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

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ABSTRACT

This study examines how contracts and bioenergy crop yield insurance incentivize biomass supply for three billion gallons of sustainable aviation fuel. Results show that meeting feedstock demand by growing uninsured miscanthus requires a fixed biomass price at $78–$86/metric ton, a revenue share of 32%–36%, or a land-leasing payment about $178/acre. Growing uninsured switchgrass requires similar terms. Bioenergy crop insurance partially substitutes for compensation for bearing production risk, decreasing required fixed prices and revenue shares by 4% (6%) for miscanthus (switchgrass), while having minimal impact on bioenergy crop acreage and average biomass production cost, but mixed effects on farmers' welfare gains.

The US 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 (DOE), U.S. Department of Transportation (DOT), and U.S. 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). 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 using corn and soybean-based biofuel requires a large amount of cropland, or significant increase in crop yields, or both. Corn and soybean production on this scale creates food-fuel competition and substantial uncertainty in greenhouse gas emission reduction (Swanson and Smith 2024). High-yielding bioenergy crops, such as miscanthus and switchgrass, are promising biofuel feedstock that can mitigate the food-fuel competition and achieve significant greenhouse gas emission reduction (Langholtz et al. 2016; USDOE 2024).

However, the commercial production of these perennial bioenergy crops has not commenced yet due to high risk associated with crop production, large upfront establishment cost, lack of market and supply chain, and delayed returns (Jensen et al. 2007; Miao and Khanna 2014, 2017a, 2017b; Witzel and Finger 2016; Zahraee et al. 2020; Clifton-Brown et al. 2023). Thus, to induce the production of these bioenergy crops and to form the biomass supply chain, long-term contracts between farmers and biorefineries are likely to be necessary (Alexander et al. 2012; Krah et al. 2018; McCarty and Sesmero 2021; Yang et al. 2016). This is because contracts can offer effective mechanisms to manage production and marketing risks for bioenergy crop producers and to ensure stable feedstock supply for

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biorefineries.[1] Furthermore, 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; Burli et al. 2019). This is likely because crop insurance has become a widely used tool to manage production and price risks among US farmers (ERS 2025). Nevertheless, few existing studies have examined the incentivizing impacts of alternative contracts and bioenergy crop insurance on supplying biomass feedstock for a given SAF production target. The present study aims to fill this research gap by (1) exploring the required contract terms of three types of stylized contracts to induce sufficient feedstock production for the three billion gallons of SAF under a farmer's utility maximization framework; (2) examining the impact of bioenergy crop insurance on these required contract terms; and (3) comparing land-use change, farmers' welfare gains, and average biomass production cost under these contracts with and without bioenergy crop insurance.

Specifically, following Yang et al. (2016), three types of contracts that differ in how risk is allocated between farmers and biorefineries are considered. The first is a fixed-price contract under which the farmers are obligated to deliver a specified amount of biomass to the biorefineries at a predetermined price. Under this contract, farmers are fully exposed to biomass yield risk but are shielded from price risk. The second type of contract is a revenue-sharing contract, under which farmers commit to deliver a specified amount of biomass in exchange for a portion of revenue from selling products derived from the delivered biomass. Under this contract, farmers are exposed to both yield risk and price risk. The third is a land-leasing contract, where farmers lease their land to biorefineries at a fixed annual rental rate, and biorefineries undertake the establishment and management of the biomass production. Under this type of contract, farmers do not bear any yield or price risks.[2]

A farmer's expected utility maximization model is developed and calibrated to examine the contract terms (i.e., biomass price under the fixed-price contract, portion of the revenue under the revenue-sharing contract, and the land rental rate under the land-leasing contract) required to induce sufficient biomass production for three billion gallons of SAF in the United States under each type of contract. Within the model, farmers choose whether to switch to growing a specific bioenergy crop (miscanthus and switchgrass in this study) from conventional crops (corn and soybeans in this study) for a given contract type and contract term. Various assumptions of farmers' risk and time preferences are employed to investigate how these required contract terms would change in these preferences. Moreover, the contract terms with and without the presence of bioenergy crop yield insurance are examined to explore the impact of insurance for bioenergy crops. We focus on yield insurance because farmers bear yield risk under both the fixed-price and revenue-sharing contracts, providing a consistent basis for comparison, whereas their exposure to price risk varies substantially across the three contract types considered in the study. Since under a land-leasing contract farmers receive a fixed rental payment and bear neither yield nor price risk, bioenergy crop insurance is irrelevant to them. However, for a fixed-price and a revenue-sharing contract, the bioenergy crop yield insurance is expected to reduce biomass production risk and thus reduce the contract term required to trigger a switch from conventional crops to bioenergy crops. The study also examines bioenergy crop acreage, farmers' welfare gains when compared with growing conventional crops that are protected by crop insurance, and average biomass production costs under each type of contract meeting the SAF production goal of three billion gallons. Therefore, the study compares these three types of contracts in terms of land-use change, farmers' welfare, and production costs under various scenarios.

Based on the farmer's expected utility maximization model described above, numerical simulation is conducted using the county-level yield data for miscanthus, switchgrass, and conventional crops generated by the DayCent model, a biogeochemical model that is widely used to simulate plant growth, as well as the production cost data of these crops obtained from Majeed et al. (2026). The simulation focuses on rainfed counties because miscanthus and switchgrass are generally expected to be most economically viable and environmentally sustainable in regions where they can be grown without irrigation. Agronomic evidence also indicates that miscanthus requires relatively high precipitation and is not well suited to arid environments (Farm Energy 2019). As a result, existing studies of bioenergy crop supply often model their production potential across the rainfed United States (e.g., Anand et al. 2019; Miao and Khanna 2017a, 2017b; Zhang et al. 2023).

