Exploring Feedstock Pathways to Three Billion Gallons of Sustainable Aviation Fuel: The Role of Contracts and Bioenergy Crop Insurance

Mohit Anand

Division of Business and Accounting, Miles College

Bijesh Mishra

Department of Agricultural Economics and Rural Sociology, Auburn University

Ruiqing Miao

Department of Agricultural Economics and Rural Sociology, Auburn University

Madhu Khanna

Institute for Sustainability, Energy and Environment, University of Illinois, Urbana-Champaign

Note: Anand and Mishra made equal contributions to the study.

Correspondence: Bijesh Mishra, Email: bzm0094@auburn.edu. Ruiqing Miao, E-mail: miaorong@auburn.edu; Phone: 515-520-1979; Fax: 334-844-5639. Mailing address: 208 B Comer Hall, Auburn, AL, 36830.

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Abstract

We investigate contract terms required to produce feedstock for three billion gallons of sustainable aviation fuel from miscanthus and switchgrass under fixed-price, revenue-sharing, or land-leasing contract, varying farmer's risk and time preferences and the availability of bioenergy crop insurance. By conducting simulation based on county-level data in rainfed US, we find that miscanthus contract terms are sensitive to farmers' time, but not risk, preference. Switchgrass contract terms are largely insensitive to either. Bioenergy crop insurance can decrease fixed price and revenue share by about 3% for miscanthus and 5% for switchgrass, while having minimal impact on their acreage and cost.

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The U.S. aviation sector consumed 25.3 billion gallons of conventional jet fuel in 2023, generating about 247 million metric ton of CO_2 in that year (Energy Information Administration (EIA), 2023; EIA, 2024; Fan et al., 2024). To reduce the greenhouse gas emissions from the aviation sector and to improve energy independence, the sustainable aviation fuel (SAF) roadmap developed by the U.S. Department of Energy (USDOE), Department of Transportation (DOT), and Department of Agriculture (USDA) in 2021 aimed at producing three billion gallons of SAF per year for aviation industry by 2030 and sufficient biofuel to meet 100% aviation fuel demand by 2050 (USDOE, 2022). The SAF demand is expected to be around 35 billion gallons per year by 2050 to completely decarbonize the aviation industry (Swanson and Smith, 2024; USDOE, 2022). Producing three billion gallons of biofuel would require about eight to eleven million acres of corn or thirty-five to fifty million acres of soybeans (Swanson and Smith, 2024), indicating that decarbonizing aviation fuel industry by 2050 using corn and soybean-based biofuel requires a large amount of land or significant increase in crop yields. Corn and soybean production on this scale creates food-fuel competition and substantial uncertainty in greenhouse gas emission reduction (Swanson and Smith, 2024). The 2016 and 2023 Billion-ton Reports published by the USDOE documented that bioenergy crops such as miscanthus and switchgrass can meet about half of the biomass demand to produce low-carbon fuels and chemicals by 2050 and benefit rural agricultural communities (Langholtz, 2016; USDOE, 2024).

The commercial production of these perennial bioenergy crops has not commenced yet due to higher risk associated with crop production, higher upfront establishment cost, lack of market and supply chain, and longer waiting time for the return (Miao and Khana, 2014, 2017a,b; Witzel and Finger, 2016; Zahraee et al., 2020; Clifton-Brown et al., 2022). In the United States, crop insurance offered by the federal government and contract arrangements between farmers and processors are two important mechanisms to reduce the risk associated with crop production for farmers (Du et al., 2015). For conventional crops such as corn and soybeans, crop insurance has become a major tool to reduce economic risk of farmers throughout the US (Barnett, 2007; Glauber, 2013). Many survey studies have shown that the availability of insurance for bioenergy crops is a key factor to increase farmers' willingness to adopt these crops (e.g., Fewell et al., 2016; Bergtold et al., 2017; Krah et al., 2018; and Burli et al., 2019). Also, Yang et al. (2016) suggest that the long-term contracts between farmers and biorefineries are crucial to reduce the economic risk associated with biofuel crop production. However, few existing studies have examined how and to what extent these risk management tools can facilitate the production of bio-energy crops to meet the demand from SAF or other biofuels or bio-chemicals. The present study aims to fill this research gap.

Specifically, by using the county-level yield data of miscanthus and switchgrass simulated by the DayCent model, a biogeochemical model that is widely used to simulate plant growth, we examine the contract terms of fixed-price contract, revenue-sharing contract, or land-leasing contract to reach the 3-billion-gallon goal of SAF production in the United States under various assumptions of farmers' risk and time preferences. We also examine bioenergy crop acreage, farmers' welfare changes when compared with growing conventional crops, and biomass production costs under each type of contract meeting the SAF production goal. Therefore, our study allows us to compare the three types of contracts in incentivizing bioenergy crop production. Moreover, we investigate how the availability of bioenergy crop insurance would affect the contract terms as well as bioenergy crop acreage, farmers' welfare, and biomass production cost.

We find that meeting the feedstock demand for 3 billion gallons of SAF requires different contract terms for miscanthus and switchgrass. For miscanthus, fixed-price, revenue-sharing, and land-leasing contracts involve terms at $42-$51 per metric ton, 23%-28% revenue share, and $95/acre, respectively. For switchgrass, these figures are $67-$71 per metric ton, 33%-35% revenue share, and $155/acre, significantly higher than those for miscanthus. Miscanthus contract terms are sensitive to farmers' discount rates but not risk aversion, while switchgrass contract terms are largely insensitive to either. Land-leasing terms for both crops are insensitive to farmers' risk and time preferences. Miscanthus would require 1.94-2.18 million acres, while switchgrass would need 4.6-4.8 million acres to supply sufficient feedstock for 3 billion gallons of SAF, depending on farmers' risk and time preferences, as well as the presence or absence of bioenergy crop insurance. Free bioenergy crop insurance can decrease fixed price by $1.5 per metric ton and revenue share by 0.7 percentage points (about 3% decrease for both terms) for miscanthus. For switchgrass, the corresponding reductions are about $3.5 per metric ton and 1.7 percentage points (about 5% decrease for both terms). We also find that free bioenergy crop insurance will decrease miscanthus farmers' welfare change by up to 7.83% while it will increase switchgrass farmers' welfare change by up to 6.58%. Finally, our results show that the insurance has minimal impact on bioenergy crop land intensity and average biomass production cost.

Our study contributes to a few strands of literature on the economics of bioenergy crop adoption and production. First, it contributes to the emerging literature on the economics of SAF feedstock pathways by examining the roles of contract arrangements between farmers and biorefineries as well as bioenergy crop insurance on shaping the feedstock supply chain for SAF. Gautam et al. (2023) study the impact of carbon payment on the viability of various feedstock pathways for SAF. Fan et al. (2024) investigate the spatial heterogeneity of the breakeven price and carbon intensity of four different feedstock for SAF production (switchgrass, miscanthus, energy sorghum, and corn stover). Ari Akdemir et al. (2025) explore optimal feedstock production accounting for extreme weather events. Majeed et al. (2025) focus on the role of credit constraint, farmers' risk and time preferences, and various carbon payment policies on farmers' willingness to produce bioenergy crops for SAF. However, none of these studies consider the roles of contract arrangements or bioenergy crop insurance in the feedstock pathway development.

Focusing on some key features of bioenergy crop production (i.e., risky yield and price, lengthy establishment period, and large establishment cost), one strand of the literature studies the impact of farmers' risk and time preferences on bioenergy crop adoption, as well as the roles of some policy interventions that may incentivize bioenergy crop production, such as establishment cost subsidy, bioenergy crop insurance, and carbon payments (e.g., Miao and Khanna, 2014; Miao and Khanna, 2017a,b; Khanna et al., 2017b; Anand et al., 2019; Majeed et al., 2023). This strand of literature, however, largely assumes that bioenergy production, if it occurs, is under a long-term fixed price contract, and does not explicitly consider the roles of contracts in incentivizing bioenergy crop production. The present study complements this strand of literature by explicitly quantifying and comparing the impact of different types of contracts on bioenergy crop production.

Another line of studies focusses on contracts between farmers and biorefineries, either theoretically exploring the optimal contract designs (e.g., Alexander et al., 2012; Yoder et al., 2015; Yang et al., 2016; and McCarty and Sesmero, 2021), or empirically examining farmers' preferences for specific contract attributes such as contract length and establishment cost share by biorefineries based on farmer surveys (e.g., Fewell et al., 2016; Lynes, et al., 2016; Bergtold et al., 2017; Hossiso et al., 2017; Khanna et al., 2017a; Krah et al., 2018; Burli et al., 2019; Yang et al., 2021; and Sant'Anna et al., 2022). The theoretical studies in this line of literature often resort to numerical simulations that are calibrated to a hypothetical and representative farmer-biorefinery pair to obtain insights, while the empirical studies do not seek to quantify the incentivizing impact of any specific type of contract on bioenergy crop adoption and production. The present study extends this line of literature by calibrating the numerical simulation to each of the selected 1,919 U.S. rainfed counties and exploring the biomass production from two bioenergy crops (i.e., miscanthus and switchgrass) under each of the three types of contracts. Thus, it provides a relatively more realistic perspective about the impact of different types of contracts on bioenergy crop production and about the roles of these contracts in facilitating the supply chain of bioenergy crops in the United States.

