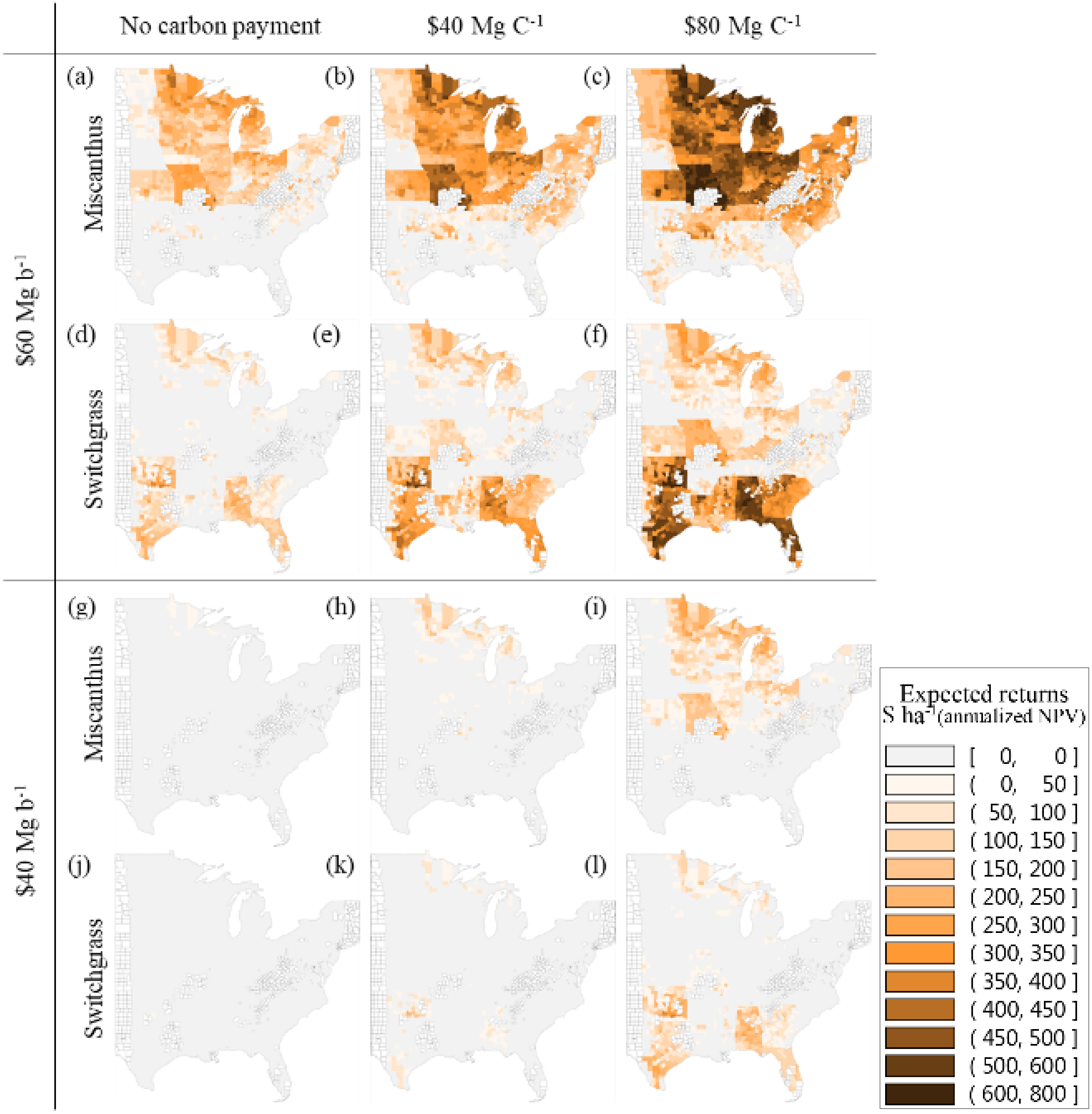
Material Use gCO2e MJ^{-1}	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	Error! Reference source not found.	**All Counties**
Miscanthus										
CL	6.62	9.31	5.54	4.67	4.68	6.25	5.27	4.63	7.28	5.94
Switchgrass										
CL	21.40	14.00	19.47	18.34	16.57	12.43	19.72	16.74	12.77	16.98
Stover										
CC_CT	16.85	17.10	17.30	15.77	15.34	14.84	16.10	15.78	15.70	16.09
CS_CT	10.75	11.25	11.04	10.11	9.89	9.68	10.36	10.13	9.76	10.31
CC_NT	11.07	11.39	11.36	10.42	10.17	9.92	10.69	10.44	10.37	10.64
CS_NT	7.29	7.28	7.47	6.91	6.75	6.52	7.08	6.93	6.78	7.00

