Received: 19 August 2022 | Accepted: 6 February 2023

DOI: 10.1002/jaa2.52

ARTICLE

JOURNAL OF THE AGRICULTURAL AND APPLIED ECONOMICS ASSOCIATION
Open Access

Carbon mitigation payments can reduce the riskiness of bioenergy crop production

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Funding information

National Institute of Food and Agriculture, Grant/Award Number: 2017-67019-26283; Hatch Project Number, Grant/Award Number: ALA011-1-17002; U.S. Department of Energy, Grant/Award Number: DE-SC0018420

Abstract

Perennial bioenergy crops provide substantial carbon mitigation benefits but have risky returns. We couple economic analysis with a biogeochemical model (DayCent) to examine the effect of carbon mitigation payments on the spatially varying bioenergy crop returns and risk profiles relative to conventional crops across the rainfed United States. These payments increase the likelihood of positive profit in the Midwest for miscanthus and southern states for switchgrass. At low biomass prices, these payments make bioenergy crops appealing to risk-averse farmers. At moderate biomass prices, these payments make bioenergy crops appealing to all farmers regardless of risk preference.

KEYWORDS

bioenergy crops, carbon mitigation payments, miscanthus, risk and uncertainty, switchgrass

JEL CLASSIFICATION

Q16, D81, Q15

1 | INTRODUCTION

The potential contributions of agriculture to mitigating climate change have attracted much attention since the United States rejoined the Paris Agreement on climate change with ambitious goals for mitigating carbon emissions, and the development of both government-enforced and state-level voluntary carbon credit markets in the United States has gained momentum (Bonnie et al., 2021; Elder, 2021). For example, the Growing Climate Solutions Act of 2021 (Braun, 2021), which supports the development of a voluntary market for carbon mitigation credits on agricultural land, recently passed the senate. Further, the Inflation Reduction Act of 2022 (Yarmuth, 2022), which in part incentivizes carbon-mitigating agricultural activities, was recently signed into law. Lignocellulosic perennial crops, such as miscanthus and switchgrass (henceforth referred to as bioenergy crops), can be used for second-generation bioethanol production, and provide substantially higher carbon mitigation benefits than conventional row crops (Dwivedi et al., 2015; Hudiburg et al., 2016; Robertson et al., 2017). Bioenergy crops provide carbon mitigation benefits over the life of the crop through the production of biomass that can be used to produce cellulosic biofuel with a lower lifecycle carbon intensity (the grams of carbon dioxide equivalent emitted over the lifecycle of producing one megajoule of energy) than energy-equivalent fossil fuels and by sequestering more soil carbon than conventional crops. Bioenergy crops are, however, subject to long establishment periods, high upfront costs, and risky yields, making them less appealing to risk-averse (i.e., those willing to accept lower but more certain returns over higher but more variable returns), impatient, and credit-constrained farmers (Alexander et al., 2012; Bocquého & Jacquet, 2010; Miao & Khanna, 2017a; Yang et al., 2016). Alternatively, farmers may harvest corn stover, a low-cost but low-yielding biomass readily available to farmers as a byproduct of planting corn that can be used to produce low-carbon cellulosic biofuels. However, harvesting stover also removes soil carbon that would have otherwise remained sequestered in the ground (Hudiburg et al., 2016); the extent of this depends on the tillage and crop rotation choices made by farmers (Chen et al., 2021a).

Payment for carbon mitigation services of bioenergy feedstocks (i.e., bioenergy crops and corn stover) can affect incentives for bioenergy crop adoption. These mitigation services generate carbon credits that can be exchanged for financial payments through voluntary carbon markets (Alejandro, 2021). The development of voluntary carbon markets is due, in part, to growing interest in companies and other organizations to purchase these credits to meet their carbon reduction goals (Wongpiyabovorn et al., 2022). These voluntary markets can function alongside government compliance schemes that generate carbon prices.[1] Such payments can monetize carbon mitigation services provided by bioenergy crops through their conversion to biofuels that displace fossil fuels and sequestration of carbon in the soil (Biggs et al., 2021; Bruner & Brokish, 2021; Chamberlain & Miller, 2012; Feng et al., 2001; Noe et al., 2016).

While carbon mitigation payments increase the returns from bioenergy crops, the effect of such payments on returns per unit of land varies spatially and across crop choices. Further, carbon mitigation payments per unit of land can affect the riskiness of these returns to farmers. First, the amount of carbon mitigated, by the conversion of each unit of land from conventional crops to bioenergy crops, through fossil fuel displacement varies with biomass yield per unit of land that depends on weather conditions. These yields and their variability differ spatially across locations and at a given location with the bioenergy crop choice (Hudiburg et al., 2016). Second, soil carbon sequestration rates per unit of land, which are linked temporally with historical soil carbon levels and crop yield dynamics, vary over the lifespan of a bioenergy crop (Chen et al., 2021b). Third, a farmer can be expected to compare the returns and risks of bioenergy crop production to those

[1]As the focus of our paper is to examine the impact of carbon payments on the cropping returns (risk and average), the sources of these carbon payments are of secondary importance. Payments for carbon mitigation can be from the federal government or state-level voluntary carbon markets. We are indebted to an anonymous reviewer whose comments led to this clarification.

under conventional crop choice with and without carbon mitigation payments. Monetization of carbon benefits may increase expected conventional crop returns as farmers can now earn more by harvesting stover with conventional crops and will compare these higher returns from conventional crops to those with bioenergy crops. The magnitude of the effects of carbon mitigation payments on bioenergy crop returns and riskiness is expected to vary spatially across the rainfed region in the United States and is expected to affect a farmer's incentives to produce bioenergy crops.

When considering whether to plant bioenergy or conventional crops, farmers will consider the anticipated returns and their riskiness; the weights they attach to each of these will depend on their risk preferences. Risk-neutral farmers care only about the magnitude of the average value of returns relative to those from current land use, while risk-averse farmers may prefer a crop with lower but more certain average returns over another with higher but more risky returns. First-order stochastic dominance (FOSD) and second-order stochastic dominance (SOSD) allow us to compare and order two risky prospects from a decision-maker's perspective when their risk preferences are unknown (we provide formal definitions of FOSD and SOSD and consider the implications of FOSD and SOSD in Supporting Information [SI] Section 1). 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 price. Understanding the geographical configurations of where bioenergy crops attain FOSD or SOSD over conventional crops will assist farmers and potential biorefinery investors in identifying regions where various types of farmers are more likely to produce bioenergy crops.

The objectives of this paper are three-fold. First, we examine the return and riskiness profiles of two promising bioenergy crops (miscanthus and switchgrass) relative to conventional crops (corn and soybean) across counties in the rainfed region (to the east of the 100th meridian) of the United States at various biomass prices. Second, we examine the effects of providing payment for the carbon mitigated through fossil fuel displacement and soil carbon sequestration in feedstock production on the spatial pattern of returns and riskiness profiles of bioenergy crops relative to conventional crops. Third, we examine the effects of carbon mitigation payments on the stochastic dominance of bioenergy crops over conventional crops and identify the counties where bioenergy crops first-order or second-order stochastically dominate conventional crops.