CONCEPTUAL FRAMEWORK

We model a representative farmer's decision-making problem of whether to switch from conventional crops to a bioenergy crop for their land. If the farmer switches, then the operation will be under one of the three types of contracts with a biorefinery: a fixed-price contract, a revenue-sharing contract, or a land-leasing contract. The contract term of these contracts is determined by the biorefinery, and the farmer can take it or leave it. The farmer will select the option (i.e., switch or not) that generates a higher net present value (NPV) of the expected utility over the contract period.

Under the fixed-price contract, the biorefinery offers a pre-determined price per metric ton of biomass ahead of production in exchange for a guaranteed amount of biomass to be delivered per year by the farmer over the contracted period. The farmer bears production cost and yield risk, and is obligated to supply the contracted amounts of biomass. The production of bioenergy crops is subject to weather conditions which may lead to production surplus or shortfall. If there is a surplus, the farmer will sell it in the spot market of biomass at the spot market price. If there is a shortfall, the farmer will need to purchase biomass from the spot market to fulfill the contract. In either case, the farmer is responsible for the transportation cost of biomass between the farm gate and the spot market. The spot-market price is assumed to be random but the distribution is known to farmers and biorefineries. Under a revenue-sharing contract, the farmer is obligated to deliver a fixed amount of biomass to the biorefinery and, in return, the farmer receives a pre-specified portion of the revenue from selling the biofuel that is produced by the delivered biomass. Under this type of contract, the farmer is exposed to both bioenergy crop production risk and biofuel marketing risk. Similar to the fixed-price contract, the farmer will rely on the spot market of biomass to sell biomass surplus or purchase the shortfall. A land-leasing contract entails a biorefinery renting land from a farmer at a fixed rental rate to produce bioenergy crops. Under this type of contract, the costs and risk of producing bioenergy crops are completely shifted from the farmer to the biorefinery.

Our analysis focuses on the farmers' decision problem, examining for a given contract type and contract term (i.e., the fixed price under the fixed-price contract, the portion of revenue allocated to the farmer under the revenue-sharing contract, and the land rental payment under the land-leasing contract), whether a representative farmer in a county would switch to a specific bioenergy crop. We then aggregate the county-level bioenergy crop production across the rainfed counties covered in our study to obtain the total biomass supply under the given contract type, contract term, and bioenergy crop type. For each contract type and bioenergy crop, we obtain an aggregate biomass supply curve with respect to the contract term by varying the contract term over a wide range of values, so that we can study the contract terms required to induce biomass production that is sufficient for producing three billion gallons of SAF annually. The biorefinery is assumed to be risk neutral and operating under perfect competition in the SAF market. We further assume that the SAF price is random, but its distribution is known to both biorefineries and farmers. Following Yang et al. (2016) and for simplicity, we assume that biorefineries are in the proximity of biomass production fields, and thus the transportation cost of biomass from farm gates to biorefineries is negligible.[1]

To examine the impact of insurance for bioenergy crops on the contract terms needed to reach a fixed amount of SAF production, we compare scenarios under which bioenergy crop insurance is unavailable with scenarios under which free bioenergy crop insurance (i.e., insurance premium fully subsidized) is available to farmers. Given that the current crop insurance premium subsidy rate is at 62% on average (U.S. Government Accountability Office (USGAO), 2023), a free insurance for bioenergy crops is not an unreasonable assumption for the impact analysis. The detailed decision-making problem for a farmer is presented as follows.

A farmer's profits from conventional crop production

Let π_t^c denote the profit per acre in year t from growing a conventional crop (corn or soybean in this study), and let p_t^c, y_t^c, v_t^c, and f_t^c denote the price, yield, variable cost, and fixed cost of the conventional crop, respectively. Because most of the conventional crop production is covered

[1] Assuming a positive transportation cost of delivering biomass from farm gates to biorefineries would obscure, but not obviate, the insights that the study provides.

under the heavily subsidized federal crop insurance program in the United States (Shields, 2015), we consider crop insurance indemnity payment (ι_t^c) and premium subsidy for corn and soybeans in profit calculation. Specifically, π_t^c can be written as

$$\pi_t^c = (p_t^c - v_t^c)\, y_t^c - f_t^c + \iota_t^c - (1-\rho)\, E[\iota_t^c], \tag{1}$$

where ρ is the insurance premium subsidy rate and $E(\cdot)$ is the expectation operator. We consider a revenue insurance policy as it is widely adopted by U.S. farmers (Shields, 2015). The indemnity payment per acre of land in year *t* for a conventional crop is specified as

$$\iota_t^c = \max\{\, \theta^c E(y_t^c) \max[\, p_t^{\text{proj}}, p_t^{\text{harv}}] - p_t^{\text{harv}} y_t^c, 0\} \tag{2}$$

where θ^c is insurance coverage level for the conventional crop; p_t^{proj} and p_t^{harv} are respectively projected price and harvest price established by Risk Management Agency (RMA) of the U.S. Department of Agriculture (USDA) to determine the indemnity payment.

A farmer's profits from bioenergy crop production under each contract type

Fixed-price contract

Let P^b and Y^b denote biomass price and quantity specified in the fixed-price contract. Note here for simplicity we assume that the quantity is on a per-acre basis at the farmer's mean yield of a bioenergy crop. Furthermore, let p_t^b and y_t^b denote the biomass price in the spot market and the actual bioenergy crop yield of the farmer in year t. Considering the transaction in the spot market to sell surplus or purchase shortfall, the farmer's revenue per acre under the fixed-price contract is

$$R_t^{b,\text{FP}} = P^b Y^b + 1\{y_t^b > Y^b\} \cdot \left(y_t^b - Y^b\right)(p^b - d) + \left(1 - 1\{y_t^b > Y^b\}\right) \cdot (y^b - Y^b)(p^b + d), \tag{3}$$

where $1\{y_t^b > Y^b\}$ is an index equal to 1 if $y_t^b > Y^b$ and 0 otherwise, and d is the transportation cost per unit of biomass between the spot market and farm gate.

Because perennial bioenergy crops typically require an establishment period (say, τ years), during which establishment cost incurs and crop yield may not reach its full potential, one should also consider the establishment cost (denoted by K^b) in the profit calculation. Therefore, the profit per acre from growing a bioenergy crop can be written as,

$$\pi_t^{b,\text{FP}} = \begin{cases} R_t^{b,\text{FP}} - v_t^b y_t^b - f_t^b - K_t^b & \text{if t} \leq \tau \\ R_t^{b,\text{FP}} - v_t^b y_t^b - f_t^b & \text{if t} = \in \{\tau+1, \tau+2, \ldots, \text{T}\} \end{cases}, \tag{4}$$

where v_t^b and f_t^b are the variable cost and fixed cost of bioenergy crop in year t, respectively; and T is the lifespan of the bioenergy crop.

If the bioenergy crop production is covered by free crop insurance, then the farmer will receive an indemnity payment (denoted by ι_t^b) when the actual yield is lower than the insured level of yield. Here we consider a yield insurance for the bioenergy crop because the price risk of bioenergy crop production is covered by the fixed-price contract. The indemnity payment can be written as,

$$\iota_t^b = \max[\bar{Y} - y_t^b, 0] \cdot \bar{P}, \tag{5}$$

where $\bar{Y}$ and $\bar{P}$ are guaranteed yield and price in the insurance policy. Therefore, the profit per acre of bioenergy crop production with free crop insurance is,

$$\pi_t^{b,\text{FP,Insu}} = \begin{cases} R_t^b - v_t^b y_t^b - f_t^b - K_t^b + \iota_t^b & \text{if } t \leq \tau \\ R_t^b - v_t^b y_t^b - f_t^b + \iota_t^b & \text{if } t = \in \{\tau+1, \tau+2\text{ , T}\} \end{cases}. \tag{6}$$

Revenue-sharing contract

Under a revenue-sharing contract, the revenue of selling the final product (i.e., SAF) derived from the biomass provided by the farmer is shared between the biorefinery and the farmer. Let $\alpha \in [0,1]$ denote the portion of the revenue allocated to the farmer, p_t^f denote the price of the final product in year t, and G denote the quantity of final product derived from one unit of biomass. Thus, the revenue per acre from producing a bioenergy crop under a revenue-sharing contract in year *t* can be written as

$$R_t^{b,\mathrm{RS}} = \alpha \cdot p_t^f \cdot G \cdot y_t^b + R_t^{\mathrm{spot}}, \tag{7}$$

where R_t^{spot} is the revenue or expense in the spot market to handle biomass surplus or shortfall. Similar to equation (3), R_t^{spot} can be calculated by using $1\{y_t^b > Y^b\} \cdot (y_t^b - Y^b)(p^b - d) + (1 - 1\{y_t^b > Y^b\}) \cdot (y^b - Y^b)(p^b + d)$, where Y^b is the contract quantity.