Figure A.1 Breakeven Prices for bioenergy crops



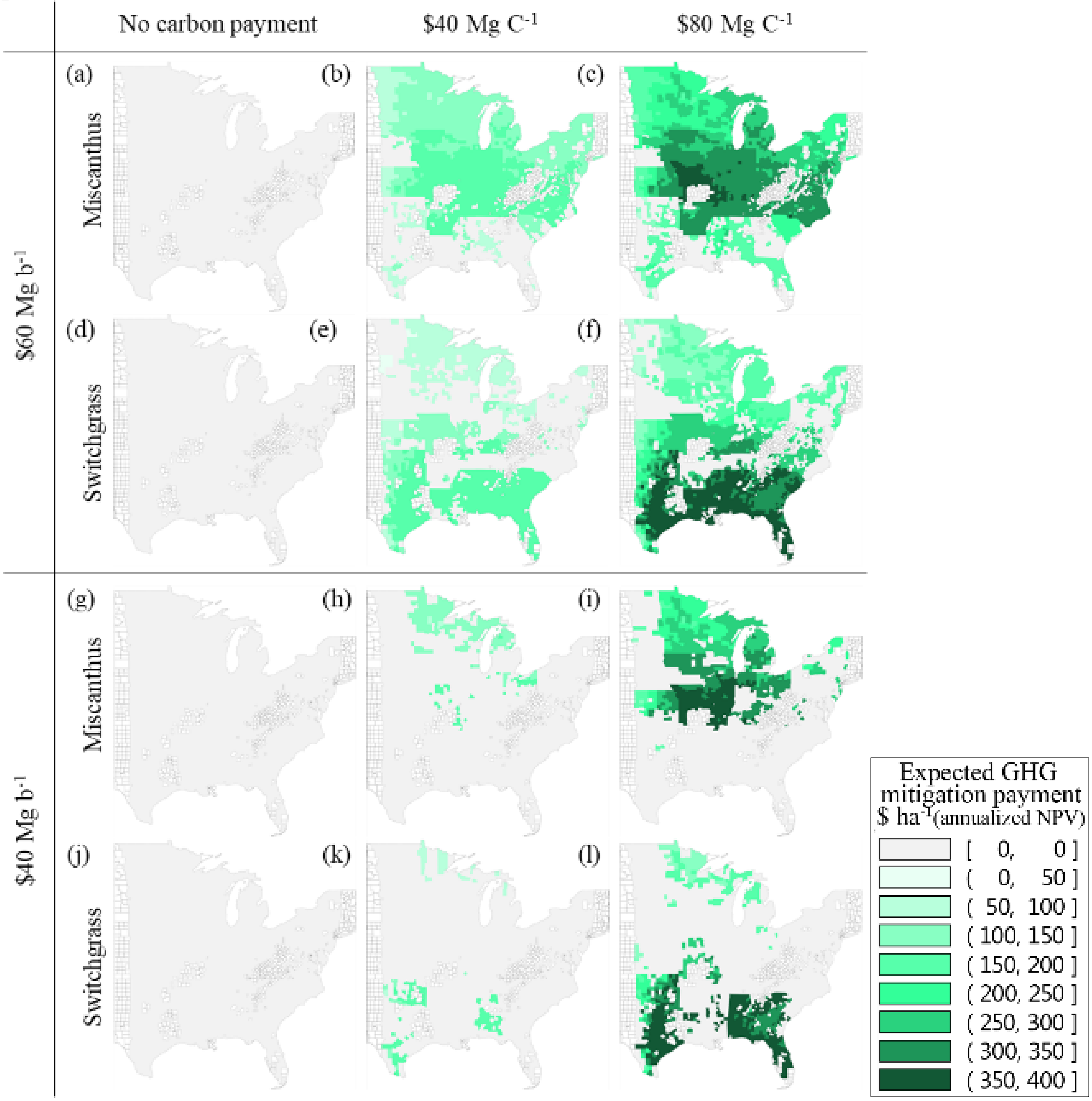
Breakeven prices for miscanthus are lowest in the Midwest around \$50 Mg b$^{-1,}$ breakeven prices for switchgrass are lowest in the southern states as well as some counties in the Midwest around \$50 Mg b$^{-1.}$

Figure 2. Expected returns (annualized NPV) at \$60 and 40 Mg b^{-1} price under Error! Reference source not found.



