Designing Cost-Effective Carbon Payments to Induce Cellulosic Feedstock Production for Sustainable Aviation Fuel

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Abstract

Perennial bioenergy crops, such as miscanthus and switchgrass, and crop residues have the potential to scale up Sustainable Aviation Fuel (SAF) production and mitigate carbon emissions. However, high establishment costs, establishment lags, and risk and return profiles with bioenergy crops that differ from those of conventional crops can adversely affect incentives to produce them. We develop an economic model that incorporates spatially varying joint yield and price distributions for the multiple crop choices a farmer faces and apply it to examine the incentives for risk-averse, present-biased, and credit-constrained farmers to produce cellulosic feedstocks under various biomass prices. We link this model to a biogeochemical model to quantify the spatially varying carbon mitigation benefits from these feedstocks in the rainfed region of the United States. We also analyze the cost-effectiveness of two carbon payment policies: annual and upfront. We find that risk-averse, present-biased, or credit-constrained farmers prefer to grow the lower-yielding but less risky switchgrass and harvest corn stover instead of producing the lower carbon, higher-yielding but riskier feedstock miscanthus, resulting in lower SAF production. Upfront carbon payments incentivize higher quantities of less carbon-intensive SAF production by risk-averse, credit-constrained, and present-biased farmers because they offset a part of the establishment costs of miscanthus. We also find that when farmers are credit-constrained, upfront payments are more cost-effective in terms of carbon mitigation per dollar spent. In contrast, annual payments are more cost-effective when farmers can access credit.

Keywords: Bioenergy crops, risk and time preferences, carbon mitigation, sustainable aviation fuel

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1 Introduction

There is growing policy support in the United States (US) for scaling up the production of Sustainable Aviation Fuel (SAF) to decarbonize the aviation sector, which accounts for about 2.5% of US greenhouse gas (GHG) emissions.[1] The US has set a Grand Challenge of meeting 100% of its aviation fuel demand, 35 billion gallons per year (132.5 billion liters per year), with SAF by 2050.[2] Recent policies, 40B and 40Z, have taken the form of performance-based tax credits that increase as the carbon intensity of SAF decreases below 50% less carbon intensive than petroleum jet fuel. Scaling up SAF production from the current level of approximately 115.8 million liters per year[34] will require transitioning from using food crops as feedstocks to high-yielding non-food crops and crop residues as feedstocks that require less land diversion from food to fuel production than food crops.

Crop residues and high-yielding perennial bioenergy crops, such as miscanthus and switchgrass, are appealing feedstocks for low-carbon intensity SAF. While corn stover is a low-yielding but low-cost source of biomass readily available to farmers planting corn, it has a relatively higher carbon intensity than high-yielding bioenergy crops. Bioenergy crops can produce negative carbon SAF due to their potential to sequester a substantial amount of carbon in the soil (Fan et al., 2024). Among these, miscanthus has a significantly higher yield and lower carbon intensity than switchgrass. However, its production involves high upfront costs and longer establishment lag than switchgrass. These bioenergy crops also require a long-term land commitment compared to annual crops, such as corn and soybeans, and impose risks that differ from those of annual crops (Bocquého & Jacquet, 2010; Miao & Khanna, 2017a, 2017b; Ouattara et al., 2019). While bioenergy crops can provide diversification benefits, they require farmers to trade off future returns for current costs, mainly when they are credit-constrained and need to bear the upfront establishment costs through their own sources.

Incentives to convert land from annual conventional crops to bioenergy crops will differ with farmer risk and time preferences and the availability of credit to cover upfront costs of establishment. The risks and returns from producing these bioenergy crops differ across crop residues and bioenergy crops, miscanthus and switchgrass, and also vary spatially due to differences in land suitability and growing conditions for these crops (Fan et al., 2024; Miao & Khanna, 2017a, 2017b). Additionally, the carbon intensity of these feedstocks also differs spatially due to differences in yields and effects on soil carbon sequestration. Thus, policy incentives that pay farmers to produce cellulosic feedstocks based on the carbon intensity of the SAF will result in payments per unit of land that differ across feedstocks and locations. The effects of a carbon payment on incentives to produce biomass and on the choice of feedstock to produce will depend on the price of biomass, the cost of producing the feedstock, the riskiness of the returns and the trade-off it involves between upfront costs and future returns, particularly if the farmer is credit constrained. The farmer's decision to produce feedstocks, the choice between the two bioenergy crops in particular, and the quantity of feedstock produced will depend on the farmer's risk-aversion, time-discounting, and credit-constraint profile.

The problem of establishment costs as a deterrent to risk-averse, present-biased, and credit-constraint farmers to produce bioenergy crops is a well-recognized problem (Miao & Khanna, 2017a, 2017b). Previously, the Biomass Crop Assistance Program (BCAP) was established and offered payments that would partially cover the establishment costs for bioenergy crops through a cost-share program. These payments did not differ with a feedstock's carbon mitigation potential and thus could not be targeted based on a feedstock's spatial and temporal carbon intensity.

The purpose of this paper is to examine the potential supply of SAF from crop residues and bioenergy crops from croplands in the rainfed region of the US at various biomass (and equivalent SAF prices) and carbon payments. To this extent, we have three objectives. First, we examine the effect of farmer risk-aversion, time-discounting, and access to credit on the potential production and mix of cellulosic feedstocks (miscanthus, switchgrass, and corn stover harvest). Second, we examine the effect of carbon payment design on the mix of cellulosic feedstock production and the cost per ton of carbon mitigated. We examine the effects of two types of mechanisms to pay farmers for carbon mitigation services provided: an annual payment per ton of carbon mitigated relative to petroleum jet and a lump sum upfront payment per ton of the carbon that will be mitigated by that feedstock over 15 years. While annual payments are likely to appeal to less risk-averse and credit-constrained farmers, upfront carbon payments are likely to appeal to more risk-averse farmers with credit-constraints. We examine the extent to which this is the case and its implications for the supply and cost of SAF. Third, we consider how the spatial pattern of production of cellulosic feedstocks for SAF differs with different designs of carbon payments.

We undertake this analysis using a stylized integrated numerical simulation framework that links an economic model with a biogeochemical model, DayCent, to analyze farmers' cropping decisions while accounting for spatial and temporal heterogeneity in crop yields and carbon intensities at a county scale across the rainfed region of the US. Each county is represented by a utility-maximizing farmer with given risk and time preferences who chooses the allocation of land to conventional and bioenergy crops and whether to harvest a portion of corn stover from areas under corn production over a 15-year horizon under a range of biomass (and corresponding SAF) prices. We then consider the effect of offering a price per ton of carbon credits generated, which could be paid as an annual payment per ton of carbon credits or a lump sum payment for carbon credits generated over 15 years. The carbon intensity of a feedstock includes the life-cycle emissions generated in the feedstock production process and conversion to SAF and the soil carbon sequestration. We examine the effects of varying degrees of risk-aversion and time-preferences and the presence or absence of credit-constraints at exogenously set SAF and carbon prices on the amount of land allocated to producing the two bioenergy crops and harvesting corn stover.

Our research contributes to the literature on the economics of SAF production using cellulosic feedstocks (Fan et al., 2024; Gautam et al., 2023). Fan et al. (2024) conducted spatially varying techno-economic and life-cycle analyses to compare the cost of SAF and GHG-intensity with various bioenergy crops and crop residues but did not directly explore the effect of temporally varying costs, yields, and carbon effects or the effect of yield and price riskiness in feedstock production. Gautam et al. (2023) examine the potential for bioenergy feedstock production from one feedstock at a time, at exogenous carbon and jet fuel prices, but did not explore how farmers choose between these feedstocks and the mix of feedstocks that would be produced at a given biomass and carbon price. Neither of these studies considers the effect of farmer profiles (risk-aversion, time-discounting, and credit-constraints) or policy design (such as upfront payments or annual payments for carbon mitigation) on feedstock adoption. Previous research has shown that long maturity periods with high establishment costs and uncertain yields due to weather variations reduce incentives for risk-averse, present-biased, and credit-constrained farmers to produce these bioenergy crops (Miao & Khanna, 2017a, 2017b). This research has not examined the role that carbon-based payments can play in inducing farmers to convert cropland to produce miscanthus and switchgrass or the impact of carbon mitigation payments on the cost-effectiveness of SAF adoption and carbon mitigation. We build on the framework developed by Miao & Khanna (2017a and 2017b) and the economic literature on the design of payments for incentivizing bioenergy crop adoption (such as Alexander et al., 2012; Brandes et al., 2018; McCarty & Sesmero, 2021; Miao & Khanna, 2017a; 2017b) by considering the effect of alternative mechanisms for payments based on carbon mitigation on the extent and costs of carbon mitigation with SAF.

The rest of the paper is as follows. Section 2 outlines a modeling framework to simulate spatially explicit incentives for producing cellulosic feedstocks by a representative risk-averse and time-discounting farmer. Section 3 details the data sources and model calibration used in the simulation model. Section 4 presents the results of the numerical simulation model, and Section 6 concludes by discussing the policy implications of efforts to induce SAF adoption.

2 Conceptual Framework

In this section, we describe the conceptual framework presented in more technical detail in Appendix A.1. We simulate the spatially heterogeneous economic incentives for producing cellulosic feedstocks by a representative risk-averse and present-biased expected utility-maximizing farmer at the county level for the rainfed region of the US. The farmer maximizes their expected net present value of utility derived from returns from land over a given time horizon (fifteen years in this study to represent one lifespan of perennial bioenergy crops).[5] Farmers allocate land between a bioenergy crop and conventional crops and choose whether to harvest crop residue from their conventional crops. As the yield risks of perennial bioenergy crops are not fully correlated with conventional crops, farmers may grow bioenergy crops on some of their land to diversify their crop portfolio and reduce overall return riskiness. Our model allows the farmer to choose a spatially heterogeneous optimal crop mix while considering the riskiness of alternative land uses and the correlations among these risks.

Our model considers the production of three cellular feedstocks, two bioenergy crops, and one crop residue. The perennial bioenergy crops in the model are miscanthus and switchgrass. We separate the lifespan of each bioenergy crop into an establishment period and a mature period. During the establishment period of bioenergy crops, yields are low or reduced. In the mature period, the farmer harvests the bioenergy crop annually.[6] To reduce the dimensionality of the simulation, we assume that the representative farmer for the county only chooses one bioenergy crop between the two.[7] Additionally, the crop residue in this model is corn stover, a by-product of corn production. Corn stover and conventional crops are planted and harvested annually over the simulation period. Corn can be grown continuously in a corn-soybean or continuous corn rotation over the simulation period. The portion of corn stover that can be harvested is fixed and higher if no-till is practiced instead of conventional tillage.[8] Yield and inputs for conventional crops vary by rotation and tillage choices, resulting in different returns from each rotation-tillage combination choice. Crop and feedstock yields are subject to weather shocks, and returns to land are subject to price risk. We assume that the farmer knows the joint distribution of yields of miscanthus, switchgrass, corn and soybeans, and corn and soybean prices.

Yields and their riskiness vary across counties. Corn stover yields (per hectare of corn) are highest in the Midwest region and lower in the Great Plains and Southern states. Bioenergy crops have higher yields than corn stover, with Switchgrass having its highest yields in the southern states. Miscanthus yields are highest in the Midwest (see Appendix B.1).

Feedstock profit calculations: Each crop's profit is determined by its yield, price, production cost with a fixed per-hectare and variable per-unit-of-output component, and policy payment. For bioenergy crops, costs vary between the establishment and mature stages of the crop's lifespan (calculation of bioenergy costs are described in Appendix B.2). Implicit in the model is the opportunity cost of land; farmers who adopt bioenergy crops forgo profits that they would have made on that portion of land from growing conventional crops (cost and stochastic prices of conventional crops are detailed in Appendix B.3 and Appendix B.4). This opportunity cost of converting land from conventional crops to bioenergy crops is highest in the Midwest and along the Mississippi river basin (Delta region) due to higher corn and soybean profits in these areas. For farmers that can obtain credit, the establishment cost of bioenergy crops is met by borrowing in the first year and paying back the cost through an annuity in the mature period. Farmers that are credit constrained need to bear the upfront cost of establishment from their own resources, which adds to the extent of temporal variability in the return profile with negative net returns in the early establishment years and positive returns in later years.

In the case of conventional crops, the net returns from any given rotation and tillage choice include the returns from corn grain and soybeans returns from the possible harvest of corn stover (calculation of corn stover costs are described in Appendix B.5). For simplicity, we assume that conventional crop and corn stover costs are time-invariant over the model period. When farmers harvest corn stover for a profit, it implicitly increases the opportunity cost of land for bioenergy crops. Bioenergy crops and corn stover receive a fixed payment per ton of biomass at the farm-gate level through a fixed-price long-term contract over a 15-year period. We assume that the cost of converting cellulosic biomass to SAF is the same for all feedstocks (biomass conversion costs are described in Appendix B.12). We add the cost of converting biomass to SAF to calculate a cost per liter for producing SAF from each feedstock.