In the absence of bioenergy crop insurance, the profit per acre in year t from growing a bioenergy crop is

$$\pi_t^{b,\mathrm{RS}} = \begin{cases} R_t^{b,\mathrm{RS}} - v_t^b y_t^b - f_t^b - K_t^b & \text{if t} \leq \tau \\ R_t^{b,\mathrm{RS}} - v_t^b y_t^b - f_t^b & \text{if t} = \in \{\tau+1, \tau+2\ , \mathrm{T}\} \end{cases}. \tag{8}$$

With free insurance, the profit becomes

$$\pi_t^{b,\mathrm{RS,Insu}} = \begin{cases} R_t^{b,\mathrm{RS}} - v_t^b y_t^b - f_t^b - K_t^b + \iota_t^b & \text{if t} \leq \tau \\ R_t^{b,\mathrm{RS}} - v_t^b y_t^b - f_t^b + \iota_t^b & \text{if t} = \in \{\tau+1, \tau+2\ , \mathrm{T}\} \end{cases}, \tag{9}$$

where ι_t^b is defined in equation (5).

Land-leasing contract

Under a land-leasing contract, the farmer receives a fixed rental payment per acre per year (denoted by ω). Thus, the profit is simply

$$\pi_t^{b,\mathrm{LL}} = \omega. \tag{10}$$

Note that under a land-leasing contract, bioenergy crop insurance is irrelevant to the farmer because production and marketing risks are borne by the biorefinery.

A farmer's optimal choice

For a given contract type and contract term, the farmer will quantify the NPV of the expected utility from growing a bioenergy crop over the contract period (i.e., *T* years), and compare it with the NPV of the expected utility from growing a conventional crop in the same period. The farmer will choose the option that provides the farmer with a higher level of expected utility. We assume that the farmer has a constant absolute risk aversion (CARA) utility function with the form $U(\pi_t) = 1 - e^{-\alpha\pi_t}$, where π_t is profit in year *t*, and α is the absolute risk aversion parameter. Let $\gamma \in [0,1]$ denote the discount rate, the farmer will make their optimal crop choice, c (conventional crops) or b (bioenergy crops), by solving the following optimization problem,

$$Max_{i\in\{c,b\}} \sum_{t=1}^{T} \left(\frac{1}{1+\gamma}\right)^{t-1} E(U(\pi_t^i)), \tag{11}$$

where π_t^i is profit from growing a conventional crop or bioenergy crop defined above.

SIMULATION FRAMEWORK AND MODEL CALIBRATION

We view a county as the decision-making unit represented by a single farmer making choice between growing corn (may be rotated with soybeans) or growing a bioenergy crop (miscanthus or switchgrass). We select 1,919 U.S. counties east of the 100th meridian that have data for both corn yield and at least one bioenergy crop yield. Corn and soybeans are assumed to be produced under conventional tillage production. For counties with historical yield data for both corn and soybeans, we assume that corn production is under a corn-soybean rotation. For counties without data for soybean yield, we assume that corn production is under a corn-corn rotation. We also assume that if profitable, the farmer will harvest 30% of total corn stover produced, which is included in the calculation of profit from corn. For corn and soybeans, the crop insurance coverage level is set to be 75% of average revenue, and the insurance premium subsidy rate is 55%. These two values are chosen because 75% is one of the most popular coverage levels farmers choose for conventional crops and 55% is the corresponding subsidy rate for the 75% coverage level specified by RMA (Shields 2015). We do not consider insurance for corn stover production.

We conduct the simulation for the three types of contracts separately. Under each type of contract, we simulate the representative farmer's decisions on crop choice in each county under a wide range of contract terms. For instance, under the fixed-price contract, we vary the fixed price of biomass from \$0 per metric ton to \$100 per metric ton, with an increment at \$1 per metric ton. We simulate and record the crop choice decisions of the representative farmer in each county under each of the fixed prices. We then sum up the bioenergy crop acreage and biomass production across all counties under a fixed price to obtain the total bioenergy crop acreage and total biomass production under this fixed price, obtaining a simulated relationship between fixed prices and bioenergy crop production levels, which can be translated into a SAF supply curve against biomass prices specified under fixed-price contracts. Similar procedures are used for revenue-sharing contracts and land-leasing contract. The results will allow us to compare the incentivizing impact of the three types of contracts on bioenergy crop production. Specifically, we focus on the total land acreage required to produce three billion gallons of SAF, the associated farmer welfare changes, and associated biomass production cost under each type of contracts.

To explore the impact of farmers' risk and time preference on farmers' bioenergy crop production under each type of contract, we consider two levels of the risk aversion parameter (0.00001 vs. 0.00005) and two levels of the discount rate (2% vs. 10%) by following Miao and Khanna (2017a,b), Anand et al. (2019), and Majeed et al. (2023). Together with the scenarios with and without bioenergy crop insurance, we simulate eight scenarios for each type of contracts, consisting of the eight permutations of two risk aversion levels, two discount rates, and two insurance availability status. We assumed that farmers are not credit-constrained to establish bioenergy crop production.

We consider two bioenergy crops individually: miscanthus and switchgrass. They are both promising candidates for biomass production but have quite different characteristics. Miscanthus needs one year or more to be established and can be harvested in the second year and after, whereas switchgrass can reach maturity during the first year of establishment. Miscanthus requires much higher establishment cost but produces much higher yield than does switchgrass (see Table 1). They also have different lifespans: around 15 years and 10 years respectively for miscanthus and switchgrass (Jain *et al*., 2010; Chen *et al*., 2014). Finally, their yield risks differ, with switchgrass has higher relative variability (standard deviation divided by mean) (see Table 1). These differences between the two bioenergy crops provide us with the opportunities to explore the impact of risk and time preferences as well as bioenergy crop insurance on the contract-biomass production relationship. They also allow us to study different feedstock pathways to produce three billion gallons of SAF through bioenergy crops. For bioenergy crop insurance, we assume that the coverage level is 75% of average yield in a county, and the premium subsidy rate is 100%. Furthermore, we consider a 15-year lifespan for miscanthus and a 10-year lifespan for switchgrass.

Following previous studies (e.g., Anand et al., 2019), we differentiate high-quality land and low-quality land in a county. High-quality land is defined as land actively used for conventional crop production, and low-quality land is inactive cropland (idle cropland or land frequently in and out of crop production). We assume that low-quality land is initially under a low-risk-low-return activity such as enrollment in a conservation program but can be readily converted to energy or conventional crops. Not all counties have both types of land. We limit land that can be converted to energy crops to maximum 25% of total low- and high-quality land in a county following Chen et al. (2014) and Miao and Khanna (2017b). The average acreage of high and low-quality land per county is 28,841 hectares and 4,507 hectares, respectively (Table 1). In the remaining part of this section, we describe the data and model parameters used in the simulation.

Crop yields

We obtain county-level yield data for high- and low-quality land for miscanthus and switchgrass using DayCent model.[2] DayCent model is a daily time-step version of the CENTURY biogeochemical model that is widely used to simulate plant growth based on information on precipitation, temperature, soil nutrient availability, and land-use practice (Del Grosso et al. 2011, 2012; Davis et al. 2012). We simulate annual yield of miscanthus and switchgrass for each selected county based on historical weather data in 1980 to 2003. The average yield of miscanthus on high and low-quality land is 27.2 and 26.8 metric tons per hectare (ha.) at 15% moisture, and for switchgrass average yield is 14.1 and 12.7 metric tons per hectare respectively (see Table 1).

Yields for corn grain, corn stover, and soybean grain on both high and low-quality land are also obtained from DayCent model simulations. We do so for the consistency in yield estimation of crops. It also allows us to avoid arbitrary assumptions to obtain corn, corn stover, and soybean yields on low-quality land. Table 1 shows that for corn grain harvested on high and low-quality land are 139.1 bushels (bu.) per acre and 127.2 bu. per acre respectively. On average, corn grain yield on low-quality land is about 8.6% lower than that on high-quality land, whereas the soybean yield on low-quality land is only about 3.3% lower than that on high-quality land.

[2] Detailed description about calibration and validation of DayCent yield simulation is described in Miao and Khanna (2017b).

Crop prices

State-level received prices from NASS are used to calculate realized profit of corn and soybean. In contrast, projected futures and harvest futures are used to calculate crop insurance indemnity for corn and soybeans. These two futures prices were determined by following RMA (2024) rules based on Chicago Board of Trade (CBOT) futures prices. We obtain the CBOT futures prices of corn and soybeans over 1980-2010 from Barchart.com. These prices have been converted to 2010 dollars using the Gross Domestic Product implicit deflator. Following Miao and Khanna (2017b), prices in each year are assumed to be drawn from the same price-yield joint distribution, and the autocorrelation of prices across years is not considered. Relaxing this assumption will not affect the study's core insights but will make the analysis more cumbersome.