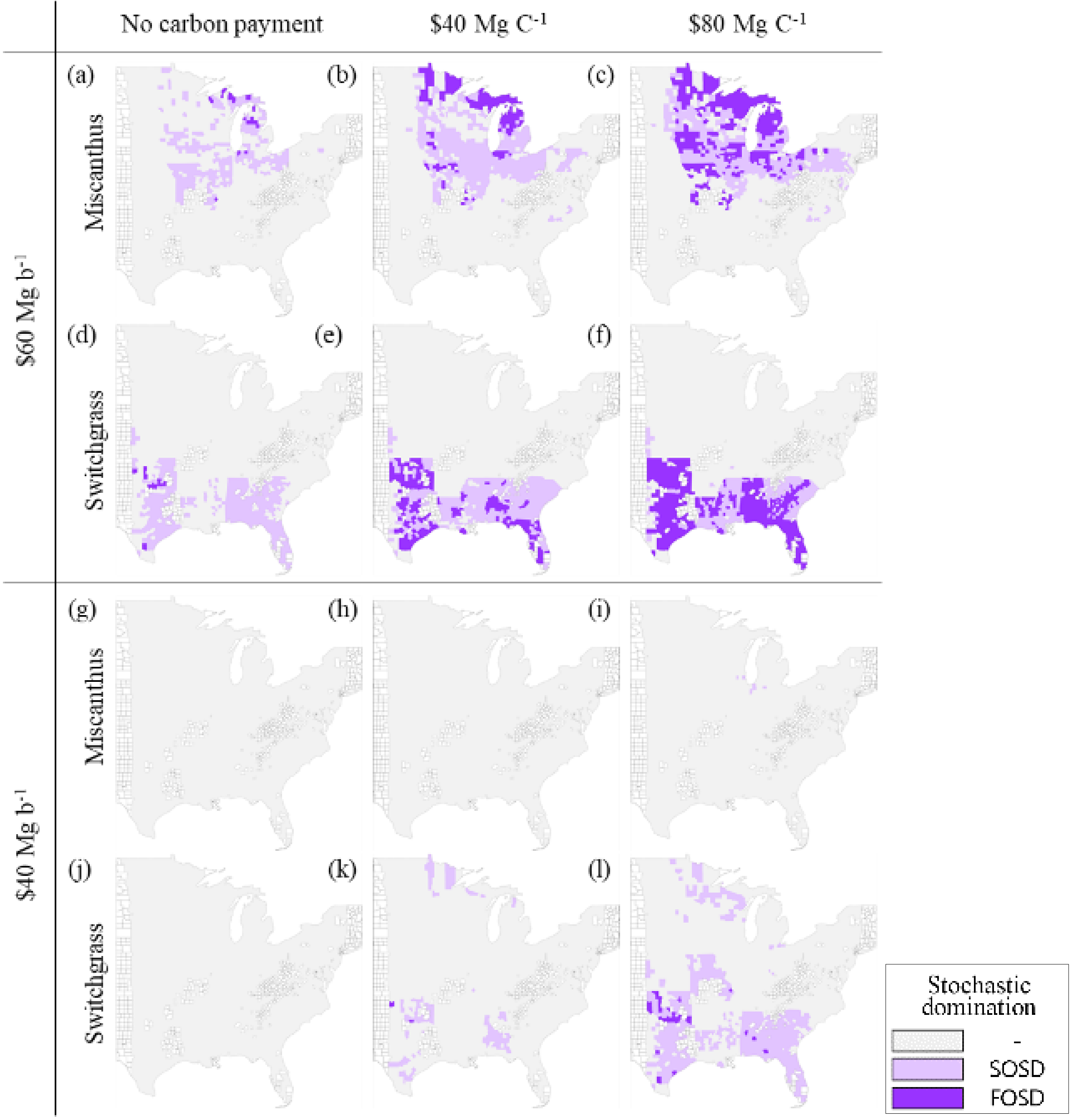
These graphs show the expected returns from bioenergy crops, which are reported as the average annualized NPV of the difference in farmer returns from bioenergy crops and conventional crops. Only counties with positive returns are shown. At \$60 Mg b^{-1}, the highest expected returns for miscanthus are in the Central Midwest. For switchgrass, the Southern Great Plains and the Southeast states have the highest expected. Carbon mitigation payment increases expected returns and expands the region where farmers achieve positive expected returns.