Carbon mitigation with SAF: The carbon intensity of SAF includes the following three components: (a) the belowground soil carbon sequestration per unit of land, which varies spatially and temporally over the bioenergy crop lifespan. Establishing bioenergy crops may incur initial soil carbon losses followed by an accrual period (Chen et al., 2021). Harvesting of corn stover has a negative impact on soil carbon that varies spatially and by rotation-tillage combination (b) Life-cycle emissions generated during biomass production each year. These emissions vary by feedstock and over the lifespan of bioenergy crops and include carbon emissions associated with fertilizer application, electricity, and diesel use on the farm and to transport biomass to the processing plant and (c) Carbon emissions during the processing of biomass to SAF, which includes the conversion of biomass to cellulosic ethanol, which is then converted to SAF through the ATJ-SPK pathway. This conversion process is assumed to be uniform for all three feedstocks in the model. These emissions are net of the co-product credit due to the cogenerated electricity used during the conversion of biomass to SAF. We compare the carbon credits from displacing petroleum jet with SAF as the difference in carbon emissions per unit of energy.

The carbon intensity of SAF from the three feedstocks considered here differs across feedstocks and locations. We find that SAF from corn stover has higher carbon intensity than bioenergy crop-based SAF. The carbon intensity of SAF from corn stover is lower in the Midwest and higher in the rest of the rainfed region. SAF from switchgrass has the lowest carbon intensity in the southern states, but its carbon intensity is higher than that of miscanthus in the Midwest region. SAF from miscanthus has the lowest carbon intensity in the Midwest.

Policy schemes: We simulate outcomes under three different policy schemes: (a) *No Carbon Payment* scheme in which farmers receive a biomass price but no payment for carbon mitigation; (b) *Annual Payment* scheme in which farmers receive a biomass price and a carbon price per ton of carbon mitigated per year and (c) *Upfront Payment* scheme in which farmers receive a biomass price and a lump sum payment of a carbon price per ton of carbon mitigated over the lifespan of 15 years. The lumpsum payment per ton of carbon mitigated is the net present value of the annual price of carbon over a 15-year period. The per-ton price of carbon is the same under the *Upfront Payment* policy and the *Annual Payment* policy to enable comparison. For example, under *Upfront Payment* at a discount rate of 2%, a farmer receiving \$60 per Mg CO_2 would receive \$828 in the first year (net present value of abating a ton of carbon annually over the 15-year lifespan) and no payment afterward. At a 10% discount, they would receive \$488 in the first year and no payment in other years (a detailed description of these calculations is provided in Appendix A.1). We assume that the entire carbon mitigation value from SAF production passes through to the farmer and is ultimately capitalized in the value of the land.

As such, our analysis provides a lower bound to the carbon price needed to incentivize feedstock production.

3 Data and Materials

We perform our analysis for 2,168 counties to the east of the 100th meridian within the continental US that produce corn or soybeans and for which data was available to simulate bioenergy and conventional crop yields and soil carbon sequestration rates using the biogeochemical model DayCent. Counties that produce corn or soybeans are determined based on pixel-level satellite data from CDL (Jiang et al., 2021). 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 apply a 25% penalty on corn yields for conservation tillage in our primary analysis following Chen et al. (2021), 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. We assume that the stover removal rate is 30% for conventional till and 50% for no-till, as determined by Hudiburg et al. (2016), to have a low impact on corn yield.

We assume that miscanthus reaches maturity after two years of establishment and provides zero and 50% harvestable yields in those two years. It reaches maximum yield in year three, which is assumed to be constant for the remaining life of the crop. In contrast, switchgrass reaches maturity within the first year (Miao & Khanna, 2017a). Following Skevas et al. (2014), we set a limit of 25% on the land that can be converted to bioenergy crops in each county to allow for the possibility of other unknown behavioral factors that may affect land use and prevent extreme changes in land use. Assumptions about production practices and fertilizer quantities for bioenergy crops, corn stover, and corn and soybeans across rotation-tillage combinations are described in Majeed et al. (2023), Chen et al. (2021), and Lee et al. (2023).

We simulate the change in soil carbon levels for each year of the planting period for miscanthus and switchgrass and eight combinations of rotation, tillage, and corn stover removal rates with conventional crops using the DayCent model. Other life-cycle analysis components for the carbon intensity of SAF from biomass and cellulosic ethanol production are calculated using carbon mitigation parameters from Dwivedi et al. (2016), Fan et al. (2024), and GREET. The carbon intensity of converting cellulosic ethanol to SAF is taken from the GREET aviation module (ANL et al., 2023).

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). The cost of converting biomass to cellulosic ethanol and cellulosic ethanol to SAF is based on Fan et al. (2024). All costs are based on inputs and prices from 2016, implying that the biomass price suggested in our model should be inflated to compare to contemporary prices.[9] The cost of conversion of farm gate biomass price at 13% moisture is set exogenously from \$0 to \$150 per metric ton (\$ per Mg) of biomass at intervals of \$10 and is assumed constant over time.

In the carbon payment schemes (*Annual Payment* and *Upfront Payment*), the carbon price is set exogenously per metric ton of CO_2 mitigated (per Mg of CO_2) and assumed to be constant over time. We assume that soil carbon sequestered during the lifespan of the crop will be permanent because the bioenergy crops are produced under long term contracts.

A joint yield-price distribution is assumed where the farmer knows the distribution of conventional crop prices and yields for all crops estimated for their county to calculate stochastic returns. We model the joint distributions using the copula approach (a modeling process that first describes and then replicates the dependence structure between multiple stochastic variables) following Miao and Khanna (2017a), Yan (2007), and Du and Hennessy (2012). The joint yield-price distribution consists of crop yields linked to eight conventional crop rotations, tillage, corn stover harvest choices, two bioenergy crop choices, and prices for corn and soybean. We use these joint yield-price distributions, associated carbon mitigation benefits, spatially varying input costs, biomass, and carbon mitigation payments to calculate stochastic returns for each crop option as described in the numerical simulation for a fifteen-year planting period at exogenously varying biomass and carbon mitigation prices.

We assume a Constant Absolute Risk-aversion (CARA) utility function for a farmer. We follow Hennessy, Babcock, and Hayes (1997) to set the Absolute Risk-Aversion (ARA) parameter to imply a risk premium of 10% for low risk-aversion (*Low Risk-Averse*) and 50% for high risk-aversion (*High Risk-Averse*). We consider two rates of discount, 2% as a low discount rate (*Low Time-Discount*) and 10% as a high discount rate (*High Time-Discount*), following Miao and Khanna (2017b). 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) and allow a comparison of carbon mitigation prices to the social cost of carbon. High discount rates indicate less willingness to wait for future returns. They will lower the value the farmer assigns to future bioenergy crop returns relative to present returns. Further, we assume that farmers either have access to credit to pay for the costly establishment of bioenergy crops (*Not Credit-Constrained*) or do not (*Credit-Constrained*). Those with access to credit can borrow to pay for the establishment costs of bioenergy crops and pay it back principle with interest in the mature period. Farmers without access to credit are assumed to pay for bioenergy crop establishment out-of-pocket. We use stochastic returns to simulate land allocation to rotation and tillage change across the eight permutations of risk-aversion (*Low Risk-Averse* and *High Risk-Averse*) and time-discounting (*Low Time-Discount* and *High Time-Discount*), with and without access to credit (*Not*

Credit-Constrained and *Credit-Constrained*) without carbon mitigation payment and under two carbon mitigation payment schemes (i.e., *No Carbon Payment*, *Annual Payment*, *Upfront Payment*) under exogenously varying carbon mitigation payment levels and biomass prices. For ease of discussion, we refer to the farmer profile of *Low Time-Discount*, *Low Risk-Averse*, and *Credit-Constrained* as the *Low-Constraint* farmer profile and the *High Time-Discount*, *High Risk-Averse*, and *Credit-Constrained* as the *High-Constraint* farmer profile. For each combination of risk-aversion, time-discounting, and access to credit, we can aggregate the total carbon mitigated and area under various cropping practices across the rainfed US and examine the spatial distribution of adoption of bioenergy crops.

4 Simulation Results

4.1 Effect of farmer profiles on supply of SAF and mix of feedstocks

Under all farmer profiles, the production of SAF from cellulosic feedstocks (under *No Payment*) requires a biomass price of at least $40 per Mg biomass in 2016 dollars (with an equivalent SAF price of $1.10 per liter) (Figure 1). As biomass prices increase beyond that, farmer time-discounting, risk-aversion, and credit-constraints affect the overall level and mix of feedstocks chosen. Under the *Low-Constraint* farmer profile (Figure 1 (h)), where farmers are not present-biased, risk-averse, or credit-constrained, the overall SAF that can be produced at $60 per Mg biomass (with an equivalent SAF price of $1.25 per liter) is 57.3 billion liters per year. At this price, the feedstock sources are mostly miscanthus (48.6 billion liters per year), with some switchgrass (1.4 billion liters per year) and corn stover (7.4 billion liters per year). While corn stover is harvested on a much larger land acreage and is the dominant feedstock in terms of land use (Figure A.1 (h)) (accounting for approximately 55% of land growing corn), it is not the dominant feedstock in terms of SAF production. This is due to bioenergy crop yield being significantly larger than the standing corn stover yield per hectare. Additionally, farmers only remove 30% of corn stover under conventional tillage and 50% under no-till from a field so as not to reduce conventional crop yield.[10]

However, under the *High-Constraint* farmer profile (Figure 1 (a)), where farmers are present-biased, risk-averse, and credit-constrained, the overall SAF that can be produced at $60 per Mg biomass is 48 percent (%) lower (at 29.7 billion liters per year) than in the *Low-Constraint* farmer profile. The feedstock sources in this case are mainly switchgrass (21.5 billion liters per year) with some corn stover (8.1 billion liters per year). The reduced SAF production in *High-Constraint* farmer profile is primarily due to risk-averse, present-biased, and credit-constrained farmers choosing lower-yielding switchgrass over miscanthus because the latter has riskier returns, a longer establishment period, and higher establishment costs. At $60 per Mg biomass, lack of access to credit has the largest effect in reducing SAF production with miscanthus as the feedstock relative to the *Low-Constraint* farmer profile (63% miscanthus production in Figure 1 (d) relative to Figure (h)) followed by high time-discounting (58% in Figure 1 (f)) and high risk-aversion (19% in Figure 1 (g)).

At a biomass price of $80 per Mg (with an equivalent SAF price of $1.40 per liter), overall SAF production increases, but the feedstock mix does not change significantly relative to the $60 per Mg biomass price in each farmer profile. As biomass price increases in the *Low-Constraint* farmer profile, miscanthus production increases further, while in the *High-Constraint* farmer profile, switchgrass production increases further (Figure 1 (h) and Figure 1 (a) respectively). Across all farmer profiles, corn stover production increases at higher biomass prices because of an increase in the corn area from which stover is harvested. At this price, corn stover is harvested from 34 million hectares while miscanthus and switchgrass are grown on 17 million hectares of cropland. At $80 per Mg biomass, SAF produced under the *High-Constraint* farmer profile is 26% lower than under the *Low-Constraint* farmer profile at the same price due to the adoption of higher yielding miscanthus in the *Low-Constraint* scenario. At this price, lack of access to credit has the largest effect in reducing SAF production because it discourages miscanthus production, followed by high risk-aversion and then high time-discounting. This implies that higher biomass payments may induce higher SAF production when farmers have high time-discounting; however, higher biomass payments are less effective in incentivizing higher SAF production when farmers are credit-constrained or risk-averse. The higher feedstock production at a price of $80 per Mg is due to increases at the intensive and extensive margins. As the biomass price increases, more counties partially adopt bioenergy crops, and the number of counties that adopt bioenergy crops and harvest corn stover increases. Crop diversification is our model, is driven part due to the yield risks of bioenergy crops are being fully correlated with yield and price risks from conventional crops.

At a biomass price of $80 per Mg, both bioenergy crops and corn stover have higher SAF production relative to $60 per Mg biomass as different mechanisms drive their adoption. Farmers may adopt more bioenergy crops on a portion of their land while also deciding to harvest their corn stover from the conventional crop portion. Additionally, farmers may choose to expand their production of feedstocks in other counties."

Feedstock supply from bioenergy crops becomes relatively inelastic at prices higher than $80 per Mg due to assumed constraints on land conversion. At higher biomass prices, more corn stover is produced as farmers switch rotation and tillage (Figure 1 and Figure A.1). For example, corn stover is harvested from 39 million hectares at a biomass price of $120 per Mg (up from 34 million hectares at a biomass price of $60 per Mg). We also find that at higher biomass prices, farmers who are risk-averse but have access to credit (Figure 1 (e) and (g) for *High Risk-Averse* profiles with *No Credit-Constraint*) choose to substitute away from miscanthus towards switchgrass; this is likely due to the higher riskiness of miscanthus relative to switchgrass.