Riskiness of crop and SAF production and marketing

To represent crop yield risk, corn and soybean price risk, and SAF price risk, we estimate a joint yield-price distribution for each county for up to eight yields and three prices by using a copula approach.[3] The eight yields are for corn grain, corn stover, soybean grain, and a bioenergy crop (miscanthus or switchgrass) on high-quality land and low-quality land, respectively. The three prices are corn grain price, soybean grain price, and ethanol price. We include ethanol price because SAF is still in its infancy, and we do not have long enough time series of data for SAF to estimate the joint distributions. Moreover, following Fan et al. (2024), we assume that biomass is first converted into cellulosic ethanol, and then the cellulosic ethanol is converted to SAF via the alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) pathway at a constant conversion cost. This implies that ethanol price and SAF price are highly correlated in the ATJ-SPK pathway, and

[3] We refer readers to Miao and Khanna (2017a,b) for a detailed documentation of the copula approach.

that the ethanol price variation can serve as a close approximation of SAF price variation. The annual ethanol prices over 1982-2023 are obtained from Nebraska Department of Environment and Energy.

Costs and revenue

The state-level production costs of both conventional crops and bioenergy crops are obtained from Chen et al. (2014), Miao and Khanna (2017a and 2017b), and Anand et al. (2019). The descriptive statistics of the costs are summarized in Table 1, from which we can see that the establishment cost of miscanthus is more than ten times larger than that of switchgrass.

Based on Fan et al. (2024), one metric ton of dry biomass from miscanthus (respectively, switchgrass) can produce 97.77 (respectively, 92.51) gallons of cellulosic ethanol, and one gallon of ethanol can produce 0.58 gallons of SAF and some by-products such as gasoline and diesel. The cost of producing one gallon of SAF from ethanol via the ATJ-SPK pathway is $0.86. Because we assume that the biorefineries' equilibrium profit is zero, the total revenue from selling one gallon of SAF and its by-products is equal to the sum of the value of cellulosic ethanol input (ethanol price times 1/0.58) and the ATJ-SPK pathway conversion cost ($0.86). We also include the revenue from selling cogenerated electricity when converting biomass to cellulosic ethanol. According to Fan et al. (2024), producing one gallon of cellulosic ethanol from miscanthus (respectively, switchgrass) generates $0.1 (respectively, $0.3) worth of electricity.

We assume that the location of the spot market is outside the contracting region and that the biomass price in the spot market is random, which is determined by the ethanol prices. Following Yang et al. (2016), the biomass transportation cost between the spot market and farm gates is assumed to be $10 per metric ton.

RESULTS

Our simulation results include total biomass supply, land-use intensity for bioenergy crops, and farmers' welfare changes under each bioenergy crop and contract type with the eight scenarios of varying risk and time preferences as well as bioenergy crop insurance availability. By comparing these results across different types of contracts and scenarios, we shed light on the incentivizing impact of different types of contracts on bioenergy crop production, and on the impact of risk and time preferences as well as bioenergy crop insurance on contract terms and bioenergy crop production for each crop. We are particularly interested in examining these impacts at the biomass production level that meets the feedstock demand from 3 billion gallons of SAF.

FAS feedstock supply and contract terms

Figure 1 depicts the relationship between SAF production quantity (horizontal axes) and the contract term (vertical axes) that can induce sufficient biomass production from miscanthus or switchgrass to be used as SAF feedstock. Each row of the graphs in Figure 1 corresponds to a specific contract type, and each curve in a graph corresponds to a specific scenario of risk and time preferences as well as bioenergy crop insurance availability (eight scenarios in total). The figure shows that miscanthus production will take off when the fixed-price contract offers a price at \$30 per metric ton (see Graph A in Figure 1) or when the revenue-sharing contract offers a revenue share to farmers at 15% or higher (Graph C in Figure 1). Under a land-leasing contract, miscanthus production commences when the rental payment is about \$25/acre. Switchgrass production requires more favorable contract terms to start when compared with miscanthus production. The corresponding threshold values under the three types of contracts are biomass price at \$40 per metric ton, revenue share at about 20%, and rental payment at \$37.5/acre.

From Graphs A to D of Figure 1 we can see that when bioenergy crop insurance is absent and when farmers have high risk aversion (i.e., RA=0.00005) and high discount rate (i.e., DR=10%), the contract terms under fixed-price contracts and revenue-sharing contracts are the highest among the eight scenarios, indicated by the gray dashed line in the graphs. This is intuitive because when farmers are more risk-averse and more present-biased, they demand a higher fixed price or revenue share to switch from the conventional crop production covered by heavily subsidized crop insurance to risky bioenergy crop production. Among all eight scenarios, the contract terms in the fixed-price contracts and the revenue-sharing contracts are the lowest when farmers are less risk averse (i.e., RA=0.00001), less present-based (i.e., DR=2%), and protected by free bioenergy crop insurance (see the black dot-dash lines in Graphs A to D).

Because the establishment cost of miscanthus is high while the risk of miscanthus yield is low (see Table 1), the contract terms under the fixed-price contracts and the revenue-sharing contract for miscanthus are more sensitive to discount rate than to risk aversion parameter. For instance, in Graph A of Figure 1, regardless of the availability of bioenergy crop insurance, when farmers' discount rate remains constant, but the risk aversion parameter increases from 0.00001 to 0.00005, then the SAF-contract term curves tilt upward only slightly (e.g., the gray dot-dash line vs. the gray solid line in Graph A or C). However, when farmers' risk aversion remains constant, but discount rate increases from 2% to 10%, then the curves tilt upward significantly (e.g., the gray solid line vs. the gray dashed line in Graph A or C). In contrast, we do not observe this pattern of changes for switchgrass because the establishment cost of switchgrass is low and the crop can reach maturity in the first year of its lifespan.

For the land-leasing contract, the SAF-contract term relationship curves under various scenarios in Graph E or F of Figure 1 are almost identical. This is reasonable because by offering a fixed annual rental payment, the land-leasing contract provides farmers with a risk-free option. Because revenue insurance for corn and soybeans significantly reduces the production and marketing risks of the two crops, farmers' risk and time preferences have negligible impact on the choice between conventional crops and bioenergy crops. If we zoom in on the relationship between SAF feedstock supply and contract terms, and focus on the relationship when SAF production is at 3 billion gallons using miscanthus, we can see that when discount rate is 10%, decreasing the risk aversion parameter from 0.00005 to 0.00001 only increases the rental payment required by $0.04 (see Scenarios 1 and 3 in the last panel of Table 2). Note that it is an increase instead of decrease because for a farmer who is less risk-averse, the risk-free rental payment should be higher to motivate the farmer to shift from the (relatively) risky conventional crop production to leasing land to biorefineries when compared with a farmer who is more risk-averse.

By comparing graphs in the left column (for miscanthus) of Figure (1) with those in the right column (for switchgrass), we can see that to meet the feedstock demand for a given SAF production level, growing miscanthus requires a much lower contract term than does growing switchgrass. For instance, to produce sufficient biomass as feedstock for 3 billion gallons of SAF, growing miscanthus would require a fixed price ranging from $42 to $51 per metric ton (see Figure 1 (Graph A) or Table 2), depending on farmers' risk and time preferences as well as bioenergy crop insurance availability. However, growing switchgrass would require a fixed price ranging from $67 to $71 per metric ton (see Figure 1 (Graph B) or Table 3). Under revenue-sharing contracts, securing sufficient biomass for 3 billion gallons of SAF from miscanthus would require the revenue share allocated to farmers to be between 23% and 28%. For switchgrass, however, the corresponding range is 33% to 35%. Under land-leasing contracts, to induce the same amount of biomass production, the land rental payments needed when growing miscanthus are about 40% lower than those when growing switchgrass. This is because miscanthus yield is about twice switchgrass yield, and growing miscanthus requires much less land to meet the feedstock demand from SAF.

Land intensity, producing counties, and production cost

Figures 2 and 3 illustrate, respectively, miscanthus and switchgrass acreage required under each type of contract to meet the feedstock demand from a given amount of SAF production.[4] From these figures we can see that the land intensity for bioenergy crops under the land-leasing contract is the highest among the three types of contracts. This is perhaps because land-leasing contract is more appealing to farmers with less productive land, implying that to produce a given amount of biomass, more land will be needed under the land-leasing contract than under the other two types of contracts. We also find that in most cases the land intensity under the fixed-price contract is only slightly lower than that under the revenue-sharing contract for both miscanthus and switchgrass.

Table 2 shows that to meet the feedstock demand from producing 3 billion gallons of SAF, about 1.94 to 1.98 million acres of miscanthus acreage will be needed under the fixed-price contract or revenue-sharing contract. The acreage requirement will increase to about 2.18 million acres if land-leasing contract is used (about 10% increase). If switchgrass is grown as the feedstock for 3 billion gallons of SAF, then about 4.6 million acres of land will be needed under the fixed-price contract or revenue-sharing contract, and 4.8 million acres will be needed under the land-leasing contract (see Table 3), as switchgrass has much lower yield than miscanthus.

[4] For better contrast and simplicity, in Figures 2 and 3 we include only four scenarios that are permutations of high risk aversion high discount rate, low risk aversion low discount rate, and the presence or absence of free bioenergy crop insurance.