Figure A.3 Expected carbon mitigation payment (Annualized NPV) at \$60 and 40 Mg b^{-1} biomass price



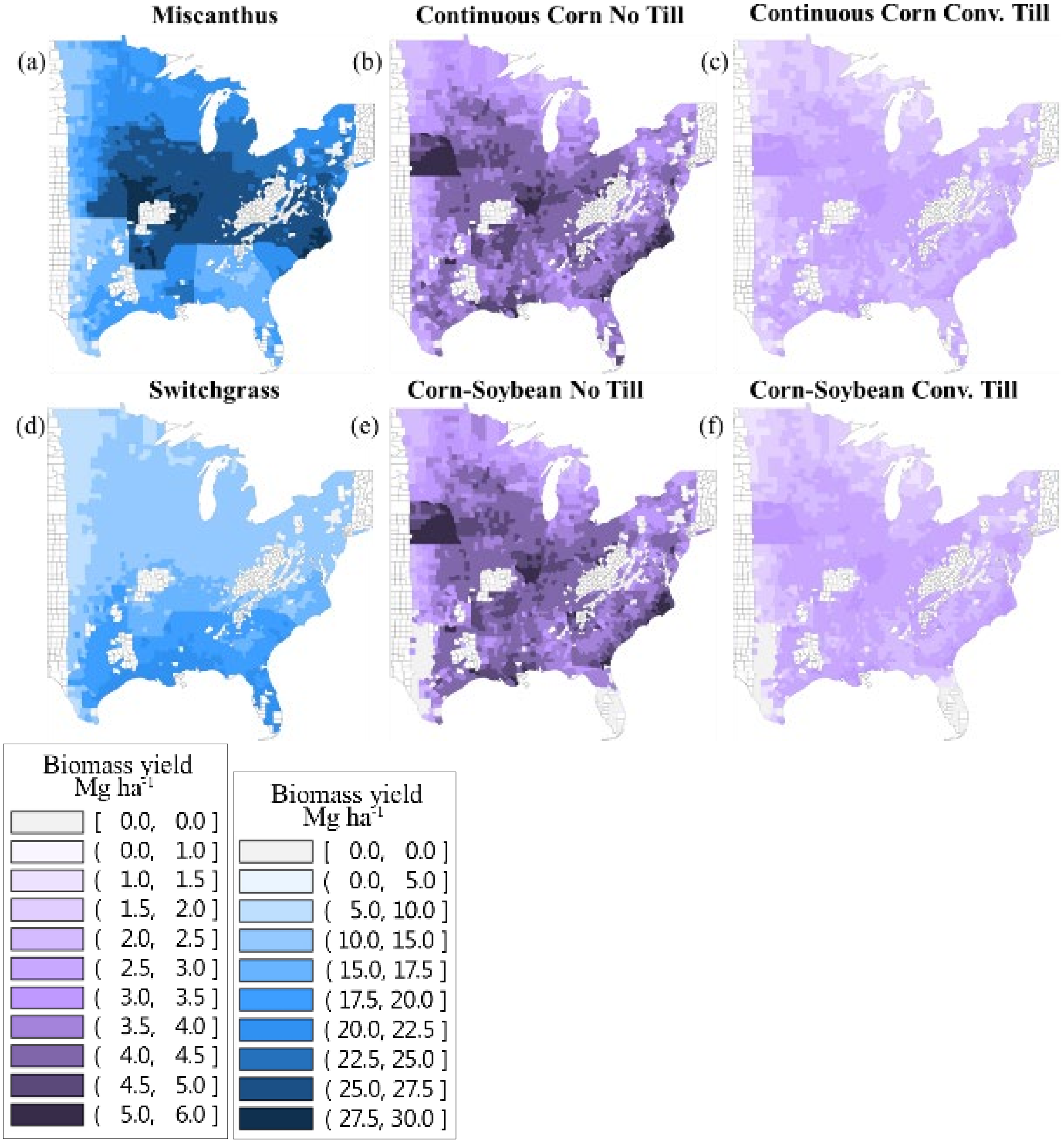
Expected **Error! Reference source not found.** is the additional average annualized NPV payment from bioenergy crops over conventional crops. Only counties with positive expected returns are shown.