The numerical simulation is conducted separately for miscanthus and switchgrass. That is, the simulation assumes that the feedstock for the three billion gallons of SAF is from either miscanthus or switchgrass but not from a mix of the two. Results indicate that meeting the feedstock demand requires different contract terms for the two crops. For miscanthus, fixed-price, revenue-sharing, and land-leasing contracts involve terms at about \$74–\$86 per metric ton, 31%–36% revenue share, and \$178/acre, respectively, depending on farmers' risk and time preferences as well as the availability of bioenergy crop yield insurance. For switchgrass, these figures are \$76–\$83 per metric ton, 31%–34% revenue share, and \$191/acre. 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 2.47–3.4 million acres, while switchgrass would need 3.6–3.8 million acres to supply sufficient feedstock for three billion gallons of SAF, depending on farmers' risk and time preferences, as well as the presence or absence of bioenergy crop yield insurance. Bioenergy crop yield insurance can decrease fixed price by \$3.5 per metric ton and revenue share by 1.6 percentage points (about 4% decrease for both terms) for miscanthus. For switchgrass, the corresponding reductions are about \$4.7 to \$4.9 per metric ton and 2 percentage points (about 6% decrease for both terms). Finally, the results show that the bioenergy crop yield insurance has mixed effects on farmers' welfare gains switching from conventional crops to bioenergy crops as well as minimal impact on bioenergy crop land intensity and average biomass production cost.

The present 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

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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. Yao et al. (2017) conduct stochastic techno-economic analysis on SAF production via the alcohol-to-jet pathway using sugarcane, corn grain, and switchgrass as potential feedstock. 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 the optimal feedstock production accounting for extreme weather events. Majeed et al. (2026) 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, 2017a, 2017b; Khanna, Zilberman, and Miao 2017; Anand et al. 2019; McCarty and Sesmero 2021; Majeed et al. 2023, 2026). 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, and by investigating the role of bioenergy crop insurance in incentivizing biomass production.

Another line of studies focuses on contracts between farmers and biorefineries, either theoretically exploring the optimal contract designs (e.g., Alexander et al. 2012; 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, Louviere, and Yang 2017; 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 without considering spatial heterogeneity in growing conditions, 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 1923 US 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.

1 | Conceptual Framework

This section formalizes 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 predetermined 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. 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.

The 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. Then the county-level bioenergy crop production is aggregated across the rain-fed counties covered in the 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, an aggregate biomass supply curve is obtained with respect to the contract term by varying the contract term over a wide range of values, so that one 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. It

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is further assumed that the SAF price is random, but its distribution is known to both biorefineries and farmers. Following Yang et al. (2016) and for simplicity, biorefineries are assumed to be in the proximity of biomass production fields, and thus the transportation cost of biomass from farm gates to biorefineries is negligible.[3]

To examine the impact of insurance for bioenergy crops on the contract terms needed to reach three billion gallons of SAF production, the study compares scenarios under which bioenergy crop insurance is unavailable with scenarios under which bioenergy crop insurance is available to farmers. Under the latter scenario, the coverage level and premium subsidy rate of bioenergy crop insurance are assumed to be the same as that of row crop insurance. For simplicity, we do not allow farmers to choose from a menu of options for insurance (e.g., various insurance types and coverage levels). That is, we do not model insurance demand in the present study. The detailed decision-making problem for a farmer is presented as follows:

1.1 | 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 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

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

where ρ is the insurance premium subsidy rate and $E(\cdot)$ is the expectation operator. Here a revenue insurance policy for the conventional crops is considered as it is widely adopted by US farmers (Schnitkey et al. 2020). The indemnity payment per acre of land in year t for a conventional crop is specified as

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

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 US Department of Agriculture (USDA) to determine the indemnity payment.

1.2 | A Farmer's Profits From Bioenergy Crop Production Under Each Contract Type

1.2.1 | Fixed-Price Contract

Let P^b and Y^b denote biomass price and quantity specified in the fixed-price contract. Following Yang et al. (2016), the quantity is assumed to be on a per-acre basis at the farmer's mean yield of a bioenergy crop.[4] 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

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

where $1\left\{y_t^b > Y^b\right\}$ 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 (τ years), during which establishment cost is incurred 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 under the fixed-price contract can be written as,

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

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 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 yield insurance is considered for the bioenergy crops. This is because under the fixed-price contract and revenue-sharing contract, the revenue of a bioenergy crop will be mainly determined by the contracts while the yield risk is borne by the farmers.[5] For the land-leasing contract under which farmers do not bear any yield or price risk, crop insurance is irrelevant. The indemnity payment can be written as,

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

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

$$\pi_t^{b,\text{FP,Insu}} = \begin{cases} R_t^b - v_t^b y_t^b - f_t^b - K_t^b - (1-\rho)E\left(\iota_t^b\right) + \iota_t^b & \text{if } t \le \tau \\ R_t^b - v_t^b y_t^b - f_t^b - (1-\rho)E\left(\iota_t^b\right) + \iota_t^b & \text{if } t \in \{\tau+1, \tau+2, \ldots, T\} \end{cases}. \tag{6}$$

Here the insurance premium subsidy rate is assumed to be equal to that of the row crops.

1.2.2 | Revenue-Sharing Contract

Under a revenue-sharing contract, the revenue of selling the final product (i.e., SAF) derived from the biomass delivered 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

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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. The revenue per acre from producing a bioenergy crop under a revenue-sharing contract in year t can be written as

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

where Y^b is the contract quantity and 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 $1\{y_t^b > Y^b\} \cdot (y_t^b - Y^b)(p^b - d) + (1 - 1\{y_t^b > Y^b\}) \cdot (y^b - Y^b)(p^b + d)$.