Figure 4 maps the county-level biomass production levels for each bioenergy crop and under each contract type to meet feedstock demand from 3 billion gallons of SAF. For simplicity, we include only maps under the scenarios of "high risk aversion and high discount rate," "low risk aversion and low discount rate," and with the absence or presence of free bioenergy crop insurance. From Figure 4 we can see that under both fixed-price contract and revenue-sharing contracts, miscanthus will be produced in Southeastern counties because they have higher miscanthus yield and lower conventional crop yields. Under the land-leasing contract, some counties around the Great Lakes will join miscanthus production. For switchgrass, the producing counties will be mainly in the Southeastern and Great Lakes regions. We do not find that changes in farmers' risk aversion or discount rate lead to significant shifts in the distribution of bioenergy crop-producing counties.

When targeting at 3 billion gallons of SAF, the farm-gate production cost for miscanthus under the fixed-price contract ranges between $29.75 and $29.57 per metric ton. Miscanthus production cost is slightly (about 6 to 18 cents) higher under the revenue-sharing contract. Under the land-leasing contract, miscanthus production cost is about $0.7 higher than that under the fixed price contract, reaching to $30.49 per metric ton. The similar pattern is observed for switchgrass production cost under the three contract types. However, switchgrass production cost is about $8 higher than miscanthus production cost on a per metric ton basis.

Farmers' welfare changes and contract

We use the change in farmers' NPV of expected utility as a measure of welfare change when farmers switch from growing conventional crops to growing a bioenergy crop under a contract with biorefineries. As specified in equation (11), farmers switch from conventional crops to bioenergy crops only if the switch will cause their NPV of expected utility to increase.

Therefore, farmers' welfare change under any contract type will be positive. Tables 2 and 3 show that, for farmers who enter a contract to produce a bioenergy crops, their welfare increases by up to 8.78% when compared with growing conventional crops. For both bioenergy crops, in most cases, the fixed-price contract brings farmers the highest welfare increases whereas land-leasing contract brings the lowest. Note that it is of modest importance to compare welfare changes across scenarios with different risk aversion or discount rate levels because the base levels of the expected utility across these scenarios are different. This caution also applies to the comparison of welfare changes among contract types because bioenergy crop producing counties, and thus the base levels of the expected utility, may differ under different contract types.

Impact of bioenergy crop insurance

As bioenergy crop insurance is irrelevant to farmers under the land-leasing contract, the discussion about its impact is only pertaining to the fixed-price contract and revenue-sharing contract. Table 4 summarizes the impact of free bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare changes, and average production cost under each contract type to meet the biomass demand for producing 3 billion gallons of SAF.

On contract terms

For both miscanthus and switchgrass, the presence of free bioenergy crop insurance will decrease the contract terms required to produce sufficient feedstock for any given amount of SAF. This is illustrated by Figure 1 where in each graph the black curve is always below the gray curve of the same line type. From Figure 1, we can also see that the difference between a pair of black and gray curves of the same line type is smaller for miscanthus than for switchgrass, indicating that for switchgrass, bioenergy crop insurance has a larger impact on reducing the contract terms required to meet a given demand from SAF production. This is unsurprising because switchgrass has larger yield risk than does miscanthus. Table 2 shows that across various risk aversion and discount rate scenarios, when the target feedstock quantity is for 3 billion gallons of SAF, the availability of bioenergy crop insurance decreases fixed price by $1.5 per metric ton and revenue share by 0.7 percentage points for miscanthus. For switchgrass, the corresponding reductions are about $3.5 per metric ton and 1.7 percentage points, respectively (see Table 3). Table 4 summarizes the impact (measured in percentage) of free bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare changes, and average production cost under each contract type to meet the biomass demand for producing 3 billion gallons of SAF, from which we can see that for miscanthus, free bioenergy crop insurance reduces the contract terms required for 3 billion gallons of SAF by about 3%. For switchgrass, this reduction is about 5%.

On land intensity

Tables 2 and 3 show that in most scenarios the free bioenergy crop will slightly increase the land intensity for producing 3 billion gallons of SAF under both fixed-price contract and revenue-sharing contract. The impact magnitude is smaller than 1% (see Table 4), which is consistent with empirical studies on crop insurance's land-use impact that find minimal impact of crop insurance (e.g., Goodwin et al., 2004; Yu et al., 2018).

On farmers' welfare changes

The presence of free bioenergy crop insurance affects farmers' welfare changes via two channels. One the one hand, the insurance decreases the welfare of farmers who produce bioenergy crops by decreasing the contract terms. Obviously, when fixed price or revenue share specified in a contract declines, bioenergy crop farmers' welfare will decrease. On the other hand, free bioenergy crop insurance provides indemnity payment when yield is low, and thus increases farmers' welfare. The overall effect of free bioenergy crop insurance on the welfare changes under a contract depends on the relative magnitude of these two opposing forces. We find that for miscanthus, the impact of free bioenergy crop insurance on the welfare changes of bioenergy crop farmers is generally negative, ranging from -7.83% to 1.48%. However, for switchgrass, the impact is all positive across the two types of contracts and the four scenarios of various risk aversion and discount rate levels, ranging from 4.92% to 6.58%. This is because switchgrass has larger yield risk than does miscanthus, and the presence of free crop insurance is more welfare-enhancing for switchgrass farmers than for miscanthus farmers.

On production cost

We find that the presence of free bioenergy crop insurance has minimal impact on average production cost of bioenergy crops to meet the feedstock demand from 3 billion gallons of SAF (see Table 4). For miscanthus, the bioenergy crop insurance increases biomass production cost by 0.22% to 0.25% under the fixed-price contract and 0.06% to 0.20% under the revenue-sharing contract. For switchgrass, the magnitude of the impact is even smaller. Under the fixed-price contract, switchgrass production cost increases by 0.01% to 0.07%, while under the revenue-sharing contract, the cost decreases by 0.07% to 0.15%.

CONCLUDING REMARKS

We develop a conceptual framework to model a representative farmer's decision-making problem of whether to switch from conventional crops to a bioenergy crop under three different types of contracts (fixed-price contract, revenue-sharing contract, and land-leasing contract) in the absence or presence of bioenergy crop insurance. Based on the conceptual framework and the county-level crop production data, we simulate the contract terms required to induce sufficient miscanthus or switchgrass production to meet a given feedstock demand from SAF. We analyze bioenergy crop acreage, farmers' welfare changes, and biomass production cost under each type of contract to generate sufficient feedstock for 3 billion gallons of SAF, and examine how these values may be affected by farmers' risk and time preferences as well as the presence of free bioenergy crop insurance.

We find that to meet the feedstock demand from 3 billion gallons of SAF, the contract terms for miscanthus under fixed-price contract, revenue-sharing contract, and land-leasing contract are \$42 to \$51 per metric ton of biomass, 23% to 28% of revenue share devoted to farmers, and about \$95/acre of rental payment, respectively. For switchgrass, however, these three groups of numbers are \$67 to \$71 per metric ton of biomass, 33% to 35% of revenue share, and about \$155/acre of rental payment, respectively, which are much higher than those for miscanthus. The results show that the fixed price and revenue share for miscanthus production are sensitive to farmers' discount rate but insensitive to farmers' risk aversion. For switchgrass, however, these contract terms are not quite sensitive to farmers' risk aversion or discount rate. The terms of land-leasing contract are not sensitive to risk aversion or discount rate either. We also find that miscanthus requires about 1.94 to 2.18 million acres of land to supply sufficient feedstock for 3 billion gallons of SAF, depending on contract types and farmers' risk and time preferences. Switchgrass would require 4.6 to 4.8 million acres of land to meet the same goal.

In terms of the impact of bioenergy crop insurance, we find that to produce feedstock for 3 billion gallons of SAF by growing miscanthus, the presence of free bioenergy crop insurance can decrease fixed price by \$1.5 per metric ton and revenue share by 0.7 percentage points (about 3% decrease for both terms). For switchgrass, the corresponding reductions are about \$3.5 per metric ton and 1.7 percentage points (about 5% decrease for both terms). We also find that free bioenergy crop insurance will decrease miscanthus farmers' welfare change by up to 7.83% while it will increase switchgrass farmers' welfare change by up to 6.58%. Our results show that free energy crop insurance has minimal impact on bioenergy crop land intensity and average biomass production cost.

Our findings provide direct insights for developing feedstock pathways and supporting policies associated with SAF. First, our comparisons among fixed-price contract, revenue-sharing contract, and land-leasing contract reveal that the impact of SAF development on land-use change, farmers' welfare, and biomass production cost depends on the contract type between farmers and biorefineries. This finding can assist farmers, biorefineries, and policymakers in reaching more informed decisions about contract options and designing policy instruments that either promote or discourage specific types of contracts.