4.2 Effect of carbon policies on feedstock production

We analyze the effects of an annual carbon payment of $60 per Mg CO_2 on the mix of feedstocks and the quantity of feedstocks that will be supplied at each biomass price. At low biomass prices, annual payments incentivize mostly switchgrass in cases where farmers are credit-constrained, which has a smaller effect on corn stover production. In this case, farmers prefer miscanthus over switchgrass when they have access to credit. For example, at $40 per Mg, in the *High-Constraint* farmer profile (Figure 2 (a)), *Annual Payments* incentivize 38.5 billion liters per year mainly through switchgrass production (relative to near-zero production without carbon payments (Figure 1 (a)). In the *Low-Constraint* farmer profile (Figure 2 (h)), *Annual Payments* incentivize 56.7 billion liters per year (relative to near-zero production without carbon payments (Figure 1 (a)) through mainly miscanthus production. Risk-averse farmers substitute away from miscanthus at higher biomass prices in favor of switchgrass, reducing the potential for SAF production. For example, at $100 per Mg, in the case where farmers have access to credit but are risk-averse (Figure 2 (e) and Figure 2 (g)), *Annual Payments* incentivize farmers to substitute switchgrass over miscanthus, resulting in a 3-5% drop in SAF production compared to *No Carbon Payment*.

Upfront payments are less effective than annual payments at incentivizing greater SAF production at lower biomass prices since, with low biomass prices, farmers receive all their payments in the first year and have very low or negative returns from biomass production for the remaining lifespan of the crop. For example, at a payment of $40 per Mg biomass, *Upfront Payments* incentivize 40% and 31% of the SAF quantity that *Annual Payments* do in the *High-Constraint* and the *Low-Constraint* farmer profiles (Figure 2(i) compared to Figure 2 (a), and Figure 2(p) compared to Figure 2 (h)).

Upfront payments are more effective than annual payments at increasing SAF production at moderate biomass prices, especially under *High-Constraint* and other credit-constrained farmer profiles. At these prices, upfront payments incentivize credit-constrained, risk-averse, or present-biased farmers to substitute lower-yielding switchgrass to miscanthus. For example, at a payment of $60 per Mg biomass, *Upfront Payments* incentivize 154% of the SAF quantity that *Annual Payments* do in the *High-Constraint* farmer profile (Figure 2 (i) compared to Figure 2 (a)). Upfront payments are less effective than annual payments in incentivizing additional SAF production when farmers have *Low-Constraint* profiles, as farmers with access to credit prefer annual payments instead of a reduction in establishment costs. For example, in the *Low-Constraint* farmer profiles, an *Upfront Payment* incentivizes only 75% of the SAF quantity that *Annual Payments* do (Figure 2(p) compared to Figure 2 (h)). A similar relationship holds at higher biomass prices, where upfront payments in the *High-Constraint* farmer profile increase SAF production more than annual payments. There is little difference between the two payment policies in the *Low-Constraint* farmer profile.

Under annual payments, farmers with access to credit but are risk-averse adopt miscanthus at low biomass prices but substitute it away from miscanthus back to switchgrass at high biomass prices, leading to a drop in SAF production relative to no payment. Under equivalent payments through upfront payments, farmers continue to produce miscanthus under higher biomass prices, resulting in higher SAF production. For example, at $100 per Mg biomass price, *Upfront Payments* incentivize 12.5 % more than under *No Carbon Payment* (Figure 2(m) compared to Figure 1 (e)).

4.3 Spatial pattern of feedstock adoption

In the *No Carbon Payment* scheme, farmers not constrained by high time-discounting, risk-aversion, and access to credit choose a crop mix based on where each one has the lowest cost per Mg of biomass. In this case, at a biomass payment of $60 per Mg, farmers harvest miscanthus in the Midwest, switchgrass in the southern states, and harvest stover primarily in the Midwest and Delta regions (Figure 3 (a-c)).[11] In the *High-Constraint* farmers profile (Figure 3 (d-f)), farmers find it cost-prohibitive to adopt miscanthus in the Midwest, resulting in switchgrass adoption across the US (including the Midwest, where switchgrass is more costly and lower yielding than miscanthus). There is no significant difference in corn stover production patterns across farmer profiles. There doesn't appear to be any fragmentation of feedstock adoption patterns across counties at a regional level. Under *No Carbon Payment*, the total share of land used to produce SAF feedstocks in each county (through bioenergy crops and corn stover harvest) remains low across the rainfed region, with little adoption in the high-yielding region of the Midwest (for example, see cropland share of feedstock adoption in the *High-Constraint* scenario (Figure A.2)).

In the *High-Constraint* farmer profile, annual payments incentivize more SAF production than without payments but do not change the spatial pattern of feedstock production. For example, at a biomass payment of $60 per Mg (Figure 4 (d-f)), the spatial pattern of production under *Annual Payment* favoring switchgrass and corn stover throughout the rainfed US is similar to that under *No Carbon Payment* (Figure 4(a-c)). Under upfront payments farmers who are *High-Constraint* can adopt feedstocks that are cost-prohibitive for them, resulting in the production of higher-yielding and lower carbon-intensive feedstocks. For example, under *Upfront Payments,* farmers adopt miscanthus in the Midwest and switchgrass in the southern states and Great Plains at a biomass payment of $60 per Mg (Figure 4 (g-i)). Similar to under no carbon payments, there doesn't appear to be any fragmentation of feedstock adoption patterns across counties when farmers receive carbon payments. The total share of land used to produce SAF feedstocks in each county remains under carbon payments, which is spatially heterogeneous and depends on the biomass price, carbon price, and payment scheme. For example, at a biomass price of $40 per Mg, carbon mitigation payments of $20 per Mg CO_2 (Figure A.2 (c, d)) incentivize low shares (as a percentage of county cropland area) of feedstock production outside the high yielding Midwest region and very little within the Midwest. At these prices, annual payments are also more effective than upfront payments. However, there is little difference in the share of land dedicated to feedstocks at higher biomass prices (Figure A.2 (e, f)) or higher carbon prices (Figure A.2 (g, h, i, j)) despite differing SAF production largely due to bioenergy crop choice.

4.4 Costs to mitigate carbon under carbon mitigation schemes

Next, we compare the cost-effectiveness of carbon mitigation policies in incentivizing aggregate carbon mitigation across farmer risk-aversion, time-discounting, and credit-constraint profiles. Without loss of generality, we consider results at a biomass price of $60 per Mg and incrementally increase the carbon payment at intervals of $20 per Mg CO_2 to calculate the quantity of carbon mitigation that can be provided from SAF production. We find that when farmers do not have access to credit (Figure 5(a-d)), there is little difference between payment schemes in the cost to mitigate up to 180 million Mg CO_2 of abatement per year (with an abatement cost of approximately $ 2 billion per year). However, the cost to mitigate beyond 180 million Mg CO_2 per year rises steeply under *Annual Payments.* This is because the pervasive feedstock of choice under *Annual Payments* for credit-constraint profiles is switchgrass, which has lower carbon mitigation potential. Under the same credit-constraints, *Upfront Payments* incentivize up to 220 million Mg CO_2 of abatement per year (with an abatement cost of approximately $ 4.5 billion per year) because they incentivize miscanthus production in the Midwest.

When farmers are not credit-constrained but are otherwise present-biased or risk-averse (Figure 5(e-g)), annual payments are generally more cost-effective than upfront payments. In this case, credit-constraints are not a barrier to miscanthus adoption, and annual payments incentivize crops with the highest carbon mitigation potential in each region. In this case, *Annual Payments* can incentivize up to 210 million Mg CO_2 of abatement per year (with an abatement cost of approximately $ 4.5 billion per year when farmers are not risk-averse or present-biased, and $ 8 billion per year when they are) and *Upfront Payments* are less effective in these cases as farmers already have access to credit.

When farmers are not constrained (Figure 5(h)), there is little difference between the cost of carbon mitigation between the two payment schemes. This is due first to high adoption without carbon payments and second to both payments having similar effects when there are no risk-aversion, time-discounting, or credit-constraint barriers.

5 Discussion and Conclusion

This paper examines the potential supply of SAF from crop residues and bioenergy crops from croplands in the rainfed region of the US at various biomass (and equivalent SAF) prices and carbon payments. We analyze the choice and quantity of various feedstocks by risk-averse, present-biased, and credit-constrained farmers under various biomass prices and carbon payment schemes. In doing so, we consider life-cycle carbon mitigation along the entire SAF value chain by producing cellulosic feedstock.

We find that high risk-aversion, time-discounting, and credit-constraints can significantly reduce supply and raise the cost of producing SAF from cellulosic feedstocks. This is due to risk-averse, present-biased, or credit-constrained farmers preferring to grow the lower yielding but less risky switchgrass instead of producing the lower carbon intensive and higher yielding but more-risky feedstock miscanthus. We find that upfront carbon payments incentivize higher quantities of less carbon-intensive SAF production among risk-averse, credit-constrained, and present-biased farmers by reducing the establishment costs of miscanthus. We also find that when farmers are credit-constrained, upfront payments are more cost-effective in terms of carbon mitigation per dollar spent and incentivize more SAF production. In contrast, annual payments are more cost-effective and incentivize SAF production when farmers can access credit.

Our work stresses the role of farmer risk-aversion, time-discounting, and credit-constraints in SAF production. Studies that have not considered farmer profiles in cellulosic feedstock production (for example, the Billion-Ton Report (Langholtz et al., 2016), Fan et al. (2024), and Gautam (2023)) are likely overestimating the potential bioenergy crops and the SAF that can be produced without incentives. Further, our work highlights the importance of designing carbon-based incentive payments that consider farmer profiles. Tax credits such as 40B and 45Z, similar to *Annual Payments*, may be ineffective in incentivizing credit-constrained farmers with high risk-aversion to produce crops with lower carbon intensities and higher yields. Crops like miscanthus, which have higher establishment costs and higher return riskiness relative to switchgrass, will be less likely to be adopted by credit-constrained or risk-averse farmers. Our analysis also emphasizes the importance of considering the spatially varying carbon mitigation that each feedstock provides. We find the suitability of switchgrass in the southern states and Great Plains region of the rainfed US while miscanthus has a relative advantage in the Midwest. Policymakers could consider an incentive payment with a component that includes funding for establishment costs (for example, a BCAP-style cost-share payment) or one that includes funding for insurance to reduce return riskiness and is based on the carbon mitigation provided by different feedstock.

Our work is an ex-ante analysis by a farmer, assuming biomass prices remain the same over 15 years. Uncertainty about biomass prices will disincentivize bioenergy crop production. The adoption of SAF feedstocks will reduce conventional crop land and, at higher biomass prices, may have a disproportional effect on soybean production. However, our model does not adjust corn and soybean prices as farmers change their conventional crop production levels. A change in conventional crop prices due to reduced aggregate production may further disincentivize bioenergy crop production. Our analysis therefore presents an upper bound on bioenergy crop production levels. Existing research has shown that bioenergy crop production will be limited to procurement areas near biofuel plants due to high transportation costs (Li et al., 2019; Sesmero et al., 2021). Unlike Sesmero et al. (2021) and Li et al. (2019), we do not model how plant behavior would affect feedstock production. Instead, we consider production up to the farm-gate and construct a county-level supply response to biomass and carbon prices under differing policy scenarios and farmer profiles. Additionally, we explore how crops and feedstocks may act as spatial substitutes, adding another layer of interaction to the supply structure of feedstocks. Our research, therefore, provides an upper bound to the potential supply of SAF feedstocks and explores how the spatial mix of feedstocks may differ due to the spatially heterogeneous return profiles of each feedstock. Existing research also shows that bioenergy crops can be produced productively on relatively low-quality (marginal), idle (non-cropland) land but that economic incentives could induce farmers to convert cropland to bioenergy crops as well (Khanna et al., 2021; Sesmero et al., 2021; Yang et al., 2021). Here, we focus on examining economic incentives for the conversion of cropland only to bioenergy crops (similar to Gautam et al., (2023b) and Majeed et al., (2023)) because we are interested in examining the extent to which the adoption of bioenergy crops could be motivated by a desire for diversification of crops by a risk-averse farmer as a mechanism to reduce riskiness. Assessment of the economic opportunity costs, their relative riskiness, and the foregone carbon storage opportunities on that land is subject to significant uncertainty. We leave this to future research to explore.