Similar to Equation (3), in the absence of bioenergy crop insurance, the profit per acre in year t from growing a bioenergy crop is

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

With bioenergy crop insurance, the profit becomes

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

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

1.2.3 | 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.

1.3 | 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., M 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 a higher level of expected utility. The farmer is assumed to have 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,

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

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

2 | Simulation Framework and Model Calibration

The simulation assumes that a county is 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). It covers 1923 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 conservation tillage, specifically a no-till management.[6] For counties with historical yield data for both corn and soybeans, it is assumed that corn production is under a corn-soybean rotation. For counties without data for soybean yield, it is assumed that corn production is under a corn-corn rotation. It is also assumed that if profitable, the farmer will harvest 50% 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 80%. These two values are chosen because 75% has historically been one of the most popular coverage levels that farmers choose for conventional crops (Biram et al. 2022) and 80% is the corresponding subsidy rate at the 75% coverage level for enterprise units (Risk Management Agency (RMA) 2025).[7] We do not consider insurance for corn stover production.

The simulation is conducted for the three types of contracts separately. Under each type of contract, the representative farmer's decisions on crop choice in each county are simulated 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 \$0.01 per metric ton. Crop choice decisions of the representative farmer in each county under each of the fixed prices are recorded. Then the bioenergy crop acreage, biomass production, and production cost are aggregated across all counties under a fixed price to obtain the total bioenergy crop acreage, total biomass production, and average production cost 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. Farmers' welfare gains from switching to bioenergy crop production are calculated as well. Similar procedures are used for revenue-sharing contracts and land-leasing contracts. The results will allow us to compare the incentivizing impact of the three types of contracts on bioenergy crop production. Specifically, the study focuses on the total land acreage required to produce three billion gallons of SAF, the associated farmer welfare gains, and associated biomass production cost under each type of contract.

To explore the impact of farmer's risk preference on bioenergy crop production under each type of contract, the risk aversion parameter is set to be equal to 0.00001 (indicating low risk aversion) or 0.00005 (indicating high risk aversion) by following Miao and Khanna (2017a, 2017b), Anand et al. (2019), and Majeed et al. (2023). When translated into risk premium (i.e., the decision maker's willingness to pay, measured in the percentage of the standard deviation of net returns, to eliminate the risk of net returns), 0.00001 and 0.00005 imply underlying risk premiums of 10% and 50%, respectively, for a CARA utility function (Hennessy et al. 1997). Moreover, to examine the impact of

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farmer's time preference, the discount rate is assumed to be 12% (indicating a lower discount rate) or 17% (indicating a higher discount rate) by following Trejo-Pech et al. (2021). Together with the scenarios with and without bioenergy crop insurance, eight scenarios are considered for each type of contracts, consisting of the eight permutations of two risk aversion levels, two discount rates, and two insurance availability cases. It is assumed that farmers are not credit-constrained to establish bioenergy crop production.

The two bioenergy crops (i.e., miscanthus and switchgrass) are examined individually. They are both promising candidates for biomass production but have quite different characteristics. Miscanthus needs 1 year or more to be established and can be harvested in the second year and after, whereas switchgrass can be harvested even in the first year of establishment at a portion (50% in this study) of its mature yield and reach its mature yield in its second year. Miscanthus requires much higher establishment cost but produces a higher yield than does switchgrass (see Table 1). They also have different lifespans: 15 years and 10 years respectively for miscanthus and switchgrass (Chen et al. 2014).[8] Finally, their yield risks differ, and miscanthus has higher yield standard deviation (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.

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). Low-quality land is assumed to be 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. The simulation limits land that can be converted to energy crops to a maximum 25% of total low- and high-quality land in a county following Chen et al. (2014) and Khanna, Zilberman, and Miao (2017).[9] The average acreage of high and low-quality land per county is 32,222 ha and 4572 ha, respectively (Table 1). The remaining part of this section describes the data and model parameters used in the simulation.

2.1 | Crop Yields

The county-level yield data for high- and low-quality land for miscanthus and switchgrass are simulated by DayCent model and are provided by Majeed et al. (2026).[10] 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). The simulated annual yields of miscanthus and switchgrass for each selected county are based on historical weather data between 1987 and 2016. The average yields of miscanthus on high- and low-quality land are 21.0 and 18.8 metric tons (MT) per hectare (ha.) at 13% moisture. For switchgrass, the average yields on the high- and low-quality land are 16.3 and 15.0 MT/ha., 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 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 yields, high- and low-quality land are 131.9 bushels (bu.) per acre and 111.0 bu. per acre, respectively. For soybeans, the corresponding yield levels are 47.8 and 41.4 bu. per acre, respectively. On average, corn grain yield on low-quality land is about 15.8% lower than that on high-quality land, and the soybean yield on low-quality land is about 13.4% lower than that on high-quality land.

2.2 | Crop Prices

State-level received prices from NASS are used to calculate realized profits 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 the RMA (2024) rules based on Chicago Board of Trade (CBOT) futures prices. The CBOT futures prices of corn and soybeans over 1987–2016 are obtained from Barchart.com. These prices have been converted to 2025 dollars using the Gross Domestic Product (GDP) Implicit Price 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.

2.3 | Riskiness of Crop and SAF Production and Marketing

To represent crop yield risk, corn and soybean price risk, and SAF price risk, a joint yield-price distribution for each county is estimated for up to eight yields and three prices by using a copula approach.[11] 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. Ethanol price is used because SAF is still in its infancy, and long enough time series of data for SAF are unavailable 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 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 and are converted to 2025 dollars using the GDP Implicit Price Deflator.

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TABLE 1 | Summary statistics of data utilized in the simulation.