Several studies have examined bioenergy crop profitability by calculating the breakeven price that equates returns from bioenergy crops and those from the alternative use of land (Brechbill et al., 2011; Jain et al., 2010; James et al., 2010; Khanna et al., 2008; Mooney et al., 2009; Perrin et al., 2008). However, these analyses do not consider the riskiness of returns for either bioenergy crops or conventional crops, and only a few consider spatial variability of bioenergy and conventional crop yields (Miao & Khanna, 2014). A few studies have conducted stochastic dominance analyses for bioenergy crops using data for yields from field trial data sites or for selected geographical areas, obtaining results that may not represent the entire United States rainfed region (Dolginow et al., 2014; Gouzaye, 2015; Griffith et al., 2012; Skevas et al., 2016). More importantly, these studies do not examine the effect of pricing the carbon mitigation benefits provided by bioenergy crops on their risk and return profiles. Studies focusing on carbon mitigation payment for bioenergy crops are limited in their scope to specific geographical areas, particular aspects of carbon mitigation (i.e., soil carbon sequestration), or a specific bioenergy crop (Chamberlain & Miller, 2012; Mishra et al., 2021; Noe et al., 2016). Further, few studies account for the riskiness of returns by incorporating variability of prices and yield (Noe et al., 2016). Many of these studies also use estimates of carbon mitigation benefits from the literature rather than conducting a complete lifecycle analysis using the same systems boundary and consistent framework.

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. We consider the riskiness of returns due to yields, production costs, input requirements, and carbon intensities in 2122 counties across the United States rainfed region. We use 30 years of weather-driven bioenergy crop and conventional crop yield data along with conventional crop price data to generate joint yield-price distributions using a copula method. In doing so, we incorporate the riskiness of returns of conventional crops to represent the alternative use of land that would be foregone (i.e., the opportunity cost of land) when growing bioenergy crops. We then estimate return distributions for bioenergy and conventional crops (with the option to change rotation and tillage and harvest corn stover when profitable) using generated yields, conventional crop prices, carbon mitigation benefits from fossil fuel displacement, and soil carbon sequestration. We estimate annualized return distributions under exogenous biomass and carbon prices assuming a 15-year bioenergy crop lifespan (Miao & Khanna, 2017b).

We conduct profitability analysis of bioenergy crops by incorporating the return riskiness of bioenergy and conventional crops and conducting stochastic dominance analyses across the entire United States rainfed region. For conventional crop returns, we consider four tillage and rotation choices for corn and soybeans, each with the option to harvest corn stover. We account for carbon mitigation provided by each cellulosic ethanol feedstock by determining its carbon mitigation through fossil fuel displacement and soil carbon sequestration. For carbon mitigation through fossil fuel displacement, we account for lifecycle emissions from cellulosic ethanol production from the farm to the refinery for each feedstock at the county level. In doing so, we consider the effects of weather riskiness on yield, which affects the carbon intensity per megajoule. For carbon mitigation through soil carbon sequestration, we consider the temporal soil carbon effect of growing these crops at the county level. For corn stover, we include soil carbon effects from harvesting stover and possible changes in crop rotation and tillage choices. Our analysis shows how bioenergy crop returns, return riskiness, and stochastic dominance change across various biomass and carbon prices.

2 | MATERIALS AND METHODS

2.1 | Crop yields

We simulate county-level yields of bioenergy crops (miscanthus and switchgrass) and conventional crops (corn and soybean) with the potential corn stover harvesting using the biogeochemical model DayCent. All crop yields are stochastic and obtained under 30 years of randomized weather conditions. We simulate conventional crop yields under eight permutations of two rotation types (corn-corn and corn-soybean), two tillage types (conventional and no-tillage), and two corn stover removal choices (with and without corn stover removal). For further details on crop yields and fertilizer application rates, see Supporting Information: Section 2.1.

We perform our analysis for 2122 counties on or to the east of the 100th meridian within the continental United States that produce corn or soybean and have simulated bioenergy and conventional crop yields using DayCent. Counties that produce corn or soybeans are determined based on pixel-level satellite data of land use from 2008 to 2015 by Jiang et al. (2021). In the economic model, we consider corn-soybean and continuous corn rotations in counties where satellite data show soybean cultivation and consider only continuous corn in counties where satellite data shows no soybean cultivation. We separate the bioenergy crop lifespan into an establishment and a mature period. In the mature period, the farmer harvests the bioenergy crop annually. We assume that miscanthus reaches its mature period after 2 years of establishment, whereas switchgrass reaches the mature period within the first year (Miao & Khanna, 2017b). Conventional crops are planted and harvested annually.

2.2 | Carbon mitigation benefits

The calculation of carbon benefits from replacing fossil fuels is the difference in grams of CO_2 for the same amount of energy produced between cellulosic ethanol and fossil fuel lifecycles. We calculate the lifecycle carbon emission intensity through a lifecycle analysis for each biomass source. Our lifecycle analysis for the carbon intensity of ethanol produced (Supporting Information: Section 2.2) includes feedstock production, processing, and conversion to ethanol. We simulate for each year of the planting period the change in soil carbon levels for miscanthus, switchgrass, and eight permutations of rotation, tillage, and corn stover removal for conventional crops using the DayCent model. To determine payments for the additional soil carbon sequestration with feedstock production that a unit of land provides, we need to determine the change in soil carbon sequestration for each feedstock choice relative to an initial rotation and tillage choice with no carbon payments. In response to the carbon payment, farmers may switch from a conventional crop to a bioenergy crop or begin harvesting corn stover while keeping their existing crop rotation and tillage choice or by changing tillage and/or rotation to increase stover harvest or to mitigate more soil carbon. We use two separate methods (a risk-neutral mean returns maximizing model and a mean-variance utility model as detailed in Supporting Information: Section 2.3) to determine an initial rotation and tillage choice with conventional crops in the absence of any biomass and carbon prices. We find that conventional crop choice does not differ much across these two methods. We then determine the soil carbon change relative to the initial rotation and tillage choice when a farmer switches to either corn stover harvest or a bioenergy crop with carbon prices at the county level. The calculation of soil carbon effects for each cropping choice is detailed in Supporting Information: Section 2.4.