Figure A.4 Stochastic dominance of bioenergy crop returns over other bioenergy and conventional crops at $60 and 40 Mg b^{-1} biomass under 10% time discounting



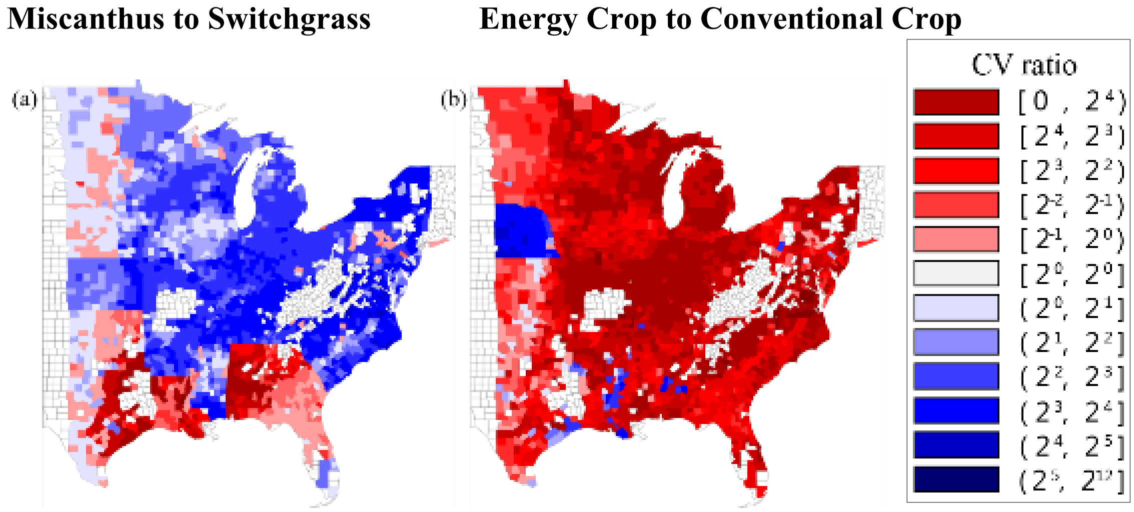
"SOSD" represents counties with second-order stochastic dominance only. "FOSD" represents counties with first-order stochastic dominance and second-order stochastic dominance. "-" represents counties where neither dominance criteria are met.

Figure A.5 Expected biomass yields from miscanthus, switchgrass, and corn stover Mg ha^{-1} .



Expected miscanthus yields are highest in the Midwest and expected switchgrass yields are highest in the southern states. Following DayCent, stover removal is kept at 50% for no-till and 30% for conventional tillage.