Second, our analysis shows the difference between two major bioenergy crops, miscanthus and switchgrass, regarding their contract terms, land requirement, farmers' welfare change, and production cost when meeting the feedstock demand from 3 billion gallons of SAF, providing market players in the feedstock supply chain with information that can help them make crop choice decisions. Our results also highlight the role of farmers' risk and time preferences in determining the contract terms for miscanthus and switchgrass, showing that discount rate is an important factor that affects fixed price and revenue share for contracting miscanthus production due to the crop's high establishment cost and long establishment period. Therefore, technologies and policy instruments that lower the establishment costs or shorten the establishment period of bioenergy crops will play a crucial role in facilitating the development of the feedstock supply chain.

Third, our results provide supporting evidence for existing survey studies showing that bioenergy crop insurance can be an important incentivizing factor for farmers to adopt bioenergy crops. We find that the presence of free bioenergy crop insurance can reduce the contract terms by 3% for miscanthus and by 5% for switchgrass, while it has minimal impact on land use and biomass production cost. This indicates that expanding the current federal crop insurance program to cover bioenergy crops can be a meaningful way to facilitate the development of feedstock supply chain.

Despite the insights provided, this study has some limitations that can be addressed in future research. For simplicity, the present study considers each type of contract individually. However, a biorefinery may offer farmers a menu of contracts with all three types of contracts on it, and let farmers choose one contract from the menu. In this case, the optimization problems will be expanded to biorefineries choosing an optimal contract menu to maximize their expected profits, considering farmers' optimal contract choice for any given menu. For farmers, with more contract options to choose, their welfare gains are expected to be larger than when only one contract is available (Yang et al. 2016). Solving the dual optimization problems for both farmers and biorefineries presents significant computational challenges due to the curse of dimensionality and the large number of counties. Moreover, to obtain clear contrast between miscanthus and switchgrass, the study considers each bioenergy crop separately in the simulation. Future studies can overcome these limitations by developing more comprehensive simulation models. Nevertheless, this study represents an initial effort to explore feedstock supply from various bioenergy crops under different contract types, both with and without bioenergy crop insurance.

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Table 1. Summary Statistics of Data Utilized in the Simulation

Variables			Mean	S.D.	Min.	Max.
Yields [b]	miscanthus on high quality land (Mt. ha.$^{-1}$)		27.2	2.9	3.5	48.3
	miscanthus on low quality land (Mt. ha.$^{-1}$)		26.8	2.8	2.8	47.4
	switchgrass on high quality land (Mt. ha.$^{-1}$)		14.1	2.8	0.4	32.1
	switchgrass on low quality land (Mt. ha.$^{-1}$)		12.7	3.3	0.4	31.1
	corn stover on high quality land (Mt. ha.$^{-1}$)		2.6	0.6	0.01	6.9
	corn stover on low quality land (Mt. ha.$^{-1}$)		2.4	0.54	0.02	6.5
	corn grain on high quality land (Bu. ac.$^{-1}$)		139.1	39.2	0.7	304.5
	corn grain on low quality land (Bu. ac.$^{-1}$)		127.2	34	0.5	297.3
	soybean grain on high quality land (Bu. ac.$^{-1}$)		42.9	20	1	112.3
	soybean grain on low quality land (Bu. ac.$^{-1}$)		41.5	19.5	0.1	109.2
Costs [c]	miscanthus (1^{st} Year)	establishment cost ($ ha.$^{-1}$)	3,108	46.2	3,033.6	3,247.9
	miscanthus (2^{nd} to 15^{th} Year)	variable cost ($ Mt.$^{-1}$)	17.2	2	14.2	19.6
		fixed cost ($ ha.$^{-1}$)	166	29	113.1	258.7
	switchgrass (1^{st} Year)	establishment cost ($ ha.$^{-1}$)	249.4	20	223	319
		variable cost ($ Mt.$^{-1}$)[b]	17.2	2	14.2	19.6
		fixed cost ($ ha.$^{-1}$)	332.7	22.8	294	392.9
	(2^{nd} Year)	fixed cost ($ ha.$^{-1}$)	254.9	53.9	143.5	368.3
	(3^{rd} to 10^{th} Year)	fixed cost ($ ha.$^{-1}$)	251.6	40.6	169.1	354.1
	corn stover	variable cost ($ Mt.$^{-1}$)	17.5	2.1	12.6	21.7
		fixed cost ($ ha.$^{-1}$)	48.5	10.9	20.3	75
	corn	variable cost ($ bu.$^{-1}$)	1.3	0.4	0.8	2.7
		fixed cost ($ ac.$^{-1}$)	136.5	28.6	91.4	221.8
	soybean	variable cost ($ bu.$^{-1}$)	1.5	0.3	0.8	1.8
		fixed cost ($ ac.$^{-1}$)	107.4	45.4	59.4	195.9
Prices	corn	projected price ($ bu.$^{-1}$)	4.1	1.2	2.6	7.8
		harvest price ($ bu.$^{-1}$)	3.8	1.3	2.2	8.1
		received price[d] ($ bu.$^{-1}$)	4	1.3	1.9	9.1
	soybeans	projected price ($ bu.$^{-1}$)	9.5	2.9	5.4	17.2
		harvest price ($ bu.$^{-1}$)	9.3	3	5.4	19.3
		received price[d] ($ bu.$^{-1}$)	9.2	2.6	5.3	17.3
Land Per County		High quality land (Ha.)	28,841	38,228	202	252,448
		Low quality land (Ha.)	4,507	4,680	0	42,154

Note: [a]: corn grain and stover yields are under corn-soybean (C.S.) rotation. Under corn-corn rotation, yields are assumed to be 12% lower than that under C.S. rotation. [b]: For switchgrass, the variable cost is constant across lifespan. [c]: Costs and prices are in 2010 dollars; Mt. refers to metric tons of biomass with 15% moisture content. [d]: The received price is state-level annual average price while the projected price and harvest price are futures prices calculated following RMA (2024).

Table 2: Land requirement, farmers' welfare change, and biomass production cost under each contract type to meet the biomass demand from producing 3 billion gallons of SAF by growing miscanthus

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Risk aversion parameter	**0.00005**	**0.00005**	**0.00001**	**0.00001**	**0.00005**	**0.00005**	**0.00001**	**0.00001**
Discount rate	**10%**	**2%**	**10%**	**2%**	**10%**	**2%**	**10%**	**2%**
Bioenergy crop insurance	**No**	**No**	**No**	**No**	**Free**	**Free**	**Free**	**Free**
Fixed price ($/ton)	50.86	44.39	49.51	43.27	49.40	42.91	47.94	42.04
Bioenergy crop acreage (acres)	1,941,565	1,957,928	1,943,423	1,961,257	1,953,201	1,972,381	1,955,767	1,976,403
Farmers' welfare change (%)	5.80	8.78	1.18	1.67	5.49	8.27	1.09	1.66
Production cost ($/metric ton)	29.75	29.79	29.76	29.79	29.82	29.86	29.83	29.87
Revenue sharing (%)	27.90	24.10	27.07	23.52	27.22	23.36	26.36	22.84
Bioenergy crop acreage (acres)	1,940,799	1,963,312	1,955,445	1,982,231	1,959,992	1,972,775	1,964,560	1,978,462
Farmers' welfare change (%)	5.51	7.55	1.12	1.49	5.52	7.44	1.11	1.51
Production cost ($/metric ton)	29.91	29.90	29.94	29.91	29.97	29.92	29.97	29.93
Land-leasing payment ($/acre)	94.79	94.79	94.83	94.83	94.79	94.79	94.83	94.83
Bioenergy crop acreage (acres)	2,183,333	2,183,333	2,183,333	2,183,333	2,183,333	2,183,333	2,183,333	2,183,333
Farmers' welfare change (%)	3.34	5.23	0.67	1.05	3.34	5.23	0.67	1.05
Production cost ($/metric ton)	30.49	30.49	30.49	30.49	30.49	30.49	30.49	30.49

Table 3: Land requirement, farmers' welfare change, and biomass production cost under each contract type to meet the biomass demand from producing 3 billion gallons of SAF by growing switchgrass

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Risk aversion parameter	**0.00005**	**0.00005**	**0.00001**	**0.00001**	**0.00005**	**0.00005**	**0.00001**	**0.00001**
Discount rate	**10%**	**2%**	**10%**	**2%**	**10%**	**2%**	**10%**	**2%**
Bioenergy crop insurance	**No**	**No**	**No**	**No**	**Free**	**Free**	**Free**	**Free**
Fixed price ($/ton)	71.33	70.20	71.15	70.00	67.84	66.87	67.69	66.79
Bioenergy crop acreage (acres)	4,584,617	4,598,447	4,605,120	4,578,110	4,595,285	4,598,934	4,595,285	4,598,934
Farmers' welfare change (%)	6.10	8.09	1.24	1.65	6.40	8.62	1.30	1.76
Production cost ($/metric ton)	37.99	37.95	37.98	37.96	38.00	37.96	38.00	37.96
Revenue sharing (%)	35.47%	34.92%	35.29%	34.83%	33.71%	33.18%	33.59%	33.09%
Bioenergy crop acreage (acres)	4,608,576	4,608,576	4,598,430	4,608,576	4,603,482	4,614,336	4,603,774	4,614,336
Farmers' welfare change (%)	5.88	7.84	1.19	1.61	6.19	8.27	1.26	1.69
Production cost ($/metric ton)	38.05	38.05	38.06	38.05	38.03	38.00	38.02	38.00
Land-leasing payment ($/acre)	154.58	154.58	154.68	154.68	154.58	154.58	154.68	154.68
Bioenergy crop acreage (acres)	4,835,746	4,835,746	4,826,592	4,826,592	4,835,746	4,835,746	4,826,592	4,826,592
Farmers' welfare change (%)	5.18	7.03	1.05	1.42	5.18	7.03	1.05	1.42
Production cost ($/metric ton)	39.04	39.04	39.03	39.03	39.04	39.04	39.03	39.03