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[1] https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

[2] The White House has set a goal of supplying at least 3 billion gallons (11.5 billion liters) of SAF per year by 2030 and 35 billion gallons (132.5 billion liters) per year by 2050, sufficient SAF to meet 100% of aviation fuel demand. https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/.

[3] 2023 SAF production was 0.6 billion liters, representing 0.2% of global jet fuel use https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-sustainable-aviation-fuels/#:~:text=Aviation%20fuel%20suppliers%20will%20have,rising%20to%2070%25%20in%202050.

[4] At the end of 2024, total US SAF production totaled 2 thousand barrels per day (115.8 million liters per year). https://www.eia.gov/todayinenergy/detail.php?id=62504

[5] Here we assume that the farmer cannot change her land allocation plan once the land-use decision has been made. We do not undertake a dynamic analysis in which new information in future periods can lead to a change in land use decisions.

[6] For simplicity, we do not consider yield reduction at the end of the lifecycle for bioenergy crops.

[7] It is arguable that the farmer may find it optimal to adopt both miscanthus and switchgrass on her land to obtain the benefit of crop diversification. However, for simplicity we have assumed that the farmer chooses a single perennial crop instead of a mix of two perennial crops. Relaxing this assumption will only obscure, but not obviate, the insights we seek to provide in the study.

[8] We do not consider in our model the additional carbon benefits of adopting no-till in order to separate out the soil carbon effects of stover harvest from other climate smart practices.

[9] We note that the biomass price and carbon prices analyzed here are in 2016 dollars; with significant inflation since 2016 these prices are expected to be substantially higher under current prices. However, we do not expect a change to the qualitative insights from this analysis.

[10] Figure A.1 shows the land use of each feedstock in which corn stover is shown to be the dominant feedstock in terms of land coverage, for example in the Low-Constraint farmer profile, at a biomass payment of $60 per Mg, 18 million hectares of cropland harvest stover (accounting for corn approximately 55% of land growing corn), whereas the total bioenergy crop acreage is 14 million hectares respectively. At higher biomass prices of $80 per Mg, 34 million hectares of cropland harvest stover (accounting for most of the land growing corn in the model) relative to 15.9 million hectares under bioenergy crops. However corn stover in our model is not the dominant feedstock for two reasons. First, bioenergy crop yield is significantly larger than corn stover yields, and second, we only remove 30% of corn stover (under conventional tillage, and 50% under no-till) from a field in order to not reduce row crop yield. Due to this, bioenergy crops have much higher output per hectare than corn stover.

[11] We observe that there is no feedstock production in Indiana at $60 per Mg while there is production in Illinois and Iowa at this price. This is because a biomass price slightly higher than 60 is required for production to be initiated. These differences across state lines arise because we are using state-level crop budgets to construct the costs of producing various feedstocks and then downscaling them to the county level due to variations in yield-driven changes in variable costs of production.

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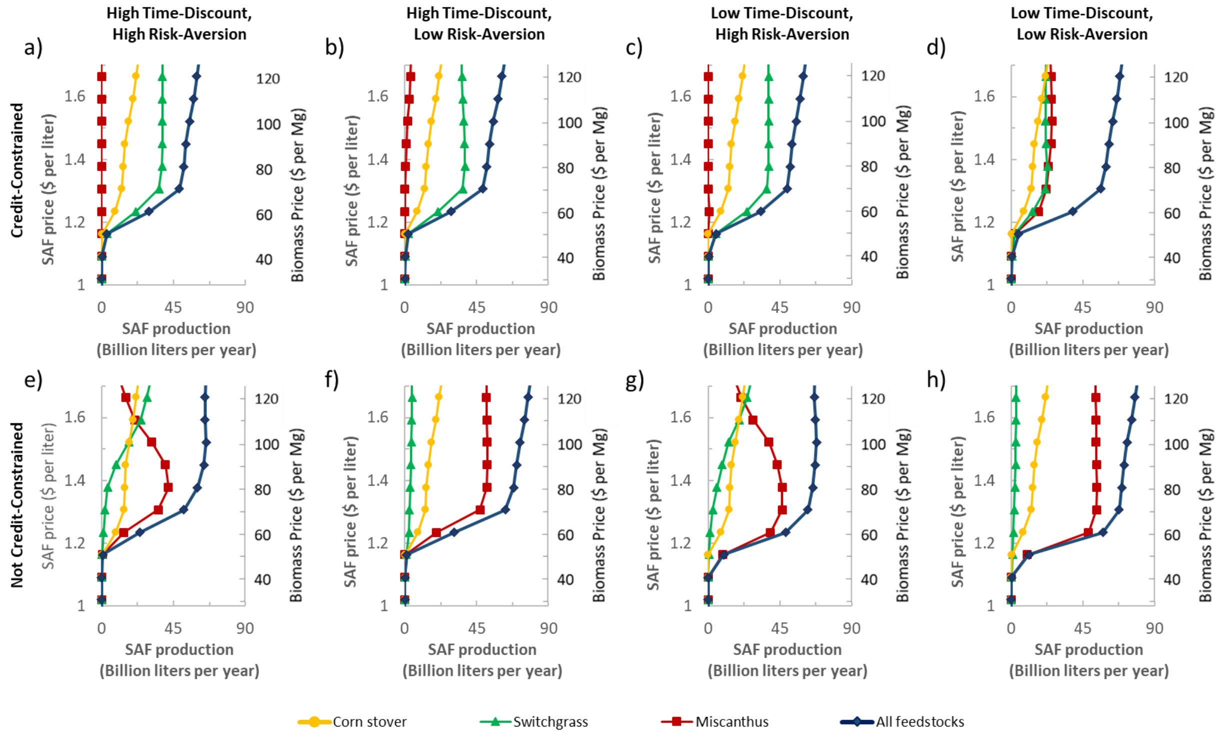
Figures

Figure 1: Sustainable Aviation Fuel production with no carbon payment under various biomass prices for differing farmer discount, risk, and credit-constraint profiles



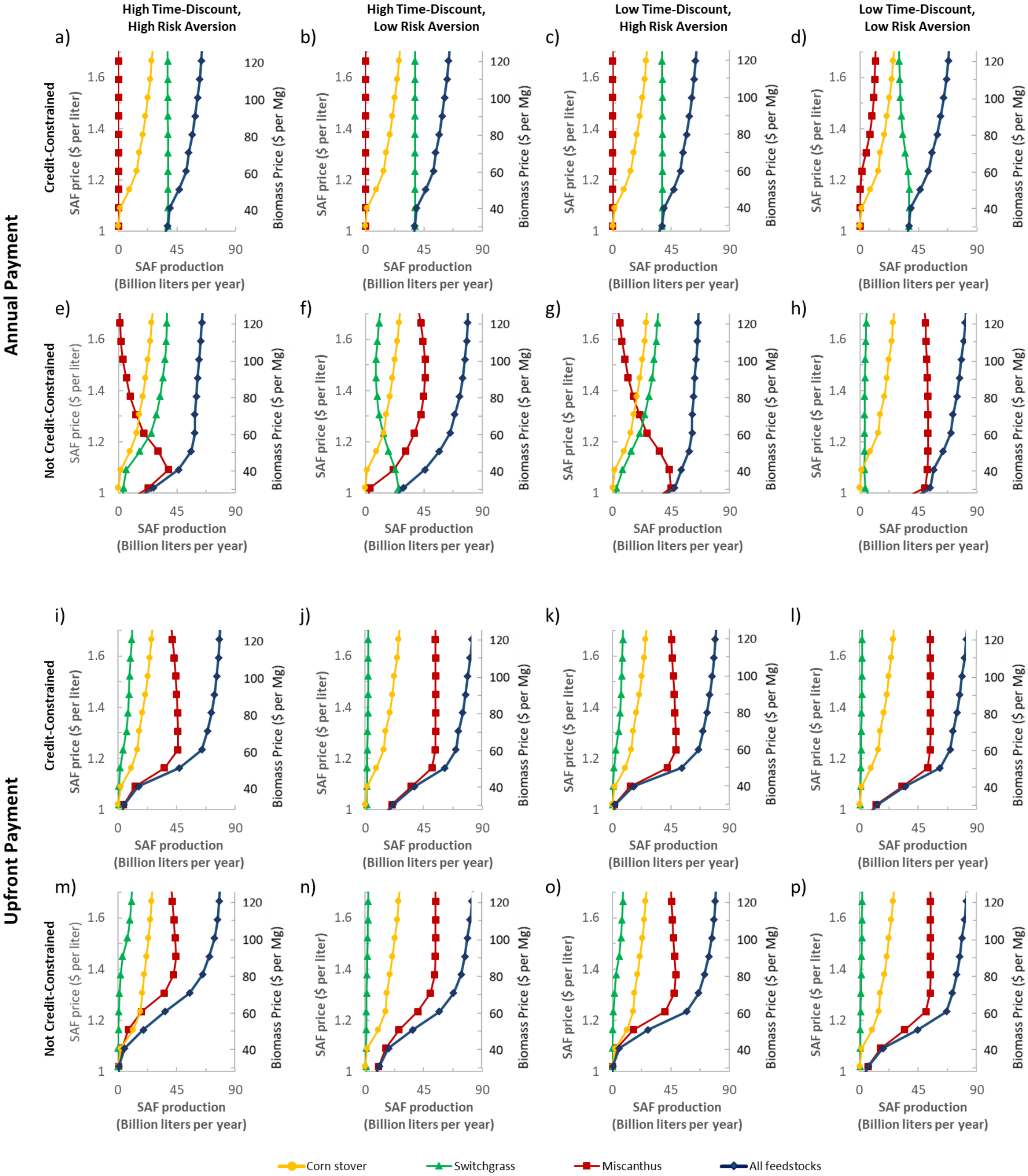
This figure shows the adoption of cellulosic feedstocks under no carbon mitigation payments (*No Carbon Payment*). The production of SAF from cellulosic feedstocks requires a biomass price of at least $40 per Mg biomass in 2016 dollars (with an equivalent SAF price of $1.10 per liter).

At a price of $60 per Mg biomass (with an equivalent SAF price of $1.25 per liter), under the *Low-Constraint* farmer profile (h), the overall SAF that can be produced is 57.3 billion liters per year from mostly miscanthus with some switchgrass and corn stover. Under the *High-Constraint* farmer profile (a), the overall SAF that can be produced is 48 percent (%) lower (at 29.7 billion liters per year) than in the *Low-Constraint* farmer profile, mainly from switchgrass with some corn stover.

At a biomass price of $80 per Mg (with an equivalent SAF price of $1.40 per liter), overall SAF production increases, but the feedstock mix does not change significantly relative to the $60 per Mg biomass price under each farmer profile. The SAF produced under the *High-Constraint* farmer profile is 26% lower than under the *Low-Constraint* farmer profile at the same price.

At biomass prices higher than $80 per Mg, the feedstock supply from bioenergy crops becomes relatively inelastic. At higher biomass prices, most additional feedstock is produced by corn stover harvesting. Also farmers who are risk-averse but have access to credit (e and g) choose to substitute away from miscanthus towards switchgrass.

Figure 2: SAF production by feedstock under annual and upfront carbon payment for differing farmer discount, risk, and credit-constraint profiles at a carbon price of \$60 per Mg CO_2



This figure shows the effect of *Annual Payment* (a-h) and *Upfront Payment* (i-p) of \$60 per Mg CO2 on the mix of feedstocks at each biomass price.