Figure A.6 Selected Ratio of Yield CV

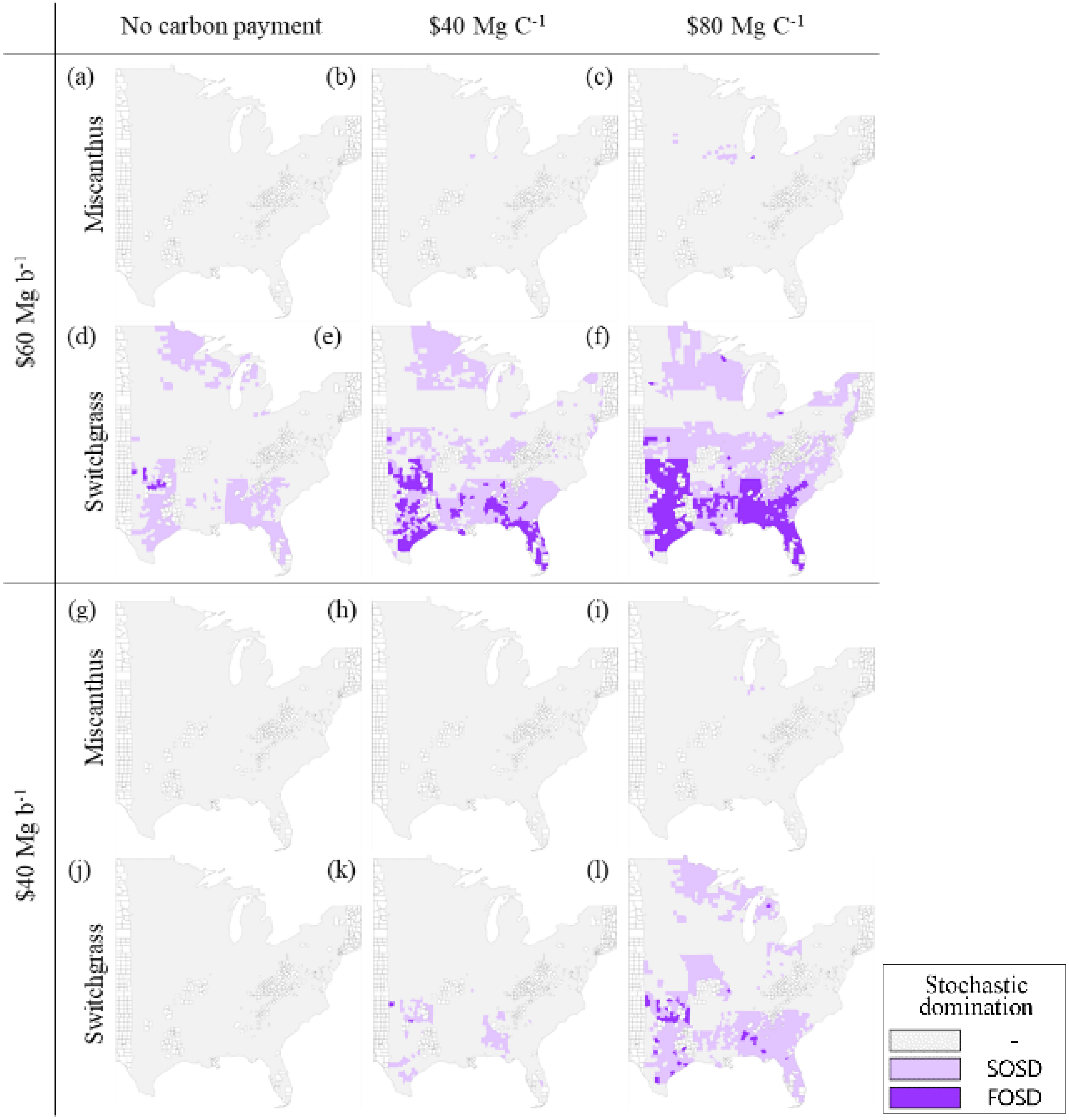


Miscanthus to Switchgrass **Energy Crop to Conventional Crop**

(a) Red areas depict counties where miscanthus is less risky (in terms of **Error! Reference source not found.**) than switchgrass crops, and blue areas depict where it is riskier.

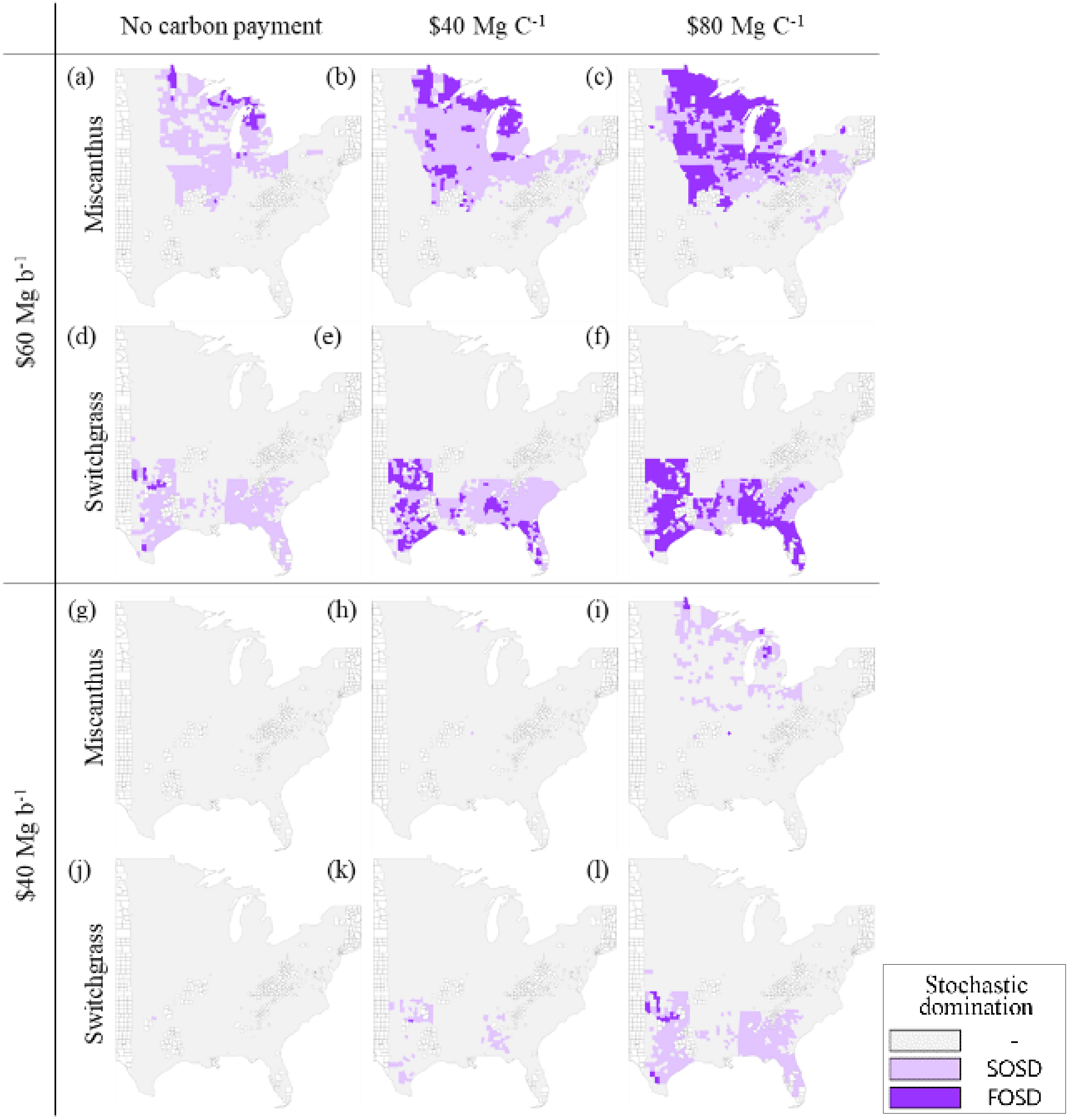
(b) As an example, the yield **Error! Reference source not found.** ratio of miscanthus to corn stover yields under conventional tillage continuous corn is used, however, results are similar for switchgrass and any other tillage or rotation for stover. Red areas depict counties where bioenergy crops are less risky (in terms of **Error! Reference source not found.**) than conventional crops, and blue areas depict where it is riskier.