2.3 | Crop returns

We calculate bioenergy crop costs at the county level for each year in the establishment and mature periods with input quantities from the Iowa State Extension and input prices from the National Agricultural Statistics Service (NASS) (Hoque et al., 2014, 2015). 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 annually and incurs costs associated with harvesting (Supporting Information: Section 2.5). Farmers receive a biomass price per unit of biomass yield each year they harvest biomass. Farm gate biomass price at 13% moisture is set exogenously from \$0 to \$100 per metric ton (\$ Mg^{-1}) of biomass at intervals of \$10 and is assumed constant over time. To illustrate our results, we select two biomass prices of \$40 Mg^{-1} and \$60 Mg^{-1} as low and moderate prices, respectively (Supporting Information: Section 2.6). Farmers also receive a carbon payment based on the carbon price per unit of carbon mitigated in the year. We assume that soil carbon sequestered during the lifespan of the crop will be permanent and do not consider the mechanisms of soil carbon loss over time or due to replanting. Our analysis, therefore, provides an upper bound to the profitability of incentivizing soil carbon sequestration through carbon mitigation payments. Further, we assume that the entire carbon payment will go to the farmer and not to other agents in the value chain (e.g., processing plants or transporters). Our analysis, therefore, provides an upper bound to a farmer's expected payment from carbon mitigation policies. We discuss these underlying assumptions for carbon mitigation payments in more detail in Supporting Information: Section 2.7. The carbon price is set exogenously at \$0 (no carbon mitigation payment scenario), \$40, and \$80 per metric ton of carbon mitigated (Mg^{-1} C) and is assumed constant over time (Supporting Information: Section 2.8). We then generate annual returns over the life of the crop for each bioenergy crop at exogenously given biomass and carbon mitigation prices (formally detailed in Supporting Information: Section 2.9). Biomass from stover harvest sells for the same price as bioenergy crops. It provides carbon mitigation benefits from fossil fuel displacement and (mostly negative) changes in soil carbon sequestration from stover harvest and (ambiguous) changes to soil carbon sequestration from changes in tillage and rotation. The net returns from any given rotation and tillage choice of conventional crops include the returns from corn grain and soybeans (cost and stochastic prices of conventional crops detailed in Supporting Information: Sections 2.10 and 2.11), as well as returns from the possible harvest of corn stover along with associated carbon mitigation payments (calculation of corn stover returns are described in Supporting Information: Section 2.12 and conventional crop net return calculations and equations are presented in Supporting Information: Section 2.13).

To calculate stochastic returns, we obtain random draws by constructing a yield-price distribution for each county by a copula approach, as detailed in Supporting Information: Section 2.14. The joint yield-price distribution consists of crop yields linked to eight conventional crop rotations, tillage, and corn stover harvest choices, two bioenergy crop choices, and prices for corn and soybean. We use these joint yield-price distributions to construct the returns for conventional crops under each combination of rotation, tillage, and corn stover harvest choice and bioenergy crops at exogenously varying biomass and carbon mitigation prices. We combine the return distributions associated with conventional crops (i.e., rotation, tillage, and corn stover harvest choices) to construct one combined conventional crop return distribution. The combined conventional crop return distribution consists of the highest returns from the rotation, tillage, and corn stover harvest choice for each draw of the joint yield-price distribution and represents the returns for the best alternative of land (as detailed in Supporting Information: Section 2.15). As bioenergy crops are perennial crops and conventional crops are annual crops, we annualize all returns to net present values (annualized NPV as detailed in Supporting Information: Section 2.16) for analysis. As there is no consensus on discount rates, we use a rate of 2%, following Miao and Khanna (2017a). In the sensitivity analysis, we also simulate the model using a higher discount rate of 10%. These rates are similar to those used by the Environmental Protection Agency (EPA) for determining the social cost of carbon (US Environmental Protection Agency, 2022; US Environmental Protection Agency, 2015) and allow a comparison of carbon mitigation prices to the social cost of carbon. We present an overview of the economic model, highlighting the sources of information and the interconnectedness of the various components of the model in Supporting Information: Figure S1.

2.4 | Return and risk analysis

We analyze annualized NPV of bioenergy crop returns relative to the annualized NPV of conventional crop returns. First, we compute the breakeven prices for bioenergy crops at various carbon mitigation prices as a comparison to previous literature. Breakeven prices are the biomass price that equates the expected NPV of returns from bioenergy crops to the expected NPV of returns from conventional crop on the same land. Next, at various biomass and carbon mitigation prices, we analyze distributions of bioenergy crop returns in terms of expected profit, the likelihood of positive profit (LPP), the coefficient of variation (CV) of returns, and stochastic dominance. Breakeven prices and expected returns give us a measure of returns without considering riskiness. LPP and CV allow us to compare the riskiness of returns of bioenergy crops relative to conventional crops. Finally, stochastic dominance tests enable us to order farmers' choices between distributions when farmer risk preferences are unknown.

Expected profits from bioenergy crops are the means of annualized NPV of returns above the mean annualized NPV of returns from growing conventional crops on the same land. For risk-neutral farmers, expected bioenergy returns need to be positive to prefer bioenergy crops over conventional crops. LPP is the likelihood that the profits, the annualized NPV of returns distribution from growing bioenergy crops subtracted by the annualized NPV of returns from conventional crops on the same land, is positive (for more information on the calculation of bioenergy crop profits, see Supporting Information: Section 2.17). The biomass and carbon price at which a farmer achieves a 50% LPP can serve as an *approximate* indicator for price levels at which risk-neutral farmers may prefer growing bioenergy crops. Because risk-averse farmers prefer more certainty than risk-neutral farmers for the same expected return, risk-averse farmers would prefer growing bioenergy crops in counties with a LPP higher than 50% at a particular biomass and carbon price.

The CV of returns is the standard deviation of returns divided by the mean annualized NPV of returns for a crop and is a measure of crop riskiness-to-returns. We use a pairwise comparison of return CVs from bioenergy crops to conventional crop returns to compare return riskiness (Hardaker et al., 2004). The CV ratio of bioenergy crop returns to those from conventional crops ranges from $(0, \infty)$ with CV ratios lower than 1, implying that the bioenergy crop returns are less risky. For details on trivial CV ratio cases, see Supporting Information: Section 2.18. However, a mean-standard deviation comparison of alternatives does not always allow us to decide which prospect is preferable over the other, for example, when prospects with higher returns also have higher standard deviations (Nolan & Santos, 2019).

We can use pairwise comparisons of distributions of annualized NPV of returns based on the stochastic dominance criterion to construct a partial ranking of a farmer's choices when risk preferences are unknown. We consider two criteria for ranking returns: FOSD and SOSD. If returns from crop A FOSD crop B, then for all possible returns, crop A has a greater likelihood than crop B to provide returns higher than or equal to that return. More formally, for returns from crop A to FOSD returns from crop B, $F_A(x) \leq F_B(x)\ \forall\ x$ with at least one strong inequality where x denotes returns and $F_A(x)$ and $F_B(x)$ are the cumulative distribution function values for portfolio A and B at point x, respectively. If farmers have an upward-sloping utility and prefer higher returns to lower returns regardless of risk preference, then crops that are FOSD will appeal to them. For more formal definitions and interpretations of FOSD, see Supporting Information: Section 1.1.