Variables			Mean	S.D.	Min.	Max.
Yields	Miscanthus on high quality land (Mt. ha.$^{-1}$)		21.0	1.5	0.2	37.0
	Miscanthus on low quality land (Mt. ha.$^{-1}$)		18.8	2.4	0.01	37.7
	Switchgrass on high quality land (Mt. ha.$^{-1}$)		16.3	1.2	0.05	25.2
	Switchgrass on low quality land (Mt. ha.$^{-1}$)		15.0	1.5	0.003	26.0
	Corn stover on high quality land (Mt. ha.$^{-1}$)		3.7	0.7	1.3	7.4
	Corn stover on low quality land (Mt. ha.$^{-1}$)		3.0	0.8	0.3	9.1
	Corn grain on high quality land (Bu. ac.$^{-1}$)		131.9	25.3	38.3	214.0
	Corn grain on low quality land (Bu. ac.$^{-1}$)		111.0	26.9	4.4	227.5
	Soybean grain on high quality land (Bu. ac.$^{-1}$)		47.8	9.1	8.5	126.3
	Soybean grain on low quality land (Bu. ac.$^{-1}$)		41.4	10.5	0.1	114.5
Costs	Miscanthus (1st year)	Establishment cost ($ ha.-1)	2891.86	8.24	2865.83	2911.81
	Miscanthus (2nd to 15th year)	Variable cost ($ Mt.-1)	29.65	0.00	29.65	29.65
		Fixed cost ($ ha.-1)	155.18	8.63	113.27	196.60
	Switchgrass	Establishment cost ($ ha.-1)	765.18	11.49	729.87	793.44
	(1st year)	Variable cost ($ Mt.-1)	26.95	0.00	26.95	26.95
	Switchgrass (2nd to 10th year)	Variable cost ($ Mt.-1) fixed cost ($ ha.-1)	29.65 280.64	0 23.05	29.65 233.19	29.65 308.05
	Corn stover	Variable cost ($ Mt.-1)	46.45	0.7	45.46	47.36
		Fixed cost ($ ha.-1)	91.39	9.92	70.61	107.14
	Corn	Variable cost ($ bu.-1)	1.97	0.31	1.33	2.57
		Fixed cost ($ ac.-1)	166.6	31.3	83.99	244.18
	Soybean	Variable cost ($ bu.-1)	4.17	1.41	2.45	7.26
		Fixed cost ($ ac.-1)	143.6	24.6	89.99	204.79
Prices	Corn	Projected price ($ bu.$^{-1}$)	5.2	1.7	3.3	10.6
		Harvest price ($ bu.$^{-1}$)	4.9	1.6	2.9	9.5
	Soybeans	Projected price ($ bu.$^{-1}$)	12.7	3.3	7.8	22.2
		Harvest price ($ bu.$^{-1}$)	12.3	3.0	7.4	19.7
	Ethanol	$ gal.$^{-1}$	2.7	0.6	1.8	4.0
Land per county		High quality land (Ha.)	32,222	40,019	202	252,448
		Low quality land (Ha.)	4572	4927	0	42,154

Note: Corn grain and stover yields are under corn-soybean rotation. Under corn-corn rotation, yields are assumed to be 12% lower than that under the corn-soybean rotation. Costs and prices are in 2025 dollars. Mt. refers to metric tons of biomass with 13% moisture content. The received price is state-level annual average price while the projected price and harvest price are futures prices calculated following Risk Management Agency (RMA) (2024).

2.4 | Costs and Revenue

The state-level production costs of both conventional crops and bioenergy crops are obtained from Majeed et al. (2023, 2026), all converted to 2025 dollars by using the GDP Implicit Price Deflator. The descriptive statistics of the costs are summarized in Table 1, from which one can see that the establishment cost of miscanthus ($2891.86/ha.) nearly quadruples that of switchgrass ($765.18/ha.).

Based on Fan et al. (2024), one metric ton of dry miscanthus biomass can produce 97.77 gal of cellulosic ethanol, whereas the same amount of switchgrass can produce 92.51 gal.[12] Further, one gallon of ethanol can produce 0.58 gal 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 the biorefineries' equilibrium profit is assumed to be 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

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input (ethanol price times 1/0.58) and the ATJ-SPK pathway conversion cost ($0.86). The revenue from selling cogenerated electricity is included when converting biomass to cellulosic ethanol. According to Fan et al. (2024), producing one gallon of cellulosic ethanol from miscanthus (switchgrass) generates $0.1 ($0.3) worth of electricity.

The location of the spot market is assumed to be 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.

3 | Results

The simulation results include total biomass supply, land-use intensity for bioenergy crops, and farmers' welfare gains 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, the analysis sheds 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. We are particularly interested in examining these impacts at the biomass production level that meets the feedstock demand from three billion gallons of SAF.

3.1 | SAF Feedstock Supply and Contract Terms

Figure 1 depicts the relationship between SAF production quantity (horizontal axes) and the contract term (vertical axes) that is required to induce sufficient biomass production from miscanthus or switchgrass for a given SAF production level. 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 about $50 per metric ton (see Graph A in Figure 1) or when the revenue-sharing contract offers a revenue share to farmers at 20% or higher (Graph C in Figure 1). Under a land-leasing contract, miscanthus production commences when the rental payment is about $15/acre. Switchgrass production requires similar contract terms to start when compared with miscanthus production (see graphs in the right column of Figure 1).

From Graphs A–D in Figure 1 one 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 = 17%), the contract terms under fixed-price contracts and revenue-sharing contracts are the highest among the eight scenarios, indicated by the gray dotted 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. For the same reason, it is unsurprising that among all eight scenarios, the contract terms in the fixed-price contracts and the revenue-sharing contracts are the lowest when farmers have low risk aversion (i.e., RA = 0.00001), low discount rate (i.e., DR = 2%), and bioenergy crop insurance (see the black solid lines in Graphs A–D).