<u>*Annual Payments*:</u> At \$40 per Mg, in the *High-Constraint* farmer profile (a), *Annual Payments* incentivize 38.5 billion liters per year mainly through switchgrass production. In the *Low-Constraint* farmer profile (h), *Annual Payments* incentivize 56.7 billion liters per year through mostly miscanthus production. Risk-averse farmers substitute away from miscanthus at higher biomass prices in favor of switchgrass, reducing the potential for SAF

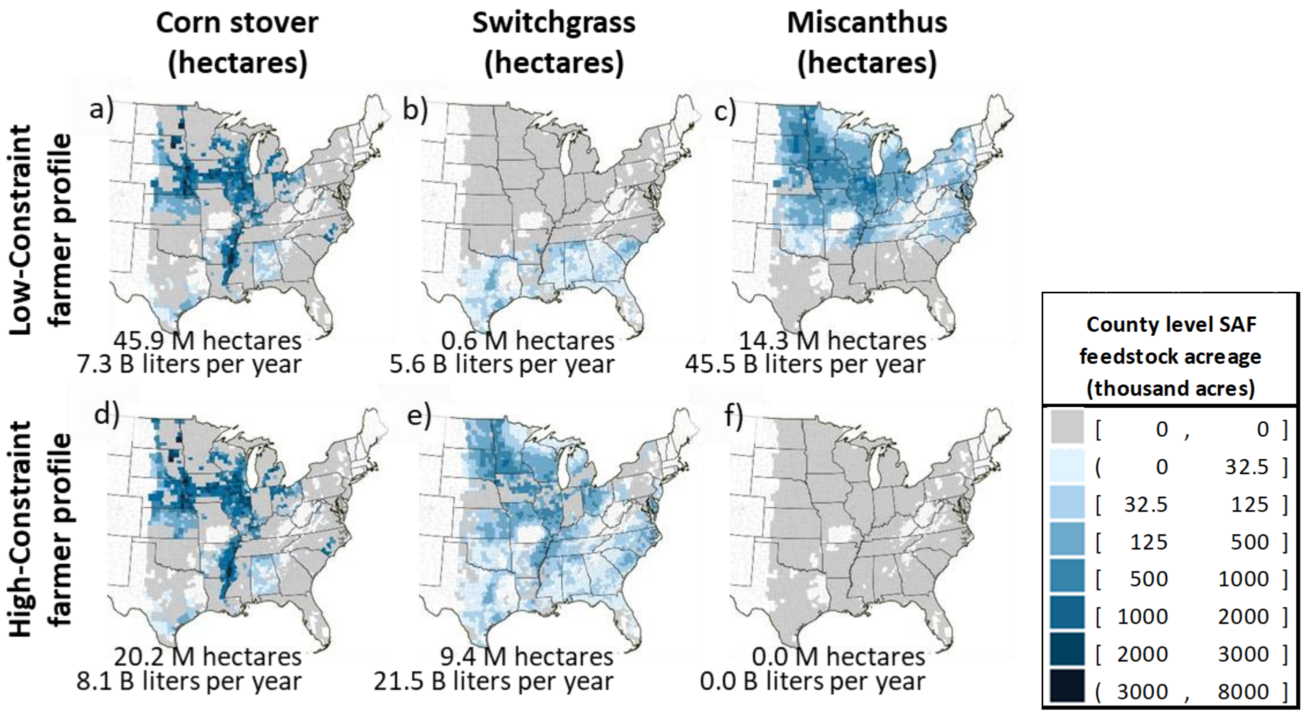
production. For example, at $100 per Mg, in the case where farmers have access to credit but are risk-averse (Figure 2 (e) and Figure 2 (g)), *Annual Payments* incentivize farmers to substitute switchgrass over miscanthus, resulting in a 3-5% drop in SAF production compared to *No Payment*.

Upfront Payments: At a payment of $40 per Mg biomass, *Upfront Payment*s incentivize 40% and 31% of the SAF quantity that *Annual Payments* do in the *High-Constraint* and the *Low-Constraint* farmer profiles (i compared to a) and (p compared to h).

At a payment of $60 per Mg biomass, *Upfront Payment*s incentivize 154% of the SAF quantity that *Annual Payments* do in the *High-Constraint* farmer profile (i compared to a). In the *Low-Constraint* farmer profiles, an *Upfront Payment* incentivizes only 75% of the SAF quantity that *Annual Payments* do (p compared to h).

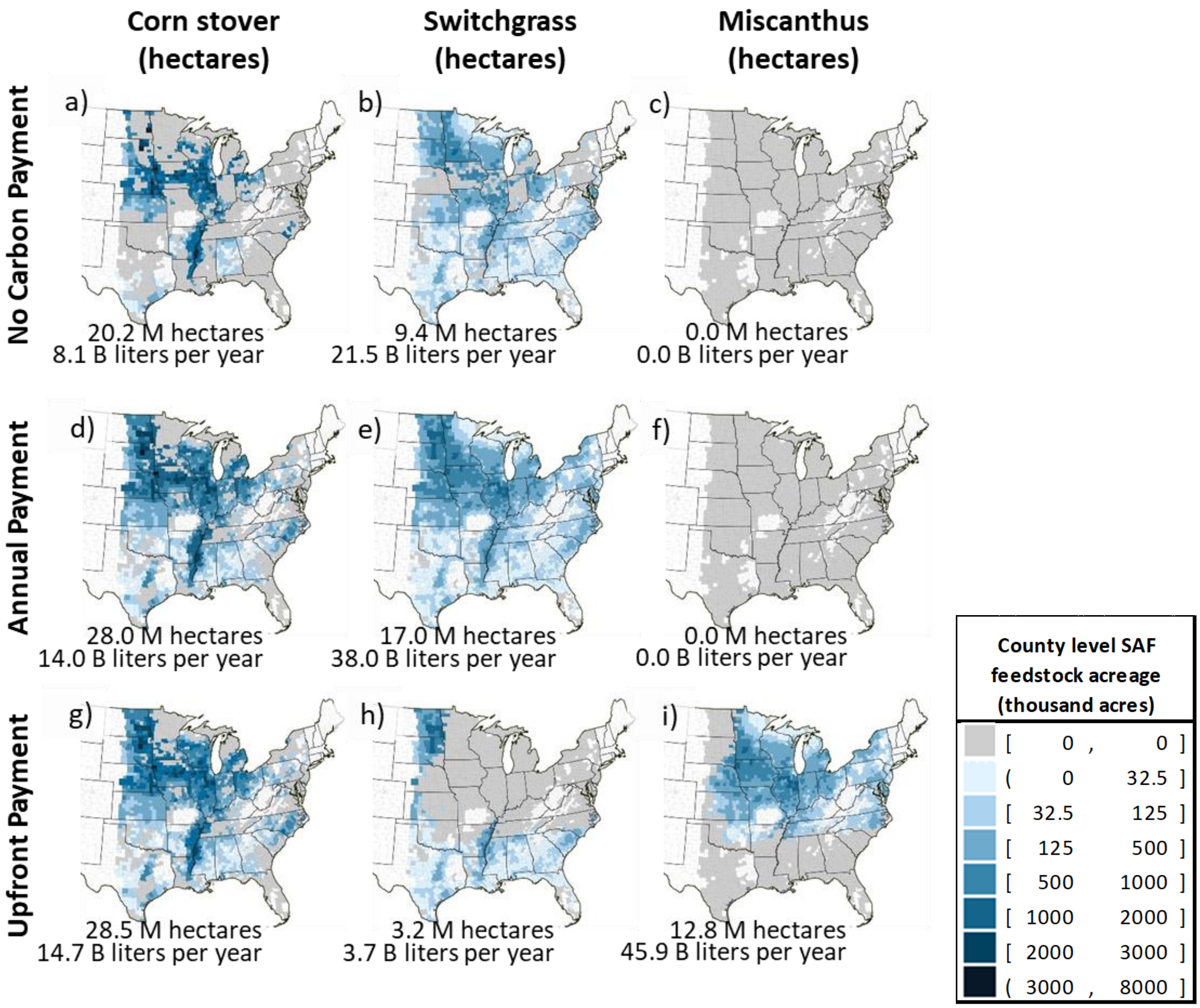
Additional: Under *Annual Payments*, farmers with access to credit but were risk-averse adopted miscanthus at low biomass prices but substituted miscanthus for switchgrass at high biomass prices, leading to a drop in SAF production relative to *No Payment*. Under equivalent payments through *Upfront Payment*s, farmers continue to produce miscanthus under higher biomass prices, resulting in higher SAF production. At $100 per Mg biomass price, *Upfront Payment*s incentivize 12.5 % more than under *No Payment* (m compared to e).

Figure 3: Spatial adoption pattern across cellulosic feedstocks (hectares) under high and low farmer discount, risk, and credit-constraint profiles at biomass prices of $60 per Mg (equivalent to approximately $1.25 per liter SAF) and no carbon payment



This figure shows feedstock adoption in the *High-Constraint* and *Low-Constraint* farmer profiles without carbon mitigation payments (*No Carbon Payment*) at a biomass payment of $60 per Mg. We assume that the representative farmer in a county chooses a portion of their land to produce bioenergy crops and the portion of the remaining land under corn from which to harvest stover. We restrict a county to choosing to produce only one bioenergy crop (either switchgrass or miscanthus). Farmers not constrained by high time-discounting, risk-aversion, and access to credit produce miscanthus in the Midwest, switchgrass in the southern states, and harvest stover primarily in the Midwest and Delta regions (a-c). In the *High-Constraint* farmer profile (d-f), farmers produce switchgrass adoption across the US with no significant difference in corn stover production patterns across farmer profiles.

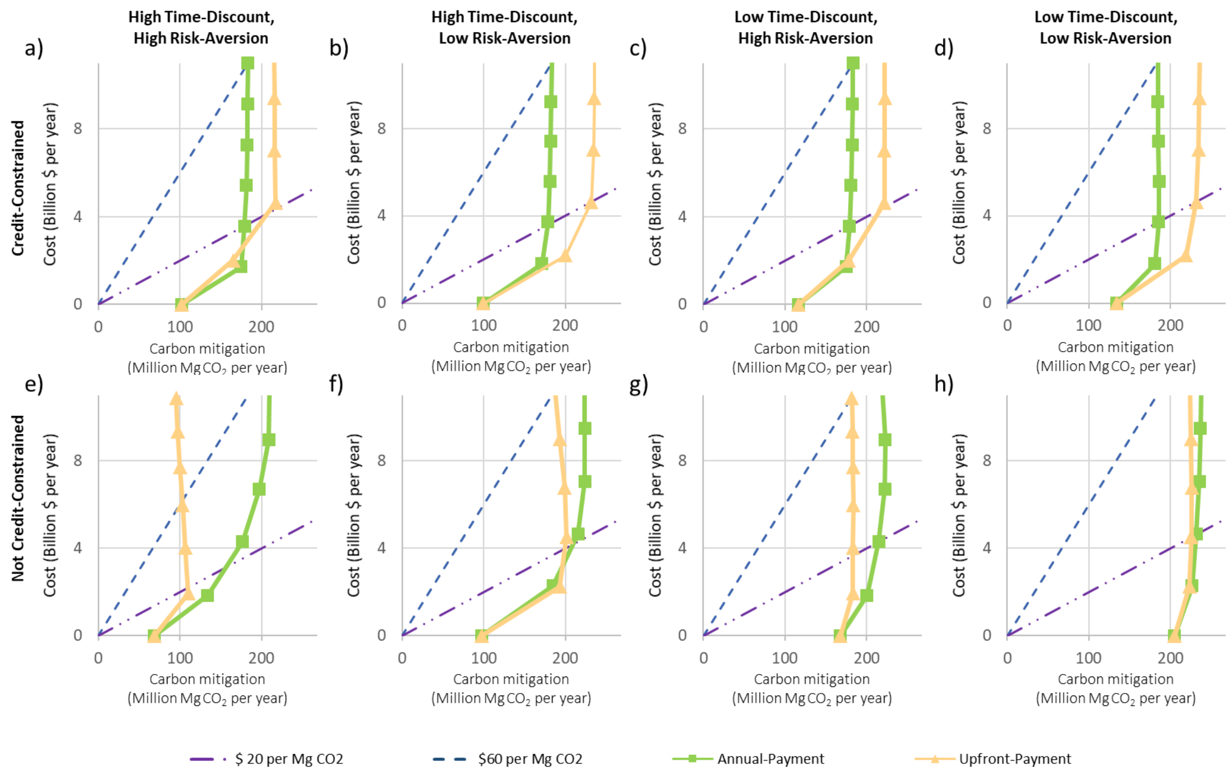
Figure 4: County-level spatial adoption pattern across cellulosic feedstocks (million hectares) under annual payment and upfront payment of $60 per Mg CO_2 at biomass prices of 60 per Mg (equivalent to approximately 1.25 per liter SAF) for high risk-aversion high time-discount and credit-constrained farmer profile



This figure shows the spatial distribution of feedstock production in the *High-Constraint* farmer profile. *Annual Payments* incentivize more SAF production over *No Carbon Payment*, but do not change the spatial pattern of feedstock production. At a biomass payment of $60 per Mg (d-f), the spatial pattern of production favoring switchgrass and corn stover throughout the rainfed US is similar to that under *No Carbon Payment* (a-c).

Under *Upfront Payment*s, farmers adopt miscanthus in the Midwest and switchgrass in the southern states and Great Plains at a biomass payment of $60 per Mg (g-i).

Figure 5: Carbon mitigation from SAF production under annual and upfront carbon payment for differing farmer discount, risk, and credit-constraint profiles at a biomass price of $60 per Mg



This figure shows the cost-effectiveness of *Upfront Payment* and *Annual Payment* carbon mitigation policies in incentivizing aggregate carbon mitigation.

When farmers do not have access to credit (a-d), there is little difference between payment schemes in the cost to mitigate up to incentivize up to 180 million Mg CO2 of abatement per year (with an abatement costs of approximately $ 2.5 billion per year). *Upfront Payment*s incentivize up to 220 million Mg CO2 of abatement per year (with an abatement cost of approximately $ 4.5 billion per year)

When farmers are not credit-constrained but are otherwise present-biased or risk-averse (e-g), *Annual Payments* are generally more cost-effective than *Upfront Payment*s. Here, *Annual Payments* can incentivize up to 210 million Mg CO2 of abatement per year (with an abatement cost of approximately $ 4.5 billion per year when farmers are not risk-averse or present-biased, and $ 8 billion per year when they are). *Upfront Payment*s are less effective in these cases as farmers already have access to credit.