SOSD provides a mechanism for comparing prospects likely to receive higher returns to prospects with more certain returns of smaller magnitudes. More formally, for returns from crop C to dominate returns from crop D, $\int_{-\infty}^{x} F_C(x) \leq \int_{-\infty}^{x} F_D(x)\ \forall\ x$ where x denotes returns and $F_C(x)$ and $F_D(x)$ are the cumulative distribution function values for crop returns C and D at point x, respectively. Farmers with an upward-sloping utility curve that is increasing at a decreasing rate (i.e., the farmer is risk-averse) will prefer a prospect that is SOSD. If returns from crop C dominate crop D in the SOSD sense, the risk-averse farmer would choose to trade off the additional variability of crop D for more certain returns from crop C. Crops that are SOSD, therefore, appeal to farmers who prefer higher returns to lower returns and are risk-averse. For more formal definitions of SOSD and interpretations of stochastic domination, see Supporting Information: Sections 1.1–1.3.

3 | RESULTS

3.1 | Breakeven prices for bioenergy crops and expected profit at selected biomass prices

We find that the breakeven prices vary across the rainfed region. The median breakeven biomass price across the rainfed region for miscanthus is between \$70–80 Mg^{-1} (Supporting Information: Figure S2a), and for switchgrass is between \$80–90 Mg^{-1} (Supporting Information: Figure S2d) (see Supporting Information: Section 2.17 for more information about breakeven price ranges). Carbon mitigation payments reduce the breakeven biomass prices for bioenergy crops. For example, at a carbon price of \$80 Mg^{-1} C, the median breakeven biomass price is lower and ranges between \$50–60 Mg^{-1} for miscanthus (Supporting Information: Figure S2c) and \$60–70 Mg^{-1} switchgrass

(Supporting Information: Figure S2f). See Supporting Information: Section 3.1 for a detailed analysis of breakeven price results.

At a biomass price of \$60 Mg^{-1}, the expected profit for miscanthus and switchgrass in the Midwest (Supporting Information: Figure S3a) and southern states (Supporting Information: Figure S3d), respectively, are positive and range between \$100 and \$200 ha^{-1}. With carbon mitigation payments, expected profits for bioenergy crops are higher, and more counties have expected positive profits. At a biomass price of \$40 Mg^{-1}, expected net bioenergy crop profits are not positive in almost any county without carbon mitigation payment (Supporting Information: Figure S3g,j). However, with a carbon price of \$80 Mg^{-1} C, the annualized NPV profits would increase to \$100–200 ha^{-1} for miscanthus in the Upper and Central Midwest (Supporting Information: Figure S3i) and switchgrass in the Southern Great Plains and Southeast (Supporting Information: Figure S3l). See Supporting Information: Section 3.2 for a detailed analysis of expected bioenergy crop profits results.

3.2 | LPP

Figure 1 shows each county's lowest biomass price at which it attains a 50% LPP. The median biomass price at which a county achieves a 50% LPP with no carbon mitigation payment for miscanthus (Figure 1a) is between \$70–80 Mg^{-1} and is lowest in the Midwest (between \$50–70 Mg^{-1}) and highest in the great plains and the Mississippi delta region (between \$70–100 Mg^{-1}). With a carbon price of \$80 Mg^{-1} C, the median biomass price for achieving 50% LPP for miscanthus is lower at \$50–60 Mg^{-1} (Figure 1c). For switchgrass, the median biomass price at which a county achieves a 50% LPP with no carbon mitigation payments for miscanthus

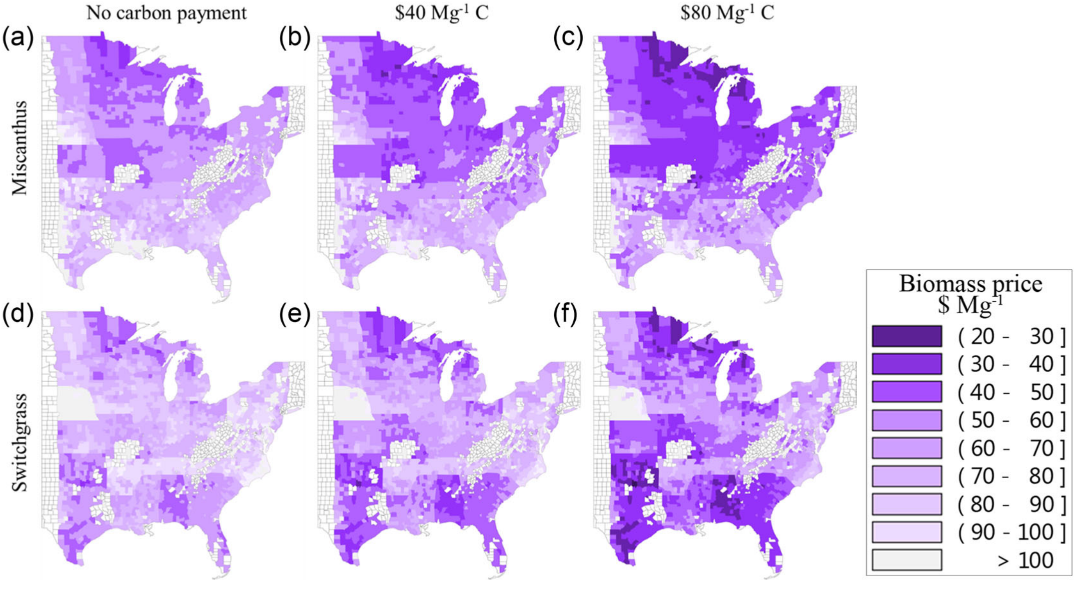

FIGURE 1 Lowest biomass price at which county attains 50% likelihood of positive profit (LPP) for miscanthus and switchgrass with and without carbon mitigation payments. Darker color represents lower biomass price. (a) Biomass price at which counties attain 50% LPP for miscanthus without carbon payments (b) Biomass price at which counties attain 50% LPP for miscanthus with carbon price of \$40 Mg^{-1} C (c) Biomasss price at which counties attain 50% LPP for miscanthus with carbon price of \$80 Mg^{-1} C (d) Biomass price at which counties attain 50% LPP for switchgrass without carbon payments (e) Biomass price at which counties attain 50% LPP for switchgrass with carbon price of \$40 Mg^{-1} C (f) Biomass price at which counties attain 50% LPP for switchgrass with carbon price of \$80 Mg^{-1} C.

(Figure 1d) is between \$70–80 Mg^{-1}, with regions with the lowest 50% LPP being in the southern states and northern Midwest (between \$50–70 Mg^{-1}). With a carbon price of \$80 Mg^{-1} C, the median biomass price of 50% LPP for switchgrass is lower (between \$60–70 Mg^{-1}, Figure 1f) across the rainfed region with counties in the southern states having 50% LPP between biomass prices of \$30–60 Mg^{-1}.

Areas where LPP is higher than 50% may appeal to risk-averse farmers to grow bioenergy crops as such areas may indicate more certainty in positive profits. We present the LPP for each county at selected biomass and carbon prices in Supporting Information: Section 3.3. We show that at a biomass price of \$60 Mg^{-1}, counties in high-yielding bioenergy crop regions have 30% or higher LPP. Carbon mitigation payments increase LPP for bioenergy crop profits in these regions and expand the region where bioenergy crops achieve at least 30% LPP. At a biomass price of \$40 Mg^{-1}, most counties have a near-zero likelihood of achieving positive bioenergy profits; however, carbon mitigation payments make these crops appealing to risk-averse farmers.