Because growing miscanthus requires a large upfront establishment cost (see Table 1), the contract terms under the fixed-price contracts and the revenue-sharing contract for miscanthus are quite sensitive to discount rate. 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 changes from low to high (i.e., increases from 0.00001 to 0.00005), then the SAF-contract term curves tilt upward only slightly (e.g., the gray dashed line vs. the gray dotted line in Graph A or C). However, when farmers' risk aversion remains constant, but discount rate increases from low to high (i.e., from 12% to 17%), then the curves tilt upward significantly (e.g., the gray dot-dashed line vs. the gray dotted line in Graph A or C). In contrast, for switchgrass, due to its low establishment cost, the contract terms are less sensitive to the changes in the discount rate (see Graphs B and D in Figure 1). Moreover, by comparing graph A with B, and C with D, one can see that the contract terms for switchgrass are less sensitive to the change in risk aversion than do the contract terms for miscanthus. This is likely because that switchgrass yield is less variable than miscanthus yield (see Table 1).

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 preference has negligible impact on the choice between conventional crops and land leasing. Examining more specifically the relationship between SAF feedstock supply and contract terms when the SAF production level is at three billion gallons using miscanthus as feedstock, one can see that when the discount rate is high (i.e., 17%), decreasing the risk aversion parameter from 0.00005 to 0.00001 only increases the rental payment required by $0.22 (see Scenarios 1 and 3 in the lowest panel of Table 2). Note that it is an increase instead of a 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.

Tables 2 and 3 present the minimum contract terms required to induce sufficient biomass production from miscanthus and switchgrass respectively for three billion gallons of SAF. Each table include results under all eight scenarios. Table 2 shows that, to produce sufficient biomass for three billion gallons of SAF, growing miscanthus would require a fixed price ranging from $74.05 to $85.9/MT, depending on farmers risk and time preferences as well as the availability of bioenergy crop insurance. To put these numbers into perspective, the USDOE's 2016 and 2023 Billion-Ton Reports evaluate energy-crop production under mature-market conditions using reference biomass prices at $76.5/MT and $74.2/MT, respectively (Langholtz

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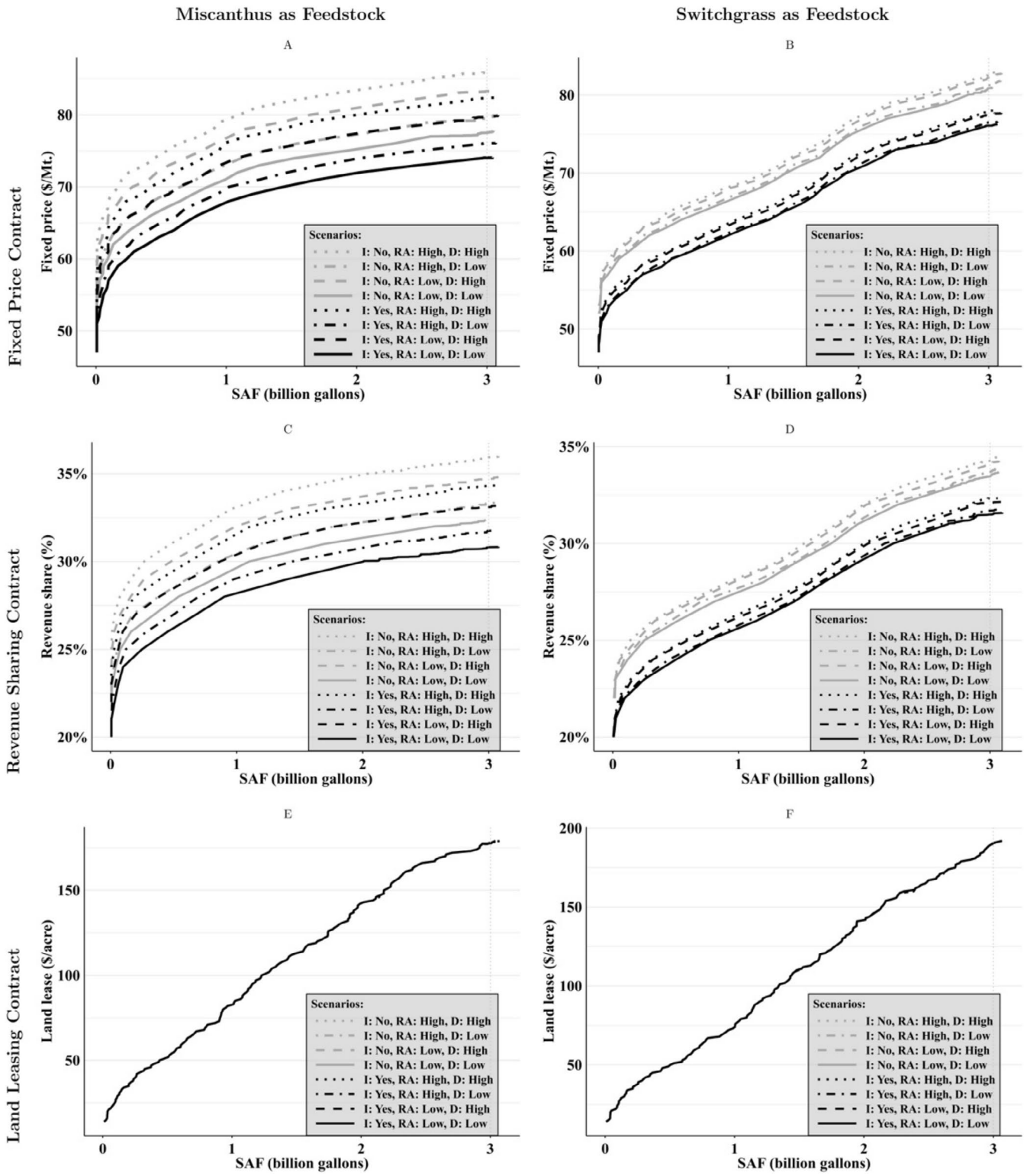