When farmers are not constrained (h), there is little difference between the cost of carbon mitigation between the two payment schemes.

Appendices

Appendix A.1. Numerical Simulation

We simulate the economic incentives for adopting cellulosic feedstocks on cropland in each county by a risk-averse, present-biased, and credit-constrained representative farmer at the county level, maximizing their expected utility over a given period. The farmer optimally allocates L units of cropland between perennial bioenergy crops and annual conventional crops on which they can harvest corn stover. Let $x \in [0,1]$ be the share of land farmers allocate to bioenergy crops and $1 - x$ the share of land to the conventional crops. Our model considers two bioenergy crop feedstocks: miscanthus and switchgrass. We use e to denote the bioenergy crop such that $e \in E \equiv \{misc, swit\}$. Further, we consider two types of rotation for conventional crops, corn-corn (cc) and corn-soybean (cs) rotation, and two types of tillage, conventional tillage (ct) and reduced/no-tillage (nt). We use c to denote the rotation and tillage combination of conventional crops such that $c \in C \equiv \{(cc, ct), (cc, nt), (cs, ct), (cs, nt)\}$. Farmers may harvest corn stover as a by-product of corn as a cellulosic feedstock. For each rotation-tillage combination c, the corn stover harvest choice is represented by h_c, such that $h_c \in \{1, 0\}$ is the condition to harvest stover or not. Let $\bar{T}$ be land tenure and t depict the discrete years during this period such that $t \in \{1,2, \dots, \bar{T}\}$. Perennial bioenergy crops complete one life-cycle in $\bar{T}$ while conventional crops complete one life-cycle each year and stover can be harvested annually.

In addition to being used as a cellulosic feedstock, bioenergy crops, and corn stover provide carbon mitigation services from conventional aviation fuel displacement, which varies with feedstock yield, and from belowground soil carbon sequestration per unit of land, which may vary temporally over the crop life-cycle. Farmers may receive no carbon payment (*No Carbon Payment*) or a carbon mitigation payment for the value of carbon mitigated in the year it was mitigated (*Annual Payment*) or the full value of carbon mitigated over the crop life-cycle at the start of the establishment period (*Upfront Payment*). We use *Pay* to denote the payment policy scheme such that $Pay \in PAY \equiv$ {*No Carbon Payment*, *Annual Payment*, *Upfront Payment*}. The profit per unit of land at time t under each payment policy scheme in PAY is $\pi_t^{PAY,e}$ for bioenergy crops and $\pi^{PAY,stover}$ for corn stover.

To reduce the dimensionality of the simulation, we assume that the representative farmer in a county only chooses one bioenergy crop between the two and only one rotation-tillage combination between the four. The farmer's overall utility function is given by $V_{x,e,c,h_c} = \sum_{t=1}^{\overline{T}} \beta^{t-1} E\left[u\left(L\left[x\pi_t^{PAY,e} + (1 - x)\left(\pi_c^{crop} + h_c \pi_c^{PAY,stover}\right)\right] | \lambda\right)\right]$ where $u(\cdot)$ is the farmer's annual utility function. The utility function takes the form of a Constant Absolute Risk-Aversion (CARA) with properties $u''(\cdot) \leq 0 \leq u'(\cdot)$ and their measure of risk-aversion is λ. The farmers discount factor is given by $\beta = 1/(1 + \gamma)$, with $\gamma \in [0,1]$ as the discount rate. For any given conventional crop choice and bioenergy crop combination, the farmer chooses x to maximize the following problem:

$$V_{x,e,c,h_c} = \max_x \sum_{t=1}^{\overline{T}} \beta^{t-1} E\left[u\left(L\left[x\pi_t^{PAY,e} + (1 - x)\left(\pi_c^{crop} + h_c \pi_c^{PAY,stover}\right)\right] | \lambda\right)\right] \quad (1.1)$$

Bioenergy crop profit: We separate the bioenergy crop life-cycle into an establishment period and a maturity period, with $\hat{t}$ being the number of years in the establishment period. In the bioenergy crop establishment period, the farmer incurs a cost, w_t^e, per unit of land to establish the bioenergy crop for each year. The farmer borrows the establishment cost if they have access to credit and pays back the annuity at interest rate i, $A(w_t^e, .. w_{\hat{t}}^e, i)$, in the mature period. The farmer harvests the bioenergy crop, where the bioenergy crop yield, y^e, is stochastic with distributions known to the farmer and yield realized at harvesting. Miscanthus is harvested only in the mature period, while switchgrass produces harvestable yield in the establishment period. Farmers harvesting cellulosic feedstocks receive a biomass payment of p^b per unit of biomass yield. For crop e at time t without carbon mitigation payments, bioenergy crop profits, $\pi_t^{No-Payment,e}$, can be written as

$$\pi_t^{No-Payment,e} = \begin{cases} -Iw_t^e, t \leq \widehat{t_m}, e = misc \\ -Iw_t^e + (p^b - v^e)y^e - f^e,\ t \leq \widehat{t_s}, e = swit \\ (p^b - v^e)y^e - f^e - (1-I)A\left(w_t^e, .. w_{\hat{t}}^e, i\right), \quad t > \widehat{t_e}, \end{cases} \quad (1.2)$$

where I is an indicator of whether the farmer has credit-constraint ($I = 1$) or not ($I = 0$), f^e is the fixed cost, v^e a variable cost, and p^b is the price per unit of biomass.

Farmers mitigate l^e per unit of biomass through life-cycle carbon mitigated from SAF production, not including belowground soil carbon sequestration, which is denoted as b_t^e and varies temporally. The farmer receives payment, p^g, per unit per unit of carbon mitigated. Under *Annual Payment*, where the farmer receives each year the value of carbon mitigated in that year, the returns per unit of land for crop e in year t can be written as

$$\pi_t^{Annual-Payment,e} = \begin{cases} \pi_t^{No-Payment,e} + p^g b_t^e, t \leq \widehat{t_m}, e = misc \\ \pi_t^{No-Payment,e} + p^g l^e y^e + p^g b_t^e,\ t \leq \widehat{t_s}, e = swit \\ \pi_t^{No-Payment,e} + p^g l^e y^e + p^g b_t^e, \quad t > \widehat{t_e}. \end{cases} \quad (1.3)$$

Alternatively, farmers may receive a lump sum upfront carbon mitigation payment (*Upfront Payment*) in the first year of planting bioenergy crops, which is determined by the total value of carbon mitigated as given by $G = \sum_t^{\overline{T}} \beta^{t-1} p^g (b_t^e + l^e E[y^e])$. For bioenergy crops, profit per unit of land in year t under upfront carbon payments can be written as

$$\pi_t^{Upfront-Payment,e} = \begin{cases} G + \pi_t^{No-Payment,e} & t = 1 \\ \pi_t^{No-Payment,e} & t > \widehat{t_e} \end{cases} \quad (1.4)$$

<u>Conventional crop and corn stover profit:</u> The yields and prices of corn grain and soybeans are denoted by y_c^{corn}, $y_c^{soybean}$, p^{corn}, and $p^{soybean}$, respectively. The yields and prices of 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 and soybeans are represented by f_c^{corn}, $f_c^{soybean}$, v_c^{corn}, $v_c^{soybean}$ respectively, where fixed costs (denoted by f_c^{corn}, and $f_c^{soybean}$) are per unit of land and variable

costs (denoted by v_c^{corn}, and $v_c^{soybean}$) are per unit of yield produced. Conventional crop returns per unit of land for corn grain and soybeans under each rotation-tillage combination in set *C* can then be written as $\pi_c^{corn} = (p^{corn} - v_c^{corn}) \times y_c^{corn} - f_c^{corn}$ and $\pi_c^{soybean} = \left(p^{soybean} - v_c^{soybean}\right) \times y_c^{soybean} - f_c^{soybean}$. For corn-soybean rotation, we assume that half of the land is used for corn and half for soybeans. The profit from conventional crops without corn stover harvest under rotation-tillage combination *c* is

$$\pi_c^{crop} = \begin{cases} 0.5\ \pi_c^{\text{corn}} + 0.5\ \pi_c^{\text{soybean}}, c \in \{(cs, ct), (cs, nt)\} \\ \pi_c^{\text{corn}} \qquad\qquad\qquad\quad , c \in \{(cc, ct), (cc, nt)\}. \end{cases} \tag{1.5}$$

Additionally, farmers may produce corn stover as a by-product of corn production. It may be harvested for biomass as an SAF only if the farmer deems it profitable. For stover, the farmer can receive a biomass price at p^b per unit of biomass. The fixed and variable costs of producing corn stover under corn production in rotation-tillage combination *c* are represented by f_c^{stover} and v_c^{stover} respectively, where fixed costs are per unit of land and variable costs are per unit of yield produced. As corn-soybean rotations produce corn on half the land, only half the quantity of stover will be produced relative to continuous corn production. Additional returns from corn stover for land under corn production in each rotation-tillage combination *c* without carbon payments can then be written as

$$\pi_c^{No-Carbon-Payment,stover} = \begin{cases} 0.5\ ((p^b - v_c^{stover})y_c^{stover} - f_c^{stover}), c \in \{(cs, ct), (cs, nt)\} \\ (p^b - v_c^{stover})y_c^{stover} - f_c^{stover}\ , c \in \{(cc, ct), (cc, nt)\}. \end{cases} \tag{1.6}$$

We assume that one unit of stover biomass generates l_c^{stover} units of life-cycle carbon mitigation and that one unit of land harvesting stover will produce b_c^{stover} units of carbon mitigation through soil carbon sequestration each year and does not vary temporally. As payments conventional crops can be replanted and corn stover can be harvested every year, returns under *Annual Payment* and *Upfront Payment* are equivalent. For each rotation-tillage combination *c*, corn stover returns under carbon payment can be written as

$$\pi_c^{Annual-Payment,stover}, \pi_c^{Upfront-Payment,stover} = \begin{cases} \pi_c^{No-Carbon-Payment,stover} + \ 0.5\left((p^g l_c^{stover}) y_c^{stover} + p^g b_c^{stover}\right), c \in \{(cs,ct),(cs, \\ \pi_c^{No-Carbon-Payment,stover} + \qquad (p^g l_c^{stover}) y_c^{stover} + p^g b_c^{stover} \ , c \in \{(cc,ct),(cc,1 \end{cases} \quad (1.7)$$

We assume that farmers harvest stover only if the expected gains, $E[\pi_c^{\text{stover}}]$, of doing so are positive. The condition to harvest (h_c = 1) or not (h_c = 0) is calculated on expected stover returns such that

$$h_c = \begin{cases} 1, \ E\left[\pi_c^{Pay,stover}\right] > \ 0 \\ 0, \ E\left[\pi_c^{Pay,stover}\right] \leq \ 0. \end{cases} \quad (1.8)$$

Farmer cropping choice: The farmer maximizes eq (1.1) to choose the land share allocated to bioenergy crops ($x \in [0, \alpha]$), the choice bioenergy crop ($e \in E$), whether to harvest corn stover ($h_c \in \{0,1\}$), along with conventional crop rotation and tillage ($c \in C$), to select the highest expected utility, V_{x,e,c,h_c}. We solve land allocation and cropping choices at various exogenous biomass price levels (p^b), carbon prices (p^g), and policy payments (*Pay)*, under various assumptions about the farmer's risk (λ) and time (β) preferences and her credit-constraint situation (I).

To reduce the dimensionality of the simulation, we assume that the representative farmer for the county only chooses a rotation-tillage combination between the four. Farmers adopt a rotation-tillage combination for their county based on each combination's relative returns and riskiness. Farmers who change their rotation-tillage combination when harvesting corn stover may reduce conventional crop returns through lower yields or increased costs offset by returns through biomass production. For example, continuous corn requires more fertilizer than corn-soybean rotations, and no-till may have lower yields than conventional tillage. Under each policy payment scheme and risk and discount factors, the farmer will adopt cover crops if their expected utility with nonzero cellulosic feedstock adoption (i.e., either $x > 0$ or $h_c = 1$) is greater than without cover crops (i.e., $x = 0$ and $h_c = 0$). As such, farmers can be incentivized to produce cellulosic feedstocks through payments that are large enough to make their expected utility with nonzero cellulosic feedstock production at least as high as their expected utility without cellulosic feedstocks under each policy payment scheme. The level of payment needed under each policy and the mix of feedstocks adopted may, however, differ by farmer profile of risk-aversion, time-discounting, and credit-constraint and across counties due to spatial heterogeneity in carbon mitigation, cost of feedstocks, and feedstock and conventional crop yield and price riskiness.