3.3 | CV of bioenergy crop returns relative to conventional crop returns

At a biomass price of \$60 Mg^{-1} and in the absence of carbon mitigation payment, the CV of returns from miscanthus (Figure 2a) and switchgrass (Figure 2d) relative to conventional crops is less than 1 across most of the rainfed region. A CV ratio of less than 1 implies that returns from bioenergy crops are relatively less risky than those from conventional crops in terms of CV. Carbon mitigation payments further make these returns from miscanthus (Figure 2b,c) and switchgrass (Figure 2e–f) relatively less risky relative to conventional crops. At a biomass price of \$40 Mg^{-1} and in the absence of carbon mitigation payments, however, bioenergy crop production is only less risky in terms of CV in a handful of counties in the central Midwest for miscanthus (red areas in Figure 2g) and southern states for switchgrass (red areas in Figure 2j). Outside of these regions, bioenergy crop returns are either negative (green areas in Figure 2j) or positive but are riskier in terms of CV than conventional crops (blue areas in Figure 2j). Carbon mitigation payment makes bioenergy crop returns less risky than returns from conventional crops. For example, with a carbon price of \$40 Mg^{-1} C, miscanthus returns in the Midwest (Figure 2h) and switchgrass returns mainly in the southern states and Midwest (Figure 2k) are less risky than conventional crops. At a higher carbon price of \$80 Mg^{-1} C, both bioenergy crops are less risky than conventional crops in most rainfed regions except in parts of the Great Plains (Figure 2i for miscanthus and Figure 2l for switchgrass). In Supporting Information: Section 3.4, we consider the CV ratios for miscanthus returns relative to switchgrass returns. We find that at lower biomass prices (i.e., \$40 Mg^{-1}), one bioenergy crop tends to be substantially riskier than the other, whereas, at higher biomass prices (i.e., \$60 Mg^{-1}), this difference is less stark. Carbon mitigation payments only slightly reduce the relative riskiness between bioenergy crops as both crops benefit from such a payment.

3.4 | Stochastic dominance of bioenergy crop returns

At a biomass price of \$60 Mg^{-1} with no carbon mitigation payment, returns for bioenergy crops are SOSD over conventional crop returns in most counties in the Midwest (for miscanthus, Supporting Information: Figure S7a) and in the southern states and northern Midwest counties (for switchgrass, Supporting Information: Figure S7d). With carbon mitigation payments at a carbon price of \$80 Mg^{-1} C, bioenergy crop returns increase enough to achieve FOSD in most counties over conventional crop returns in these regions. Further, carbon mitigation payments expand the areas where bioenergy crops achieve SOSD over conventional crop returns to span most of the United States rainfed region (Supporting Information: Figure S7c for miscanthus and Supporting Information: Figure S7f for switchgrass). This is because carbon mitigation payments make