FIGURE 1 | Contract terms required to induce sufficient biomass feedstock for a specific quantity of SAF production. Note: For the legends in the figure, "I" indicates bioenergy crop insurance, "RA" indicates risk aversion, and "D" indicates discount rate. "No" indicates that bioenergy crop insurance is not available, where "Yes" indicates that it is available. High and low risk aversion parameters are 0.00005 and 0.00001, respectively; and high and low discount rates are 17% and 12%, respectively.

et al. 2016; USDOE 2024), which are close to the fixed price range identified in the present study.[13] For additional context, the national average hay price in 2025 was approximately $175.3/MT (NASS 2026). The biomass prices identified in the present study are slightly lower than half of this average hay price. For growing switchgrass, this fixed price range is $76–$82/MT (see the top panel in Table 3). By comparing the fixed prices between Tables 2 and 3, it is clear that whenever the

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TABLE 2 | Contract terms required to induce adequate biomass production from miscanthus for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Risk aversion	**High**	**High**	**Low**	**Low**	**High**	**High**	**Low**	**Low**
Discount rate	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**
Bioenergy crop insurance	**No**	**No**	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**
Fixed price ($/MT)	85.90	79.52	83.27	77.51	82.32	76.05	79.71	74.05
Bio. crop acreage (acres)	2,482,374	2,508,782	2,481,742	2,500,028	2,492,633	2,465,579	2,475,175	2,467,794
Welfare gains (%)	3.49	4.19	0.71	0.86	3.49	4.36	0.72	0.89
Production cost ($/MT)	44.47	44.57	44.48	44.58	44.42	44.49	44.42	44.51
Revenue sharing (%)	35.93	33.32	34.71	32.38	34.30	31.73	33.10	30.81
Bio. crop acreage (acres)	2,466,182	2,489,544	2,513,762	2,486,054	2,473,857	2,485,344	2,478,888	2,489,754
Welfare gains (%)	3.64	4.49	0.72	0.91	3.48	4.37	0.70	0.89
Production cost ($/MT)	44.49	44.59	44.48	44.59	44.38	44.52	44.36	44.51
Land leasing ($/Acre)	177.57	177.57	177.79	177.79	177.57	177.57	177.79	177.79
Bio. crop acreage (acres)	3,403,835	3,403,835	3,403,835	3,403,835	3,403,835	3,403,835	3,403,835	3,403,835
Welfare gains (%)	5.76	7.05	1.17	1.43	5.76	7.05	1.17	1.43
Production cost ($/MT)	49.79	49.79	49.79	49.79	49.79	49.79	49.79	49.79

Note: High risk aversion indicates a risk aversion parameter at 0.00005, and low risk aversion indicates 0.00001. High and low discount rates are 17% and 12%, respectively. Bioenergy crop insurance is yield insurance with a 75% coverage level and an 80% premium subsidy rate.

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TABLE 3 | Contract terms required to induce adequate biomass production from switchgrass for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Risk aversion	**High**	**High**	**Low**	**Low**	**High**	**High**	**Low**	**Low**
Discount rate	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**
Bioenergy crop insurance	**No**	**No**	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**
Fixed price ($/MT)	82.65	81.24	82.24	80.89	77.99	76.45	77.50	76.00
Bio. crop acreage (acres)	3,621,021	3,616,259	3,619,144	3,619,144	3,608,670	3,605,784	3,592,330	3,588,953
Welfare gains (%)	4.56	5.35	0.93	1.09	4.59	5.31	0.92	1.07
Production cost ($/MT)	46.74	46.74	46.74	46.74	46.70	46.70	46.69	46.69
Revenue sharing (%)	34.27	33.69	34.06	33.46	32.32	31.67	32.10	31.49
Bio. crop acreage (acres)	3,628,027	3,628,027	3,611,512	3,617,285	3,597,706	3,598,191	3,611,600	3,601,997
Welfare gains (%)	4.54	5.32	0.92	1.07	4.57	5.26	0.91	1.06
Production cost ($/MT)	46.74	46.74	46.72	46.74	46.72	46.72	46.70	46.70
Land leasing ($/Acre)	190.45	190.45	190.50	190.50	190.45	190.45	190.50	190.50
Bio. crop acreage (acres)	3,788,050	3,788,050	3,788,050	3,788,050	3,788,050	3,788,050	3,788,050	3,788,050
Welfare gains (%)	5.52	6.40	1.12	1.30	5.52	6.40	1.12	1.30
Production cost ($/MT)	47.46	47.46	47.46	47.46	47.46	47.46	47.46	47.46

Note: High risk aversion indicates a risk aversion parameter at 0.00005, and low risk aversion indicates 0.00001. High and low discount rates are 17% and 12%, respectively. Bioenergy crop insurance is yield insurance with a 75% coverage level and an 80% premium subsidy rate.