Figure A.7 Stochastic dominance of bioenergy crop returns over other bioenergy and conventional crops at $60 and 40 Mg b^{-1} biomass under 100% miscanthus establishment failure



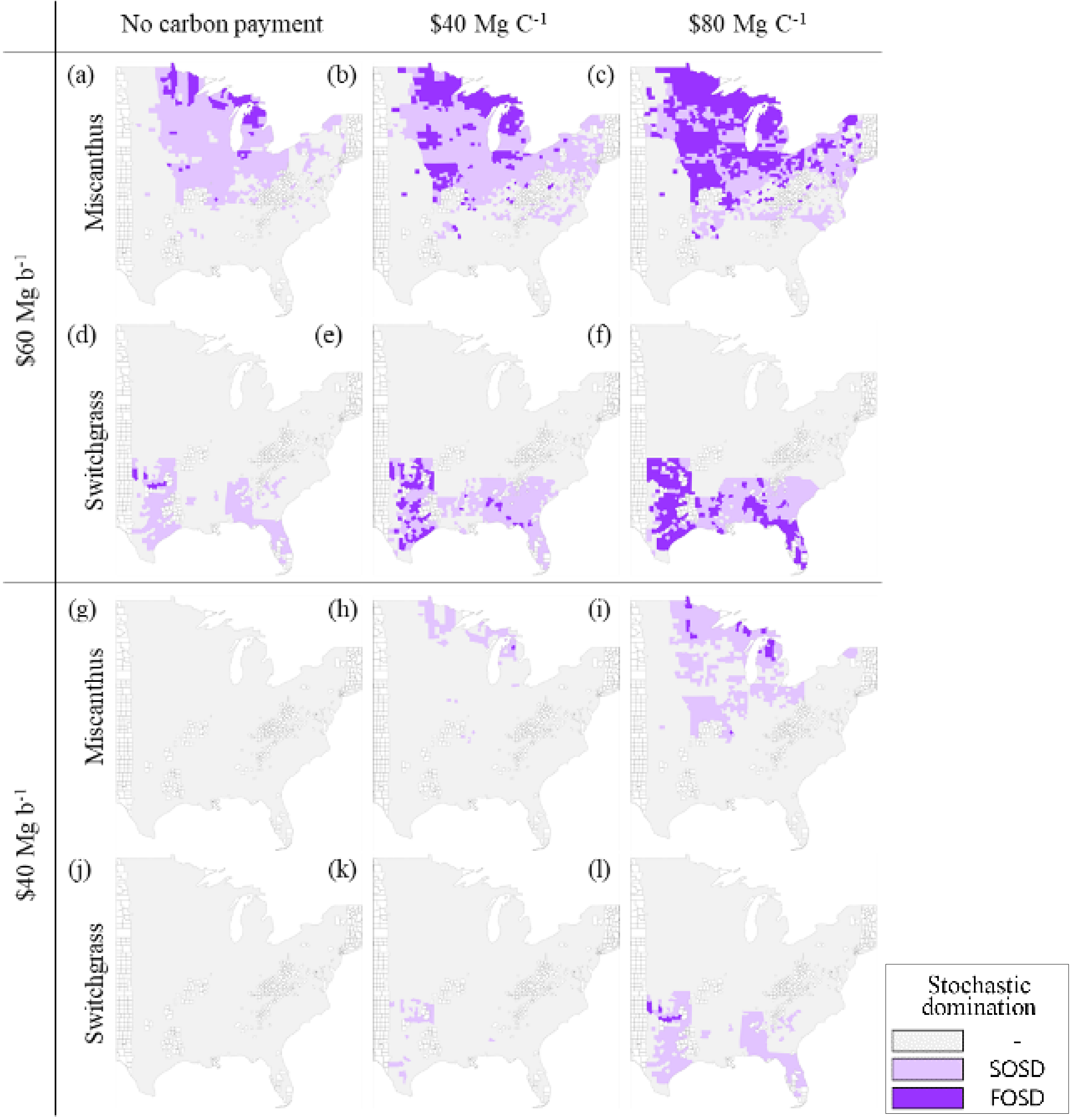
"SOSD" represents counties with second-order stochastic dominance only. "FOSD" represents counties with first-order stochastic dominance and second-order stochastic dominance. "-" represents counties where neither dominance criteria are met.