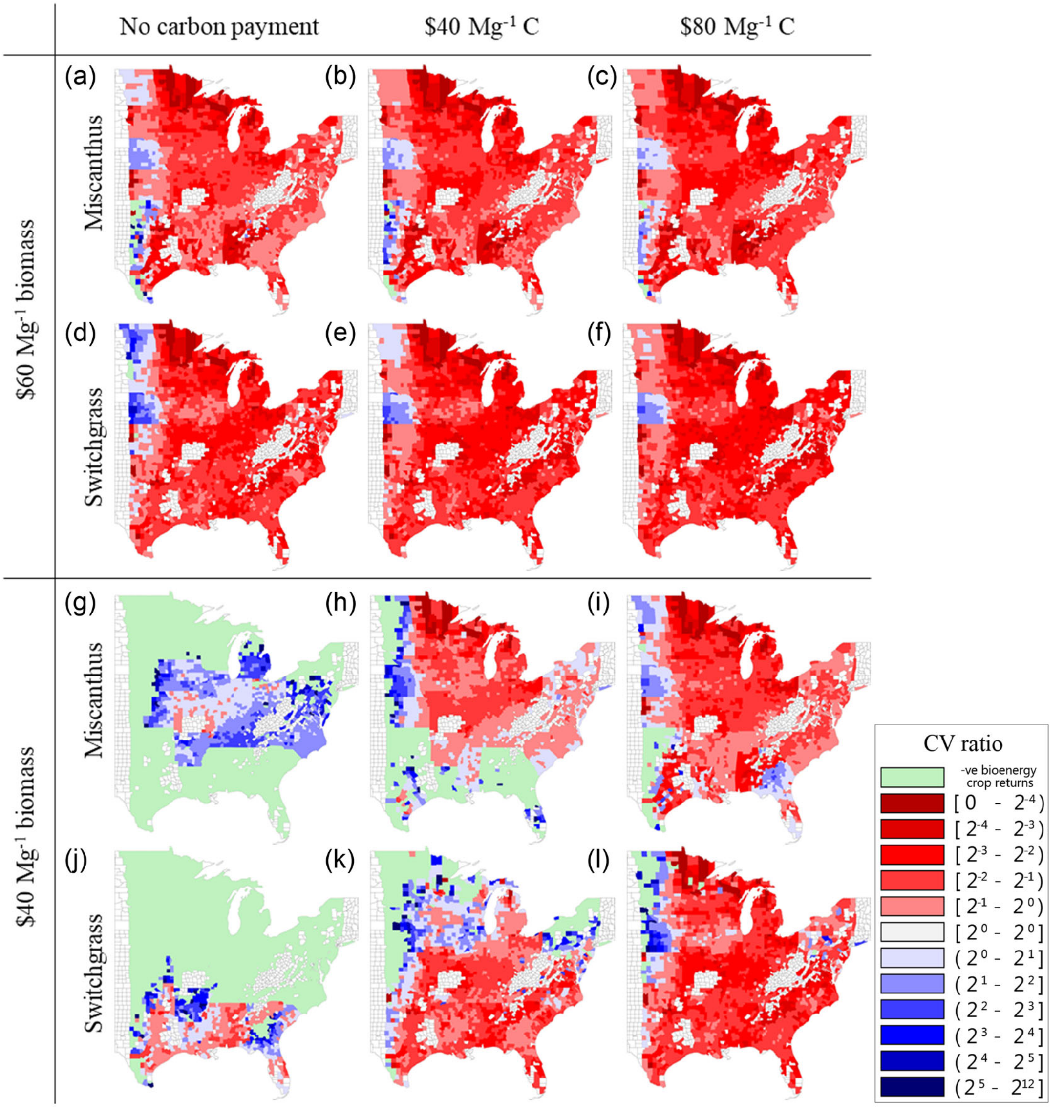

FIGURE 2 The ratio of the coefficient of variation (CV) of the returns with bioenergy crops to the CV of returns with conventional crops at biomass prices of \$60 Mg^{-1} and 40 Mg^{-1}. Red areas depict counties where bioenergy crop returns are less risky (in terms of CV) than conventional crops, and the blue regions depict where they are riskier than conventional crops. Green areas are those where bioenergy crop returns are negative. (a) Ratio of CV of returns with miscanthus to CV of returns with conventional crops without carbon payments at a biomass price of \$60 Mg^{-1} (b) Ratio of CV of returns with miscanthus to CV of returns with conventional crops with carbon price of \$40 Mg^{-1} C and biomass price of \$60 Mg^{-1} (c) Ratio of CV of returns with miscanthus to CV of returns with conventional crops with carbon price of \$80 Mg^{-1} C and biomass price of \$60 Mg^{-1} (d) Ratio of CV of returns with switchgrass to CV of returns with conventional crops without carbon payments at a biomass price of \$60 Mg^{-1} (e) Ratio of CV of returns with switchgrass to CV of returns with conventional crops with carbon price of \$40 Mg^{-1} C and biomass price of \$60 Mg^{-1} (f) Ratio of CV of returns with switchgrass to CV of returns with conventional crops with carbon price of \$80 Mg^{-1} C and biomass price of \$60 Mg^{-1}. (g) Ratio of CV of returns with miscanthus to CV of returns with conventional crops without carbon payments at a biomass price of \$40 Mg^{-1} (h) Ratio of CV of returns with miscanthus to CV of returns with conventional crops with carbon price of \$40 Mg^{-1} C and biomass price of \$40 Mg^{-1} (i) Ratio of CV of returns with miscanthus to CV of returns with conventional crops with carbon price of \$80 Mg^{-1} C and biomass price of \$40 Mg^{-1} (j) Ratio of CV of returns with switchgrass to CV of returns with conventional crops to conventional crop returns without carbon payments at a biomass price of \$40 Mg^{-1} (k) Ratio of CV of returns with switchgrass to CV of returns with conventional crops with carbon price of \$40 Mg^{-1} C and biomass price of \$40 Mg^{-1} (l) Ratio of CV of returns with switchgrass to CV of returns with conventional crops with carbon price of \$80 Mg^{-1} C and biomass price of \$40 Mg^{-1}.

bioenergy crops more profitable and reduce the risk-to-return ratio relative to conventional crops in areas where bioenergy crops are not profitable without carbon mitigation payments. Miscanthus returns (Supporting Information: Figure S8a) achieve FOSD over switchgrass returns in the northern rainfed United States, and switchgrass returns (Supporting Information: Figure S8d) do the same over miscanthus in the southern states. Neither bioenergy crop return achieves SOSD over the other, as miscanthus and switchgrass have spatially different return profiles and regions where each crop is profitable across the rainfed region. Carbon mitigation payments increase returns and reduce the risk-to-returns ratio for miscanthus (Supporting Information: Figure S8b,c), most significantly where returns from miscanthus crops are stochastically dominant over switchgrass without carbon mitigation payments. The same is true for switchgrass returns being stochastically dominant over miscanthus. Therefore, adding carbon mitigation payments does not change the spatial pattern of stochastic dominance between miscanthus and switchgrass. Further, miscanthus returns achieve SOSD (Figure 3a) under no carbon mitigation payments and FOSD (Figure 3c) under carbon mitigation payments (at a carbon price of $\$80\,\mathrm{Mg}^{-1}$ C) over all other crops in our analysis (i.e., conventional crops and switchgrass) only in the northern half of the rainfed region and no stochastic dominance elsewhere. Similarly, switchgrass returns achieve SOSD (Figure 3d) under no carbon mitigation payments and FOSD (Figure 3f) under carbon mitigation payments (at a carbon price of $\$80\,\mathrm{Mg}^{-1}$ C) over all other crops in our analysis (i.e., conventional crops and miscanthus) only in the southern half of the rainfed region and no stochastic dominance elsewhere. At moderate biomass prices, bioenergy crops may appeal to risk-averse farmers without carbon mitigation payments; however, carbon mitigation payments increase bioenergy crop profitability and reduce bioenergy crop risk-to-returns ratios relative to other crops in our analysis, making them crops appeal to farmers regardless of their risk preference.

At a biomass price of $\$40\,\mathrm{Mg}^{-1}$, bioenergy crops without carbon mitigation payment returns are not profitable throughout the rainfed United States and do not achieve any stochastic dominance over conventional crops (Supporting Information: Figure S7g for miscanthus, Supporting Information: Figure S7j for switchgrass). Carbon mitigation payments (at a carbon price of $\$80\,\mathrm{Mg}^{-1}$ C) increase bioenergy crop returns to be close to breakeven prices (Supporting Information: Figure S3i for miscanthus and Supporting Information: Figure S3l for switchgrass) and lower the risk-to-returns ratio relative to conventional crops in some parts of the rainfed United States (Figure 2i for miscanthus and Figure 3l for switchgrass). Under carbon mitigation payments, miscanthus and switchgrass achieve mainly SOSD over conventional crop returns in the Midwest (Supporting Information: Figure S7i) and in the southern states (Supporting Information: Figure S7l), respectively. Similar to the higher biomass price case, miscanthus returns (Supporting Information: Figure S8g) achieve FOSD over switchgrass returns in parts of the Midwest, and switchgrass returns (Supporting Information: Figure S8j) do the same over miscanthus in the southern states. However, under lower biomass prices, bioenergy crops attain FOSD over other bioenergy crops in a smaller number of counties as fewer counties have positive biomass returns without carbon mitigation payments. Carbon mitigation payments increase returns and reduce the risk-to-returns ratio for both miscanthus (Supporting Information: Figure S8b,c) and switchgrass (Supporting Information: Figure S8d–f) such that the spatial pattern of stochastic dominance is similar to that under higher biomass prices (i.e., Supporting Information: Figure S8a–f). Further, miscanthus (Figure 3g) and switchgrass (Figure 3j) returns achieve no stochastic dominance over all other crops in our analysis (i.e., conventional crops and switchgrass for miscanthus and conventional crops and miscanthus for switchgrass). Carbon mitigation payments (e.g., at a carbon price of $\$80\,\mathrm{Mg}^{-1}$ C) increase miscanthus (Figure 3i) and switchgrass (Figure 3l) returns to breakeven prices and lower the risk-to-return ratio relative to other crops in our analysis, such that bioenergy crop returns achieve SOSD in the central Midwest (for miscanthus) and in the southern states (for switchgrass) no stochastic dominance elsewhere. At low biomass prices, bioenergy crops are not profitable and, therefore, not preferred by farmers; however, carbon mitigation payments make the crops appealing to risk-averse farmers by increasing returns and reducing risk-to-returns ratios.