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discount rate is high (i.e., 17%), then producing sufficient biomass by growing miscanthus would require higher fixed price than by growing switchgrass. Whenever the discount rate is low (i.e., 12%), however, the opposite is true. Intuitively, this is because the establishment cost of miscanthus is nearly four times as large as that of switchgrass, when farmers are more present-biased (i.e., with higher discount rate), then they will require higher fixed price to compensate the delay in returns. If revenue-sharing contracts were to be chosen, then growing miscanthus would require 30.81%–35.93% of revenue share (see the middle panel in Table 2), while growing switchgrass would require 31.49%–34.27% of revenue share (see the middle panel in Table 3). Similar to the pattern under fixed-price contracts, it is generally the case that growing miscanthus requires larger revenue share than growing switchgrass when the discount rate is high. Under land-leasing contracts, to induce the same amount of biomass production, the land rental payments needed when growing miscanthus are about \$178/acre. To provide context for this value, the US national average cropland cash rent in 2025 was \$161/acre (NASS 2026). When growing switchgrass, the required land rental payments are approximately \$13 higher than those when growing miscanthus. This is because miscanthus yield is about 25% higher than switchgrass yield, and growing miscanthus requires less land to meet the feedstock demand from SAF.

3.2 | 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.[14] From these figures, one 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 the land-leasing contract is more appealing to farmers whose land is less productive, 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. The results also show that the difference in land density between the fixed-price contract and the land-leasing contract is negligible for both miscanthus

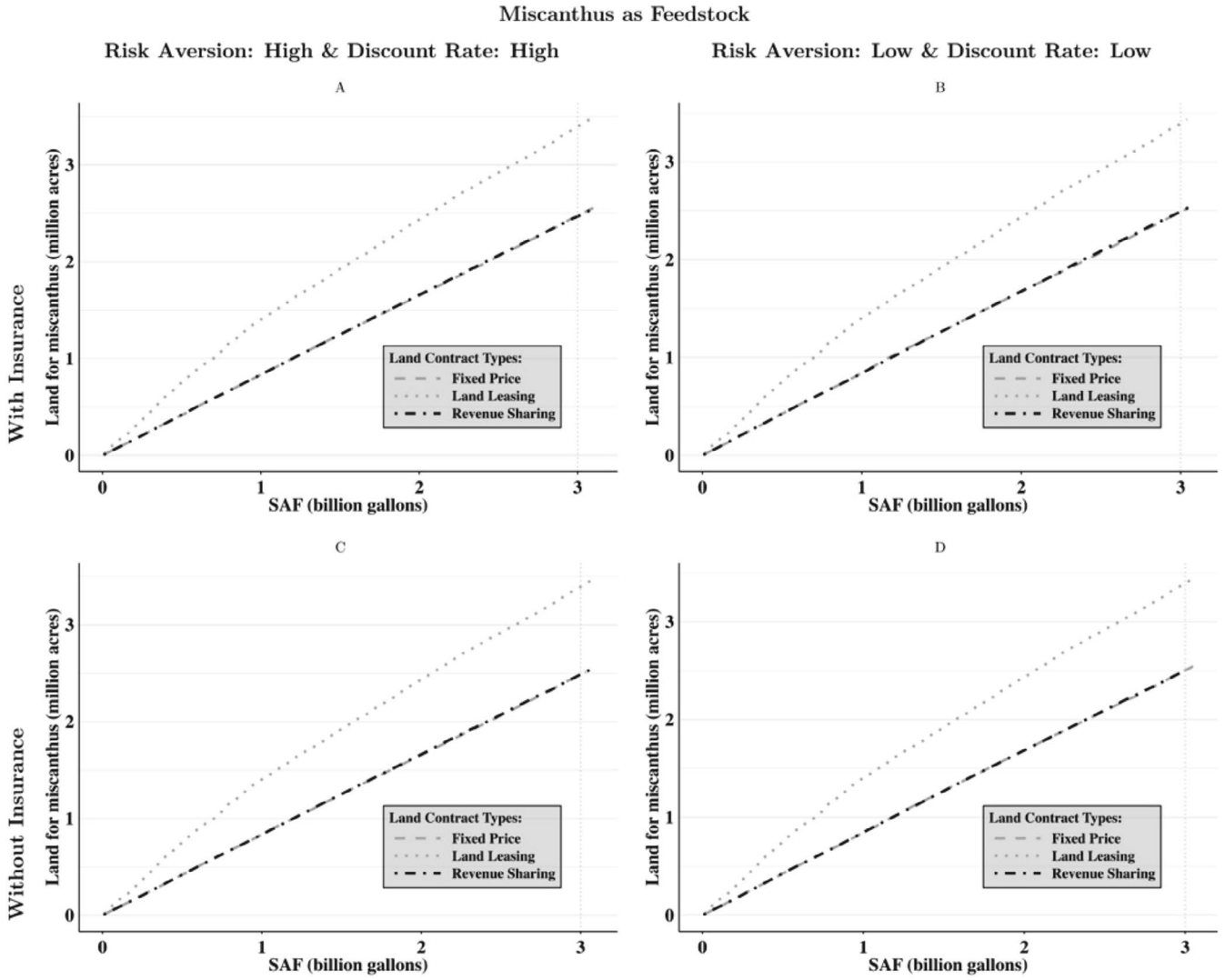

FIGURE 2 | Land requirement under the three contract types for a given SAF production when miscanthus is used as feedstock. Note: High and low risk aversion parameter is 0.00005 and 0.00001, respectively; high and low discount rate is 17% and 12%, respectively.