Appendix B.1. Crop Yield Details

We take simulated yields of corn, corn stover, soybean, miscanthus, and switchgrass from the biogeochemical model, DayCent, using output mass and conversion rates provided by DayCent (Hudiburg et al., 2016). We use yield data for conventional crops for corn-soybean and corn-corn rotations, conventional and no-tillage, and corn stover removed and not removed. DayCent is the daily version of the CENTURY model.(Parton et al., 1994) It 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 United States, we use data from field experiments with miscanthus and switchgrass across the rainfed region to calibrate the productivity parameters in the DayCent model that relate soil attributes and weather with yields.(Hudiburg et al., 2016) We use DayCent to obtain simulated yields of miscanthus and switchgrass, assuming that the previous thirty years of historical weather conditions for each county cycle are randomly distributed. Table A.1 presents the summary statistics of the average mature yields and standard deviation across counties for bioenergy crops. 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 corn's four rotation/tillage options. Additionally, switchgrass yields have a higher variation, making it possible to have higher switchgrass yields in certain counties.

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 depend on the DayCent model parameters. We set the removal rates at 0% for no stover removal, 50% for stover removal under no-till, and 30% for stover removal under tillage. These removal rates have little effect on soil nutrients and allow for more significant removal of corn stover. DayCent Corn yields for when farmers remove corn stover and when they do not remove corn stover do not differ significantly, so we only consider corn yield farmers remove when corn stover for each rotation/tillage and use for both corn stover removal and non-removal.

For corn-soybean rotations, the DayCent simulated two schemes for each tillage option, corn-soybean and soybean-corn, with the base year starting with corn and soybeans, respectively. As yields are independent 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. Further, nitrogen application rates are those assumed by the DayCent model for bioenergy crops and conventional crops based on public databases (USDA), published historical data, and recommended fertilization rates. Additionally, we take potassium and phosphorus application rates from Dwivedi et al.(2015).

Appendix B.2. Bioenergy crop costs

Table A.2 shows the fixed cost per hectare over the life of the crop. The farmers' most considerable expense is the high establishment and fixed costs in the first few years before bioenergy crops produce yield at a mature level.

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). In the establishment period, the farmer incurs a cost per unit of land to establish the bioenergy crop. 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. In the mature period, the farmer harvests the bioenergy crop annually and incurs costs associated with harvesting. Establishment period costs include land preparation and planting, such as disking, rhizomes or seed drilling, soil finishing, and chemical sprays. Table A.3

presents the operating cost per ton of biomass produced, using the farmer's expected yield in each county.

Appendix B.3. Conventional Crop Costs

We construct conventional crop costs for each rotation and tillage option at the state level using crop budget quantities and prices provided by state extension services. These include chemicals, seeds, harvesting, storage, drying, and inputs. N, P, and K prices are applied using prices consistent with corn and soybean crops. We present a summary of conventional crop costs in Table A.3. We construct state-level production costs of conventional crops (corn and soybean) for each rotation and tillage option using quantities and prices provided by state extension service budgets; these include chemicals, seeds, harvesting, drying, fuel, insurance, labor, machinery, and interest on capital costs.

Appendix B.4. Conventional Crop Prices

Table A.4 shows the mean of the three prices used to generate a distribution of prices for corn and soybeans. The prices for conventional crops (corn and soybean) are estimated first at the national level using 30-year national-level harvest prices (NASS) and futures prices (Chicago Board of Trade) to reflect the riskiness of conventional crop prices. We use the difference in historical harvest and futures prices for each year from 1986-2015 to calculate a distribution of national-level projected crop prices following RMA("Risk Management Agency (RMA), 2011. Commodity Exchange Price Provisions (CEPP)," 2011) rules. We then scale national prices to state-level prices using the national and state-level harvest prices for 2016 (USDA NASS), as detailed below.

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 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 unavailable—national prices over this period at $3.71 per bushel for corn and $9.41 for soybean. Annual national-level historical prices are taken from NASS for the past thirty years, from 1987 to 2016. Country-level historical futures prices for corn and soybeans are derived from the Chicago Board of Trade futures prices for the same years, averaging from Sept to Nov, taken from https://www.macrotrends.net/. Both historical prices are converted to 2016 dollars using the Gross Domestic Product: Implicit Price Deflator obtained from the St Louis Federal Reserve, with third-quarter values used to adjust historical prices. We consider prices to be stochastic along with yields, the difference in state-level prices and use national-level prices, while the log difference in realized and futures prices to calculate the distribution in risk, which is calculated using a Copula method to generate a distribution of costs and yields for the model following RMA (2011) rules. We then scale national-level prices to state-level prices using the national and state-level harvest prices to calculate a price basis for each state (USDA NASS).

Appendix B.5. Corn stover costs

Corn stover costs are constructed at the state level for each corn rotation and tillage combination, including mowing, raking, staging, loading, baling, and storage. As there is no significant difference in harvesting and storage costs between tillage choices and rotations, the considerable difference in prices is due to replacement nitrogen application rates, which differ over the four tillage and rotations. Potassium and Phosphorus applications are applied at a variable cost, as given by Dwivedi et al.(2015). Presented in Table A.5 is the total cost per bushel of corn and soybean divided by region rotation and tillage.

Appendix B.6. Biomass conversion costs

In our analysis, we consider two cost components (biomass to cellulosic ethanol and cellulosic ethanol to SAF) in converting biomass to SAF. We take the cost of biomass to cellulosic ethanol and the cost of cellulosic ethanol to SAF from Fan et al. (2024). We take the volumetric conversions at each stage from GREET. The costs and volumetric conversions are shown in Table A.6. We assume no transportation cost between cellulosic ethanol and SAF production.

Appendix B.7. Soil carbon mitigation from feedstock production

To account for temporal soil carbon dynamics, we use annual soil carbon sequestration rates for the first three years of establishment and an average soil carbon sequestration rate over the remaining period, as detailed below.

We take the annual total carbon levels in the soil organic matter pool for all crops from the DayCent model for each year of the planting period. This data includes the effect of corn stover harvest on annual soil carbon levels for all rotations, tillage combinations, and all choices of bioenergy crops. We use the difference between soil carbon levels over the planting period to calculate the annual rate of soil carbon sequestration during the planting period. For bioenergy crops, we independently calculate the soil carbon change each year of the establishment period and the rates during the mature period. Bioenergy crop sequestration rates used in the model are divided into sequestration in the first and second years and an average sequestration rate for later years per county. In contrast, conventional crop sequestration rates are an average value over the crop's life. Table A.7 shows regional averages for the baseline county-level sequestration rates.

Appendix B.8. Carbon mitigation from feedstock production

Carbon intensity calculations in $g\ CO_2 eq\ Mj^{-1}$ are computed for each feedstock for the establishment and full yield years using the methodology highlighted in Dwivedi et al.(2015). We calculate the lifecycle carbon intensity of biomass production as a sum of emissions through lifecycle analysis. Our lifecycle analysis for calculating the carbon intensity of ethanol produced across various sectors, including feedstock production, processing, transportation fuel use (as defined as farming and collection energy use in GREET), conversion to ethanol, and conversion to SAF (ATJ-SPK). We aggregate emission intensities across major components such as material input usage, electricity, diesel, bioenergy use, electrification co-credits, ethanol production emissions, and soil carbon rates resulting over the lifecycle of the various cellulosic ethanol feedstocks. Next, we consider nitrogen, potassium, phosphorus, insecticide, lime, and herbicide application rates for material input usage. Sources of application rates are detailed in earlier sections and are applied as either Kg Input ha^{-1} or Kg Mg^{-1} biomass and multiplied by the gCO_2 emitted per g of input used. We take emissions related to electricity, diesel, and transportation fuel usage as parameters of the global warming intensity of the service used. The electricity co-product credit is a constant parameter per MJ used and is negative. We apply ethanol production emissions as a constant parameter followed by SAF conversion factors related to the emissions produced while converting a feedstock to ethanol and then to SAF.

We take carbon emission factors of gCO_2 per MJ energy, electricity co-credit, and calorific values of fuels from the GREET model. We also take nitrogen application rates for biomass production from the DayCent model. We 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 in Table A.8 and Table A.9. In Table A.10; we present the estimated lifecycle material input carbon intensities of the various sources of cellulosic feedstocks. 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. We then convert the total carbon mitigated lifecycle to a carbon saved per hectare to incentivize the complete life cycle.

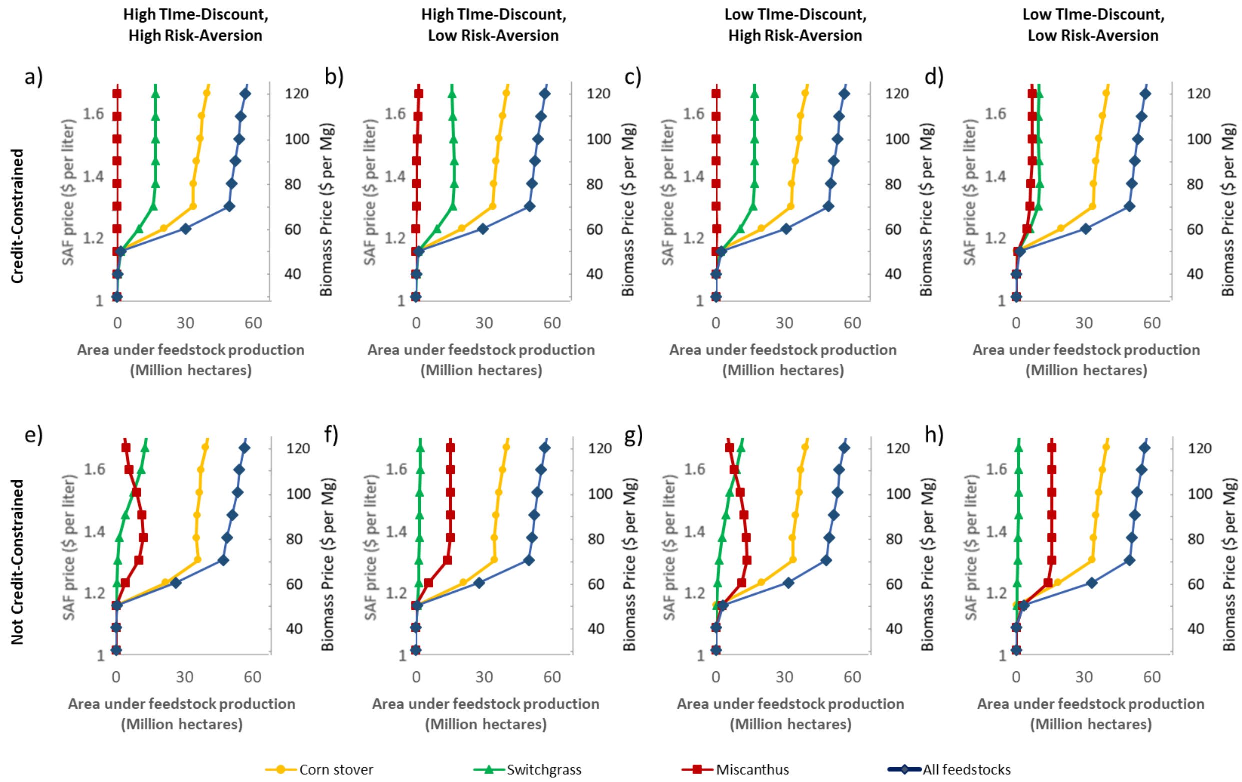
Appendix B.9. Generation of Joint Yield-Price Distribution

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. To calculate stochastic returns, we first construct the yield-price distribution for each county by a copula approach (a modeling process that first describes and then replicates the dependence structure between multiple stochastic variables).(Miao & Khanna, 2017b) We model the joint yield-price distributions using the copula approach following Miao & Khanna (2017b), Yan(2007), and Du & Hennessy(2012). We model stochastic yields and obtain one thousand random draws for each county from the joint distribution for twelve crop yields linked to eight conventional crop rotation, tillage, and corn stover harvest choices and two bioenergy crop choices (i.e., corn and corn stover (each under four rotation and tillage combinations), soybeans (under two tillage combinations), and miscanthus, and switchgrass) and prices for two conventional crops (corn and soybean). Like Du & Hennessy(2012), we assume yields to have beta and price lognormal distributions. Once joint distributions are estimated, draws are taken to conduct a Monte Carlo simulation. Next, a linear detrending approach is applied to remove each county’s systematic components of yield variation, adding to the county-level yield trend for 2016.