Figure A.8 Stochastic dominance of bioenergy crop returns over other bioenergy and conventional crops at \$60 and 40 Mg b^{-1} biomass under delayed miscanthus yield maturation



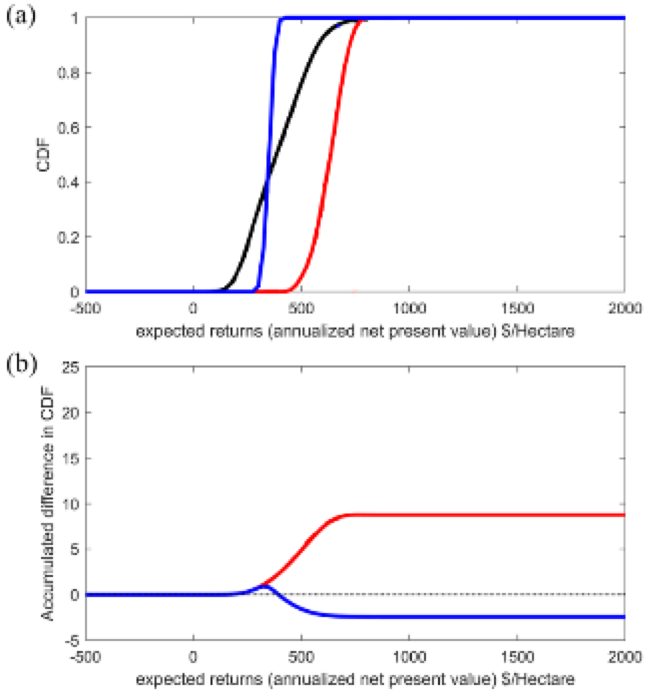
"SOSD" represents counties with second-order stochastic dominance only. "FOSD" represents counties with first-order stochastic dominance and second-order stochastic dominance. "-" represents counties where neither dominance criteria are met.

Figure A.9 Stochastic dominance of bioenergy crop returns over other bioenergy and conventional crops at \$60 and 40 Mg b^{-1} biomass without no-till yield reduction



“SOSD” represents counties with second-order stochastic dominance only. “FOSD” represents counties with first-order stochastic dominance and second-order stochastic dominance. “-” represents counties where neither dominance criteria are met.

Figure A.10. Example of the first-order and second-order stochastic dominance



This is an example of FOSD and SOSD. In Figure.A.1 (a) we show the cumulative distributions of NPVs for three annualized NPVs for expected returns. The red line has first-order stochastic dominance over the black line as the two lines do not cross whereas the blue line does not have first-order stochastic dominance over the black line. In Figure A.1 (b) we show the difference of area underneath cumulative distributions for the red and blue returns from those from the black line in the. Here we show that the red line has second-order stochastic dominance over the black line as it is equal to zero or positive throughout. The blue line does not remain positive throughout and therefore does not have second-order stochastic dominance over the black line. It is possible that a distribution is not FOSD over another but is still SOSD over it.