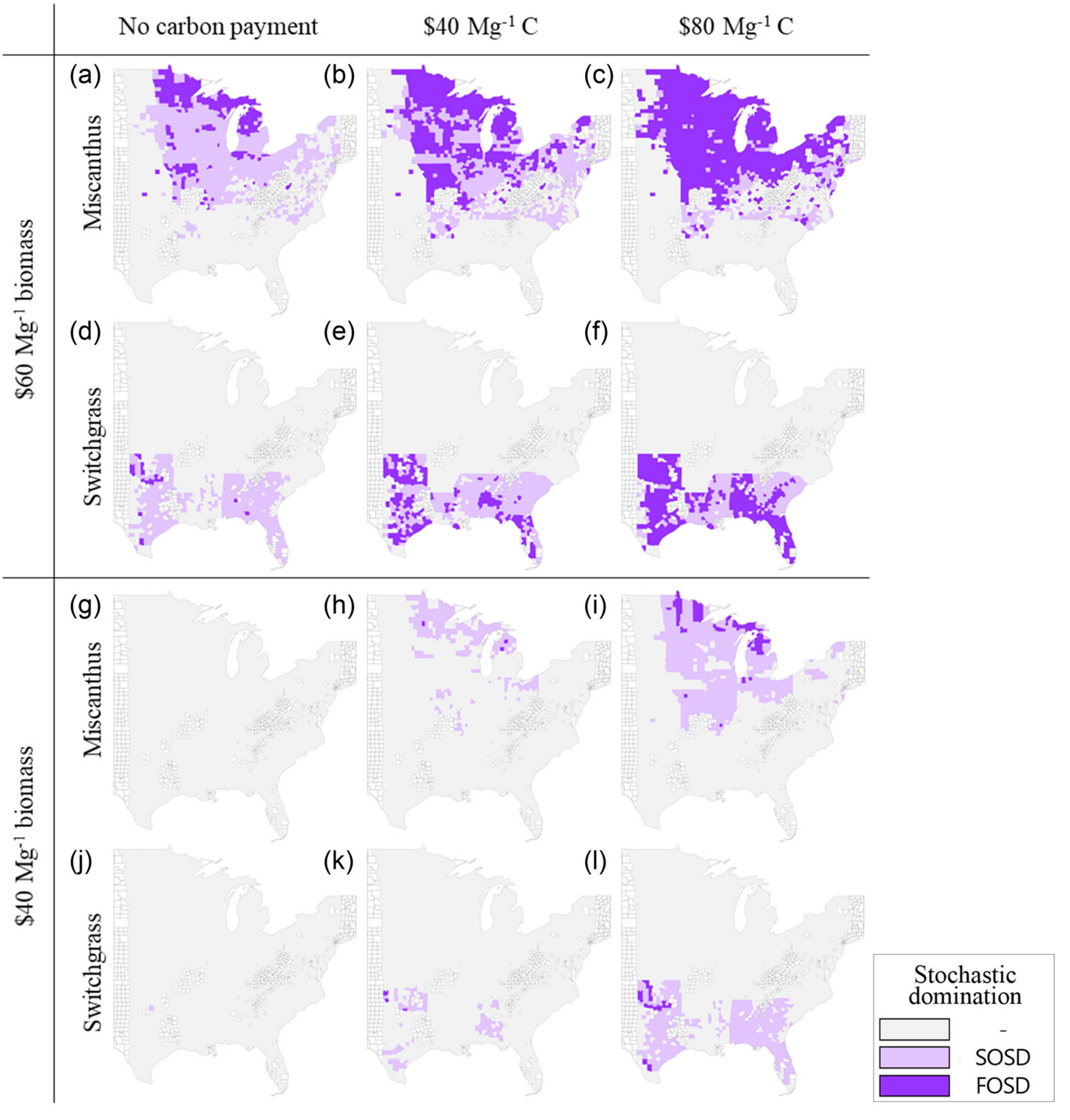

FIGURE 3 (See caption on next page)

3.5 | Sensitivity analysis

We conduct four sets of sensitivity analyses on our results. First, we consider a case where the farmer has a higher discount rate (10%) following Miao and Khanna (2017a). Second, we consider survival risk in miscanthus crops following Clifton-Brown and Lewandowski (2000) and Kucharik et al. (2013). Third, following we consider the case of maturation risk following Skevas et al. (2016), 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. Fourth, we relax the yield penalty that we apply for conservation tillage in our primary analysis following Chen et al. (2021a), who show that yield under conservation tillage is not statistically different from conventional tillage however, a yield penalty could arise when farmers adopt conservation tillage but do not change other management practices. The results of the sensitivity analysis are presented in detail in Supporting Information:

Section 5; in general, they show that the qualitative directions of the findings of our benchmark case remain unchanged.

4 | DISCUSSION

Our analysis provides insights into the riskiness of bioenergy crop returns and the effect of carbon mitigation payments on bioenergy crop profitability and riskiness of returns at different biomass and carbon prices across the rainfed United States We find that without carbon mitigation payments at low biomass prices (i.e., \$40 Mg^{-1}), miscanthus and switchgrass are not profitable relative to conventional crops. Further, bioenergy returns have a high risk-to-return ratio relative to conventional crop returns, especially in areas where corn and soybean are most productive (i.e., Midwestern and Delta regions of the rainfed United States). At moderate biomass prices (i.e., \$80 Mg^{-1}) and without carbon mitigation payments, miscanthus and switchgrass have positive but low expected profits relative to conventional crops in the central Midwest and the southern states. However, similar to the case with low biomass prices, bioenergy returns have a low risk-to-return ratio relative to conventional crop returns and achieve only SOSD over conventional crops. As such, bioenergy crops would appeal to risk-averse farmers (i.e., those willing to accept lower but more certain returns over higher but more variable returns).

We find that at low biomass prices, although bioenergy crops are still not as profitable as conventional crops even with the provision of \$80 Mg^{-1} C price, they would now appeal to risk-averse farmers, that is, those willing to accept lower returns for more certainty. Bioenergy crops achieve SOSD in a few counties despite expected returns being lower than those of conventional crops. At higher carbon mitigation payments (such as at a carbon price of \$80 Mg^{-1} C), miscanthus becomes FOSD in the more productive regions of the Midwest and switchgrass in the southern states. Therefore, bioenergy crops in these regions would appeal to farmers regardless of their risk preferences. Further, bioenergy crop profitability expands beyond the most productive regions of the rainfed region to achieve SOSD over conventional crops across the rainfed region. Comparing the risk and return profiles of miscanthus and switchgrass to each other, we find that miscanthus is FOSD in the Midwest and switchgrass is FOSD in the southern states, irrespective of whether there is a carbon mitigation payment.