Appendix Figures and Tables

Figures

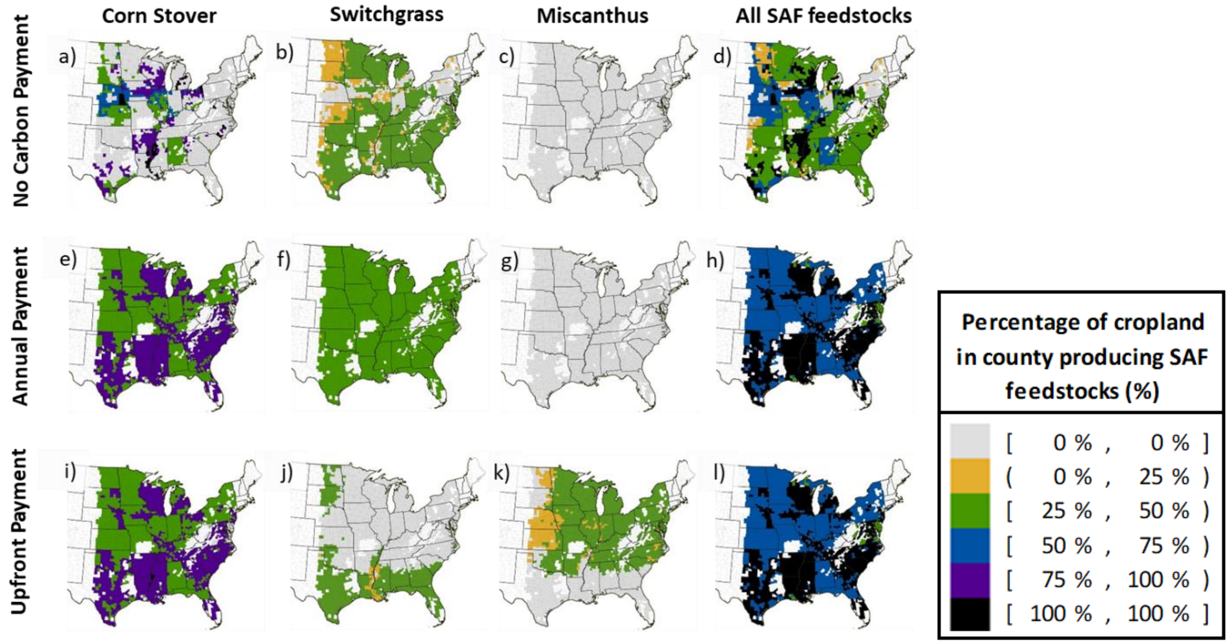
Figure A.1: Sustainable Aviation Fuel production with no carbon payment under various biomass prices for differing farmer discount, risk, and credit-constraint profiles



This figure shows the adoption of cellulosic feedstocks under no carbon mitigation payments (*No Carbon Payment*). The production of SAF from cellulosic feedstocks requires a biomass price of at least $40 per Mg biomass in 2016 dollars (with an equivalent SAF price of $1.10 per liter). At a price of $60 per Mg biomass (with an equivalent SAF price of $1.25 per liter), under the *Low-Constraint* farmer profile (h), the cellulosic feedstocks are adopted on 33.5 million hectares, with most land being used to produce corn stover (18.5 million hectares) and fewer hectares to miscanthus (14.3 million hectares) and switchgrass (0.5 million hectares). Under the *High-Constraint* farmer profile (a), the overall hectares producing cellulosic feedstocks are 10 percent (%) lower (at 30 million hectares) than in the *Low-Constraint* farmer profile, with most land being used to produce corn stover (20.5 million hectares) and some land producing switchgrass (9.5 million hectares) and no land producing miscanthus.
Feedstock hectares increase at a biomass price of $80 per Mg (with an equivalent SAF price of $1.40 per liter), but the feedstock mix does not change significantly under each farmer profile relative to the $60 per Mg biomass price. The crop hectares producing SAF feedstocks under the *High-Constraint* farmer profile are 2% lower than under the *Low-Constraint* farmer profile at the same price.

The feedstock supply from bioenergy crops becomes relatively inelastic at biomass prices higher than $80 per Mg. At higher biomass prices, most additional feedstock is produced by farmers changing their conventional crop cropping choices in order to increase the land on which corn stover can be harvested. Also, risk-averse farmers with access to credit (e and g) choose to substitute away from miscanthus for switchgrass.

Figure A.2: Share of cropland under Sustainable Aviation Fuel feedstock production at $ 40 and $60 per Mg biomass price, without carbon payment and carbon payment of $20 and $60 per Mg CO_2 for annual and upfront payment schemes for high risk-averse, high time-discount, and credit-constrained farmer profiles



This figure shows the share of cropland under SAF feedstock production at $60 per Mg biomass price, without carbon payment and carbon payment of $60 per Mg CO_2 for annual and upfront payment schemes for the *High Risk-Averse, High Time-Discount*, and *Credit-Constraint* farmer profile. Farmers, when they receive no carbon payment, adopt low shares of feedstocks across the rainfed region, with stover being more dominant in terms of land share in the Midwest. With carbon payments, higher land shares of bioenergy crops are adopted in the midwest, which reduces the acreage of corn stover grown in some counties. At higher carbon prices, corn stover is also adopted in regions outside the high-yielding midwest region; the land share dedicated to stover harvest differs by region (higher in regions where corn is grown continuously and lower in regions with corn-soybean rotations). Land share for carbon payments also differs by feedstock, with annual payments incentivizing a higher share of land dedicated to bioenergy crops than upfront payments. However, upfront payments also incentivize miscanthus in the larger Midwest, resulting in much larger SAF production.

Table A.1 Generated Yield Distributions (average for regions)

Crop	Rot.	Tillage	Unit	Northern Great Plains	Southern Great Plains	Upper Midwest	Central Midwest	South Central	Delta Region	Northeast	Central East	Southeastern states	All Counties	All Counties SD
Corn	Cont.	Conv. Till	bu ac^{-1}	121.3	84.9	138.3	166.4	131.9	143.0	114.0	141.8	122.8	131.4	31.73
		No-Till		91.2	69.9	101.5	125.0	104.9	115.5	84.5	105.4	97.4	101.1	22.69
	CS rot	Conv. Till		110.2	85.5	125.2	143.1	121.3	123.5	115.7	112.9	114.1	118.8	24.14
		No-Till		85.8	69.8	96.6	112.5	101.3	104.1	91.6	90.6	91.3	94.8	18.57
Stover	Cont.	Conv. Till	Mg ha^{-1}	2.2	1.6	2.2	2.7	2.4	2.4	1.9	2.3	1.9	2.2	0.51
		No-Till		3.6	2.9	3.6	4.6	4.2	4.2	3.1	3.8	3.4	3.8	0.82
	CS rot	Conv. Till		2.0	1.5	2.0	2.4	2.2	2.0	1.9	1.8	1.9	2.0	0.39
		No-Till		3.4	2.8	3.4	4.1	4.0	3.8	3.3	3.3	3.3	3.6	0.67
Soybean	CS rot	Conv. Till	bu ac^{-1}	42.8	40.6	47.8	55.9	45.3	50.3	47.2	54.0	42.0	47.1	8.70
		No-Till		43.4	40.8	48.5	56.4	45.5	50.4	47.7	54.3	42.1	47.5	8.79
Miscanthus	-	-	Mg ha^{-1}	20.1	15.2	24.2	26.9	24.6	16.5	23.9	24.5	17.5	21.6	5.40
Switchgrass	-	-	Mg ha^{-1}	13.3	14.3	15.7	17.6	18.0	18.6	16.5	16.9	18.3	16.5	2.59

Table A.2 Bioenergy Crop Fixed Costs per Hectare (average for regions)

$ ha^{-1}	Northern Great Plains	Southern Great Plains	Upper Midwest	Central Midwest	South Central	Delta Region	Northeast	Central East	Southeastern states	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-end	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-end	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.3 Total operating costs for bioenergy crops (average for regions)

$ Mg^{-1} biomass	Northern Great Plains	Southern Great Plains	Upper Midwest	Central Midwest	South Central	Delta Region	Northeast	Central East	Southeastern states	All Counties	All Counties SD
Miscanthus	42.09	51.14	40.02	37.53	37.51	42.60	39.37	37.38	46.50	**41.33**	4.20
Switchgrass	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.3 Conventional Crop Costs (average for regions)

$ bushel	Northern Great Plains	Southern Great Plains	Upper Midwest	Central Midwest	South Central	Delta Region	Northeast	Central East	Southeastern states	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.4 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.5 Stover Production Costs (average for regions)

$ Mg^{-1} biomass	Northern Great Plains	Southern Great Plains	Upper Midwest	Central Midwest	South Central	Delta Region	Northeast	Central East	Southeastern states	All Counties	All Counties SD
CC_CT	50.39	51.73	53.37	48.93	50.88	50.65	56.90	53.21	52.11	51.53	3.80
CC_NT	44.28	45.44	46.22	43.31	44.96	44.48	48.92	46.63	45.91	45.23	2.58
CS_CT	57.31	58.69	60.50	55.54	57.66	56.57	65.01	60.05	60.46	58.60	5.33
CS_NT	61.61	62.63	64.56	60.32	63.12	62.19	68.79	66.25	67.50	63.66	5.88

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.6 Biomass to SAF conversion costs

Costs		
Conversion cost of biomass to cellulosic ethanol (per gallon of ethanol)	$1.27	per gallon
Conversion cost of cellulosic ethanol to SAF (per gallon of ATJ-SPK)	$0.86	per gallon
Volumetric conversions		
1 Mg biomass to cellulosic ethanol	63.2	gallons
1 gallon cellulosic ethanol to SAF (ATJ-SPK)	0.58	gallons

Based on Fan et al. (2024)

Table A.7: Soil Carbon Sequestration Rates (average for regions)

Baseline Sequestration Mg C ha^{-1}	**Northern Great Plains**	**Southern Great Plains**	**Upper Midwest**	**Central Midwest**	**South Central**	**Delta Region**	**Northeast**	**Central East**	**Southeastern states**	**All Counties**
Miscanthus										
y1	-1.16	-0.84	-0.93	-0.93	-1.16	-0.94	-0.84	-0.92	-0.86	-0.96
y2	1.08	1.12	0.91	1.09	1.11	1.21	0.89	0.95	1.08	1.07
y3-end	1.71	1.08	1.67	2.00	1.70	0.98	1.65	1.82	0.90	1.53
Switchgrass										
y1	-0.79	-0.50	-0.64	-0.59	-0.79	-0.55	-0.54	-0.60	-0.50	-0.62
y2	1.84	1.85	1.75	2.04	2.09	2.24	1.80	1.94	1.95	1.95
y3-end	1.25	1.06	1.25	1.56	1.44	1.28	1.30	1.48	0.95	1.29
Corn stover										
CC_CT	-0.08	-0.07	-0.03	-0.01	-0.11	-0.09	-0.07	-0.03	-0.06	-0.05
CS_CT	-0.14	-0.08	-0.09	-0.07	-0.09	-0.06	-0.08	-0.09	-0.04	-0.08
CC_NT	0.01	-0.03	0.02	0.08	0.02	-0.02	0.01	0.03	0.00	0.02
CS_NT	-0.07	-0.04	-0.04	-0.03	-0.05	-0.05	-0.03	-0.05	-0.02	-0.04

Computed from DayCent

Table A.8 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
Carbon intensity of converting ethanol to SAF (ATJ-SPK)	g CO2e MJ^{-1}	21.00
Other		
Gallons of ethanol Mg^{-1} biomass	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.9 Input Application Rates

Input	Unit	Miscanthus	Switchgrass	Corn Stover
Nitrogen	Kg N ha^{-1}	DayCent	DayCent	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.10 Feedstock production carbon intensity rates not including carbon sequestration (estimated mean)

Material Use gCO2e MJ^{-1}	**Northern Great Plains**	**Southern Great Plains**	**Upper Midwest**	**Central Midwest**	**South Central**	**Delta Region**	**Northeast**	**Central East**	**Southeastern states**	**All Counties**
Miscanthus	21.45	23.23	20.90	20.69	21.01	22.26	20.13	20.38	22.10	21.42
Switchgrass	29.05	28.87	28.39	27.87	28.56	27.63	29.45	29.77	28.44	28.47
Stover										
CC_CT	29.82	30.52	31.99	30.12	30.76	30.97	33.45	30.18	31.85	30.89
CS_CT	30.90	30.63	33.31	31.97	31.78	32.53	33.29	33.09	32.35	32.01
CC_NT	29.82	29.14	32.30	30.09	29.91	29.95	33.56	30.32	31.10	30.49
CS_NT	30.43	29.53	32.89	31.34	30.43	31.01	32.46	32.12	31.46	31.16

Note, we do not include soil carbon sequestration in this table, which differs temporally and spatially.

Table A.11 Average Correlation Coefficients Matrix for Yield and Price Draws

		Corn				Stover				Soybean		Misc.	Swit.	Row Prices	
		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**	**Sb**
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	1.00

Computed Value