Table 4. Impact of free bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare changes, and average production cost to meet the biomass demand from producing 3 billion gallons of SAF

	Risk aversion parameter	0.00005	0.00005	0.00001	0.00001
	Discount rate (%)	10	2	10	2
For miscanthus					
Fixed-price contract	Fixed price	-2.87%	-3.33%	-3.17%	-2.84%
	Bioenergy crop acreage	0.60%	0.74%	0.64%	0.77%
	Farmers' welfare change	-5.39%	-5.89%	-7.83%	-0.77%
	Biomass production cost	0.22%	0.23%	0.22%	0.25%
Revenue-sharing contract	Revenue share to farmers	-2.44%	-3.07%	-2.62%	-2.89%
	Bioenergy crop acreage	0.99%	0.48%	0.47%	-0.19%
	Farmers' welfare change	0.23%	-1.48%	-0.78%	1.48%
	Biomass production cost	0.20%	0.06%	0.11%	0.09%
For switchgrass					
Fixed-price contract	Fixed price	-4.89%	-4.74%	-4.86%	-4.59%
	Bioenergy crop acreage	0.23%	0.01%	-0.21%	0.45%
	Farmers' welfare change	5.01%	6.57%	5.24%	6.58%
	Biomass production cost	0.03%	0.02%	0.07%	0.01%
Revenue-sharing contract	Revenue share to farmers	-4.96%	-4.98%	-4.82%	-5.00%
	Bioenergy crop acreage	-0.11%	0.12%	0.12%	0.12%
	Farmers' welfare change	5.38%	5.47%	5.62%	4.92%
	Biomass production cost	-0.07%	-0.15%	-0.10%	-0.15%

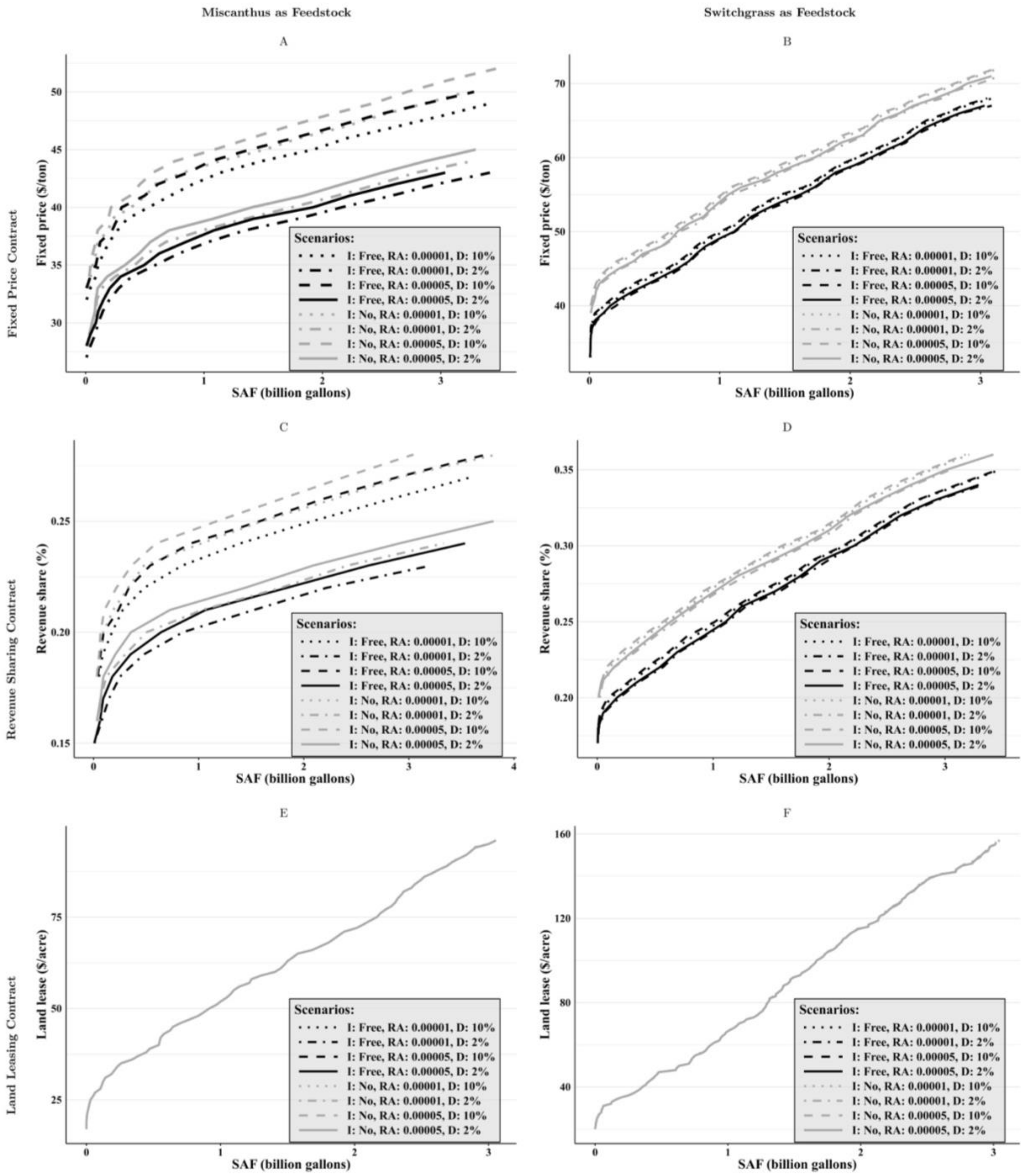

Figure 1. SAF production quantity and the contract terms required to induce sufficient biomass production

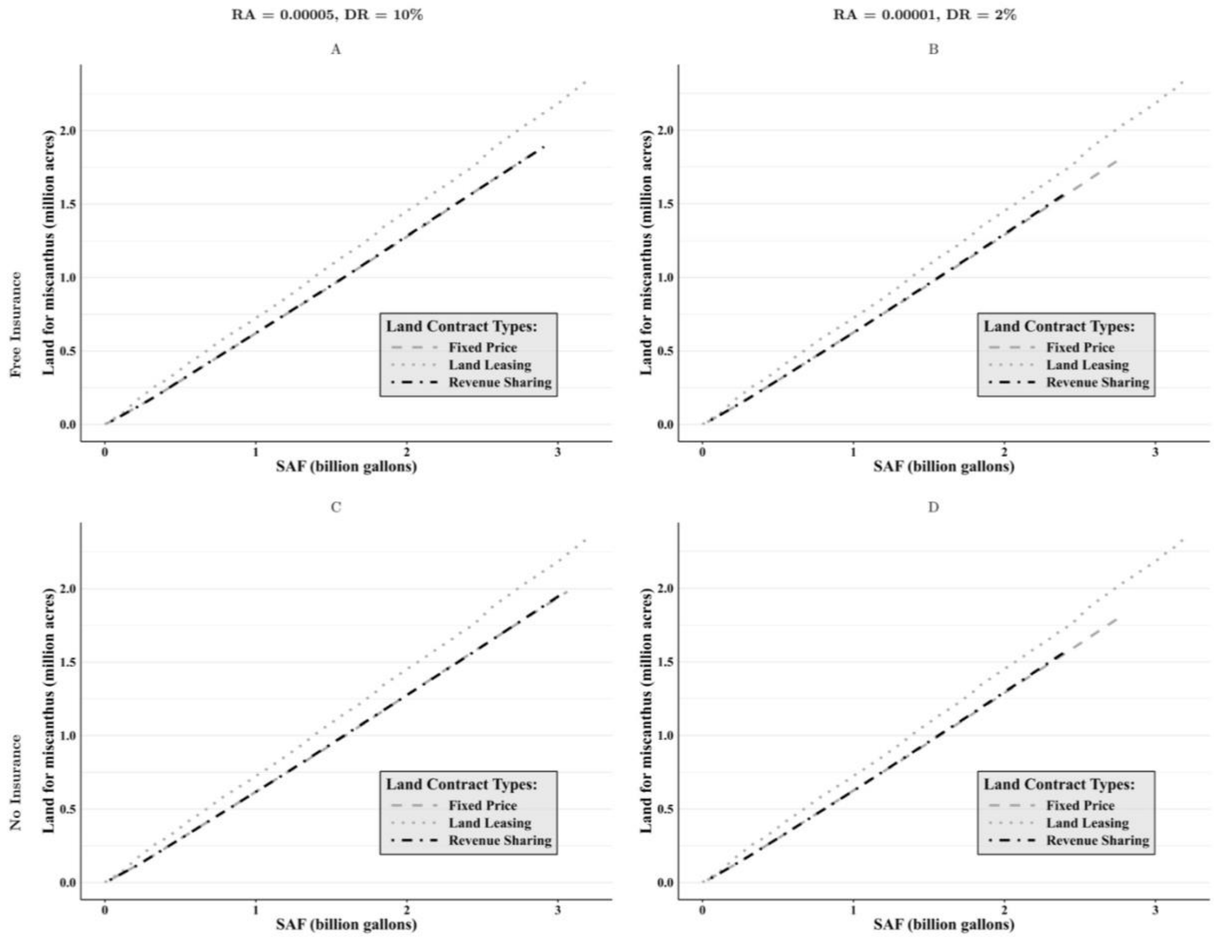

Figure 2. Land requirement under the three contract types for a given SAF production when miscanthus is used as feedstock