FIGURE 3 Stochastic dominance of miscanthus over conventional crops and switchgrass and stochastic dominance of switchgrass over conventional crops and miscanthus at biomass prices of \$60 Mg^{-1} and \$40 Mg^{-1}. "Second-order stochastic dominance (SOSD)" here represents counties where bioenergy crops only achieve SOSD over conventional crops *and other bioenergy crops* (for miscanthus, this means SOSD over switchgrass and other conventional crops, for switchgrass, the comparison bioenergy crop is miscanthus). "First-order stochastic dominance (FOSD)" represents counties where bioenergy crops achieve FOSD over conventional and other bioenergy crops. Areas with no color represent counties where bioenergy crop returns meet neither dominance criteria. (a) Stochastic dominance of miscanthus over conventional crops and switchgrass without carbon payments at a biomass price of \$60 Mg^{-1} (b) Stochastic dominance of miscanthus over conventional crops and switchgrass with carbon price of \$40 Mg^{-1} C at a biomass price of \$60 Mg^{-1} (c) Stochastic dominance of miscanthus over conventional crops and switchgrass with carbon price of \$80 Mg^{-1} C at a biomass price of \$60 Mg^{-1} (d) Stochastic dominance of switchgrass over conventional crops and miscanthus without carbon payments at a biomass price of \$60 Mg^{-1} (e) Stochastic dominance of switchgrass over conventional crops and miscanthus with carbon price of \$40 Mg^{-1} C at a biomass price of \$60 Mg^{-1} 3(f) Stochastic dominance of switchgrass over conventional crops and miscanthus with carbon price of \$80 Mg^{-1} C at a biomass price of \$60 Mg^{-1} (g) Stochastic dominance of miscanthus over conventional crops and switchgrass without carbon payments at a biomass price of \$40 Mg^{-1} (h) Stochastic dominance of miscanthus over conventional crops and switchgrass with carbon price of \$40 Mg^{-1} C at a biomass price of \$40 Mg^{-1} (i) Stochastic dominance of miscanthus over conventional crops and switchgrass with carbon price of \$80 Mg^{-1} C at a biomass price of \$40 Mg^{-1} (j) Stochastic dominance of switchgrass over conventional crops and miscanthus without carbon payments at a biomass price of \$40 Mg^{-1} (k) Stochastic dominance of switchgrass over conventional crops and miscanthus with carbon price of \$40 Mg^{-1} C at a biomass price of \$40 Mg^{-1} (l) Stochastic dominance of switchgrass over conventional crops and miscanthus with carbon price of \$80 Mg^{-1} C at a biomass price of \$40 Mg^{-1}.

Previous research, which found that bioenergy crop adoption may be limited in the productive regions of the rainfed region, has typically not considered the riskiness of bioenergy and conventional crops) or the effect of carbon mitigation payments on bioenergy crop returns and riskiness. We find that bioenergy crops with carbon mitigation payments are more resilient to weather-related risk than conventional crops and may be preferred by farmers who care about reducing the riskiness of their returns. The extent to which this is the case varies across the rainfed region and depends on biomass price and carbon mitigation payment. We show that carbon mitigation payments are particularly important when biomass prices are low, whereas small carbon mitigation payments can make bioenergy crops appealing at higher biomass prices. These findings can inform the development of policies to promote the production of bioenergy crops to mitigate GHG emissions.

Our analysis has several implications for the design of carbon payments. It shows that carbon and biomass prices can complement each other in increasing the returns to bioenergy crops over a wider geographical region. Moreover, at low biomass prices, carbon prices can make bioenergy crop production particularly appealing to risk-averse farmers by reducing the riskiness of these crops. At higher biomass prices, they make them appealing to all farmers, regardless of risk preferences. We also find heterogeneity in yields and carbon mitigation potential per unit of land for a bioenergy crop and across bioenergy crops. As a result, a uniform carbon price can result in different carbon mitigation payments per unit of land across the region and spatially heterogenous effects on returns and risks of bioenergy crops. Since a uniform carbon price (based on the social cost of carbon) is the cost-effective approach to addressing a global externality like carbon, our analysis implies that this would result in spatially heterogeneous carbon mitigation payments per unit of land. Carbon credit programs that offer a uniform practice-based carbon mitigation payment per unit of land disregard this heterogeneity and are likely to be inefficient. Instead, these programs should specify a uniform carbon price and a mechanism for determining the spatially varying carbon mitigation benefits across the region. Further, carbon mitigation payments can substitute for other policies, such as the Biomass Crop Assistance Program (BCAP), to incentivize bioenergy crops. However, policies such as BCAP that subsidize bioenergy crops using per ton of biomass payments instead of their carbon mitigation benefits may differ in the resulting spatial pattern of bioenergy crop production and their cost-effectiveness in achieving given levels of carbon mitigation. We leave it to future research to examine these issues.

Our analysis presents an ex-post comparison of risk and returns of bioenergy crops to conventional crops where the farmers are assumed to know the distributions of returns which vary stochastically in yields and conventional crop prices. Further, we do not consider uncertainty about climate policy and risks involved with the payments in our model. We also assume certainty of carbon mitigation payments being provided throughout the planting period and certainty of farmers growing and maintaining bioenergy crops till the end of the planting period. We leave it to future research to consider policy uncertainty and the ability of farmers to change to more profitable cropping practices during the lifespan of an energy crop. Further, as we conduct our analysis at the county level, our analysis does not provide insight into subregions within each county which may vary in soil quality and yield potential. We expect more spatial variation in finer-scale data within a region but do not expect overall results to change qualitatively. For simplicity, we also do not consider the implications of offering direct carbon mitigation payments for adopting carbon mitigating practices under conventional crops, such as no-till or cover cropping on bioenergy crop returns and riskiness. Their effect on incentives for switching to bioenergy crops will depend on the magnitude of the carbon mitigation payments and the effect of these practices on the riskiness of conventional crop yields. We leave it to future research to go beyond our analysis and explore the effect of different methods of paying farmers for carbon mitigation on risk, returns, and adoption. Further, we leave it to future research to simulate how carbon mitigation payments may be distributed across the biofuel supply chain, how they may affect crop management choices and, the cost-effectiveness of such payments relative to other programs, or to analyze the effect of other sources of risk on bioenergy crop adoption.

SYNOPSIS

Bioenergy crops provide substantial carbon mitigation benefits but may have low and risky returns, depending on biomass prices. We show that carbon mitigation payments increase miscanthus and switchgrass profitability and their potential appeal to risk-neutral and risk-averse farmers in the Midwestern and southern United States.

ACKNOWLEDGMENTS

This work was supported by the Department of Energy, Office of Science, and Office of Biological and Environmental Research under Award Number DE-SC0018420). Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the U.S. Department of Energy. We also thank the financial support from an award from the National Institute of Food and Agriculture (NIFA), the USDA (Award number: 2017-67019-26283). Ruiqing Miao is grateful for support from Alabama Agricultural Experiment Station and the Hatch program of the NIFA/USDA (Hatch project number: ALA011-1-17002).

DATA AVAILABILITY STATEMENT

This article has earned Open Data and Open Materials badges. Data and materials are available at https://doi.org/10.13012/B2IDB-6296964_V1.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Majeed, Fahd, Madhu Khanna, Ruiqing Miao, Elena Blanc-Betes, Tara Hudiburg, and Evan DeLucia. 2023. "Carbon mitigation payments can reduce the riskiness of bioenergy crop production." *Journal of the Agricultural and Applied Economics Association*. 2: 181–197. https://doi.org/10.1002/jaa2.52