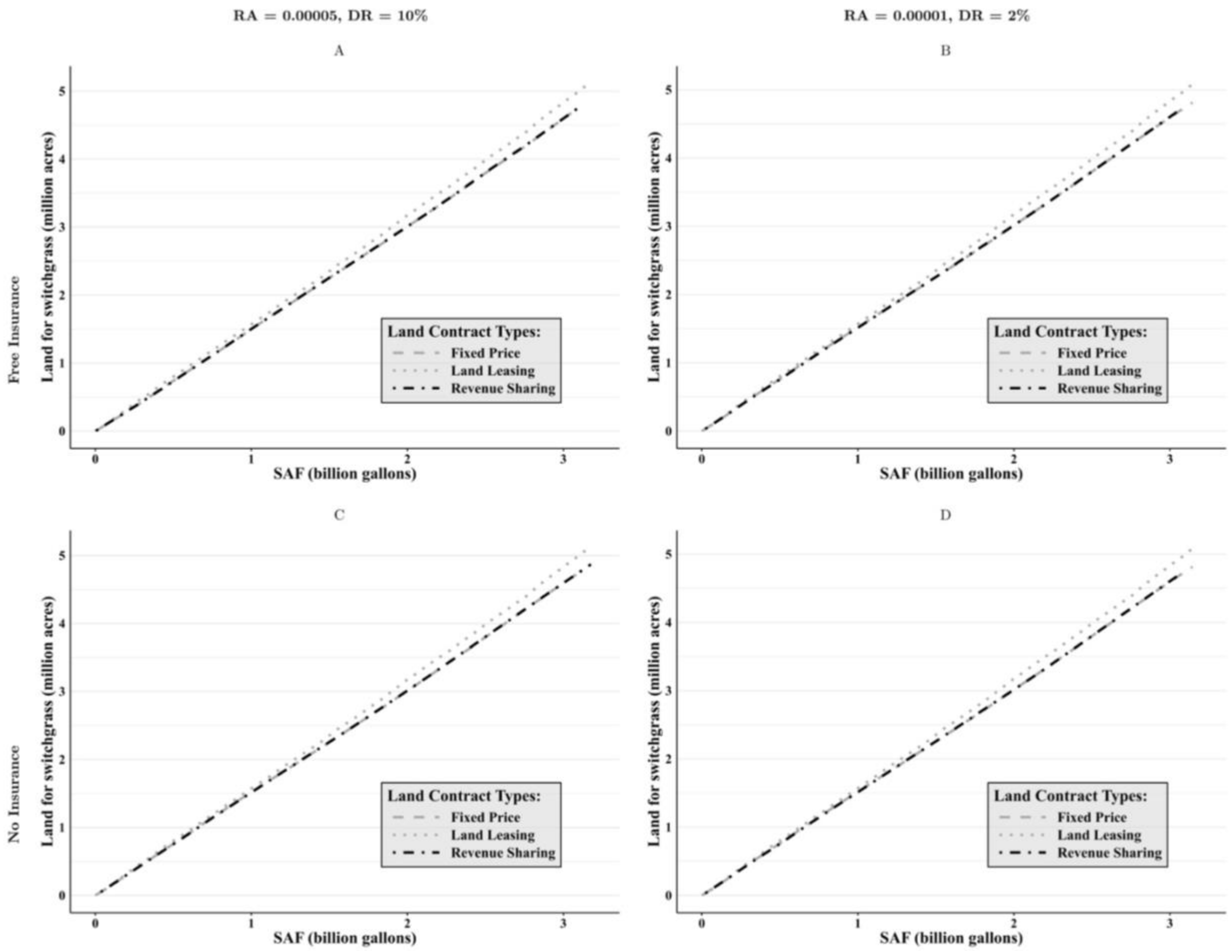

Figure 3. Land requirement under the three contract types for a given SAF production when switchgrass is used as feedstock

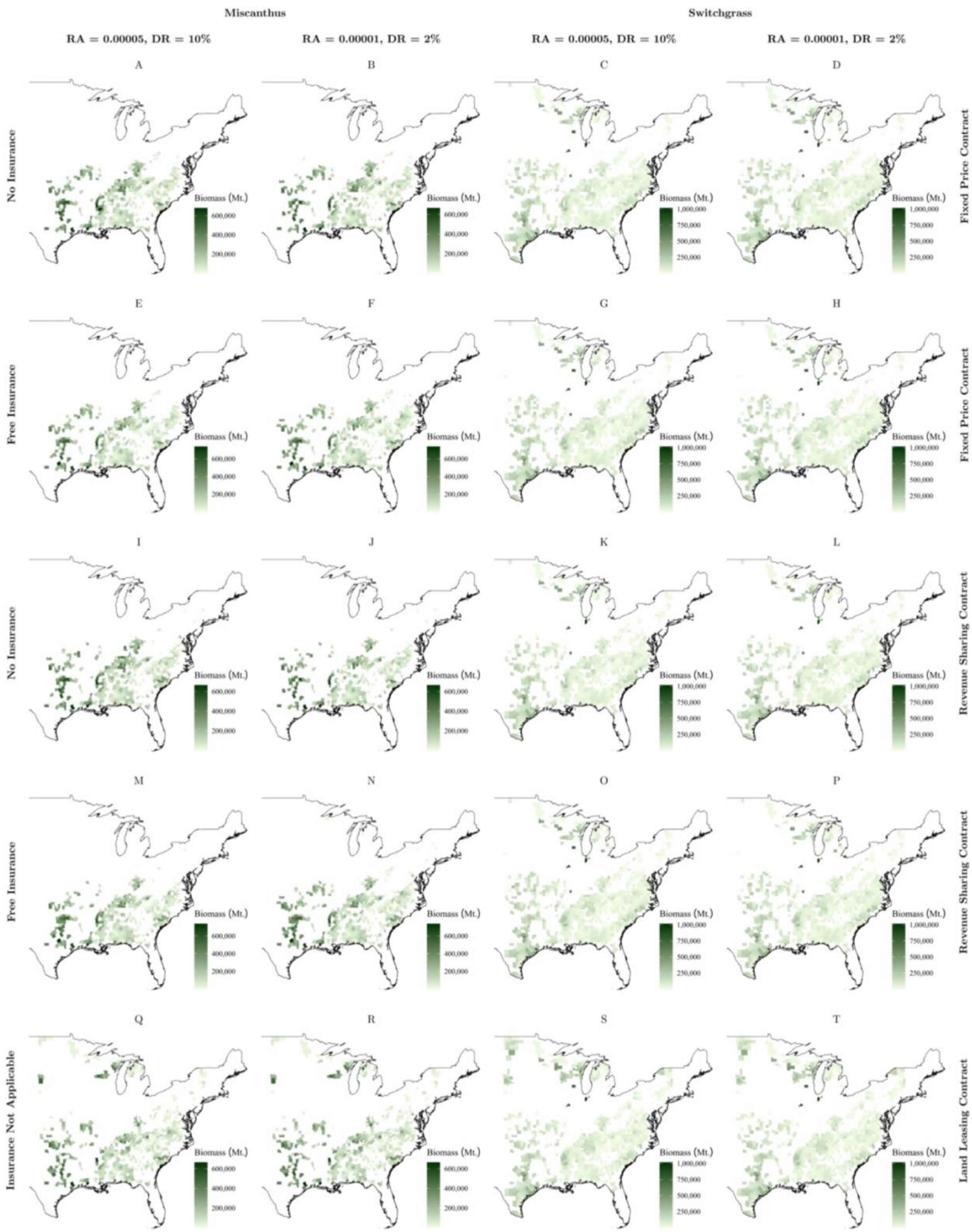

Figure 4. County-level biomass production under different contract types and farmers' risk and time preferences

Notes: The first two columns of maps are for miscanthus, and the last two columns are for switchgrass. The first two rows of maps are under fixed-price contract, the third and fourth rows are for revenue-sharing contract, and the last row is for land-leasing contract. The first and third rows are in the absence of bioenergy crop insurance. The second and fourth rows are in the presence of bioenergy crop insurance. For the last row, bioenergy crop insurance is irrelevant.