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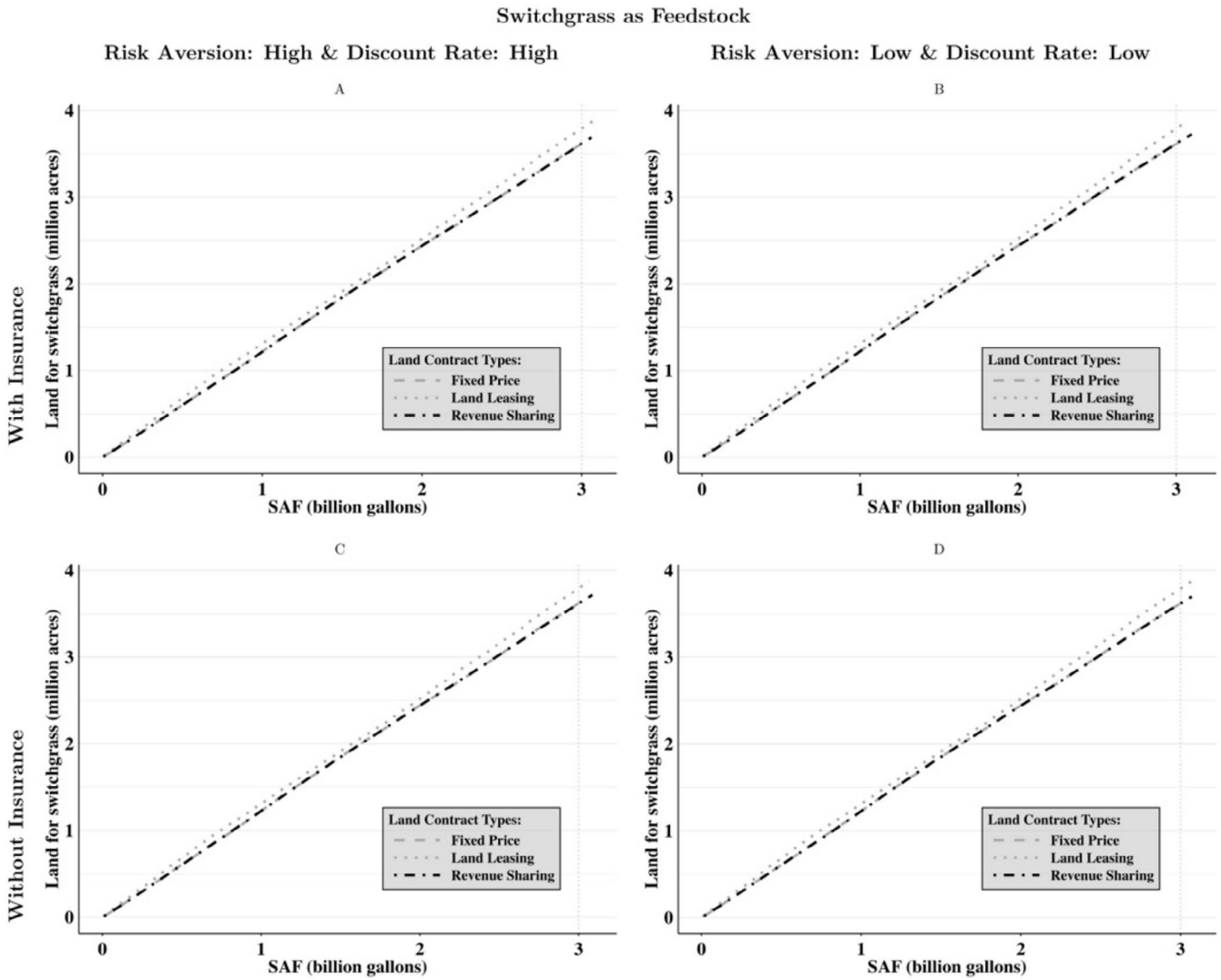

FIGURE 3 | Land requirement under the three contract types for a given SAF production when switchgrass is used as feedstock. Note: High and low risk aversion parameter is 0.00005 and 0.00001, respectively; high and low discount rate is 17% and 12%, respectively.

and switchgrass (evidenced by the almost completely overlapped dashed line and dot-dashed line in the graphs of Figures 2 and 3). The reason is that the two types of contracts largely induce the same biomass-producing counties, as shown in Figure 4.

Specifically, Figure 4 maps the county-level biomass production levels for each bioenergy crop and under each contract type to meet feedstock demand from three billion gallons of SAF. For simplicity, maps included are under the scenarios of "high risk aversion and high discount rate," "low risk aversion and low discount rate," and with or without bioenergy crop insurance. Figure 4 shows that under both fixed-price contract and revenue-sharing contracts, miscanthus will be produced in central Southeastern counties because they have higher miscanthus yield and lower conventional crop yields. Under the land-leasing contract, however, the producing counties are mainly located in the Great Plains and the Southeast due to their low land cost. For switchgrass, the producing counties will be mainly in the Great Plains and Southeast. We do not find that changes in farmers' risk aversion or discount rate lead to significant geographical shifts in the distribution of bioenergy crop-producing counties.

Table 2 shows that to meet the feedstock demand from producing three billion gallons of SAF, about 2.47 to 2.51 million acres of miscanthus acreage will be needed under the fixed-price contract or revenue-sharing contract. The acreage requirement will increase to about 3.4 million acres if a land-leasing contract is used (about 36% increase). If switchgrass is grown as the feedstock for 3 billion gallons of SAF, then about 3.6 million acres of land will be needed under the fixed-price contract or revenue-sharing contract, and 3.8 million acres will be needed under the land-leasing contract (see Table 3), as switchgrass has a lower yield than miscanthus.

When targeting at three billion gallons of SAF, the average farm-gate production cost for miscanthus under the fixed-price contract ranges between $44.42 and $44.58/MT. Miscanthus production cost is similar under the revenue-sharing contract, ranging between $44.36/MT and $44.59/MT. Under the land-leasing contract, miscanthus production cost is about $5 higher than that under the fixed price contract or revenue-sharing contract, reaching $49.79/MT. The similar pattern is observed for switchgrass production cost under the three contract types,

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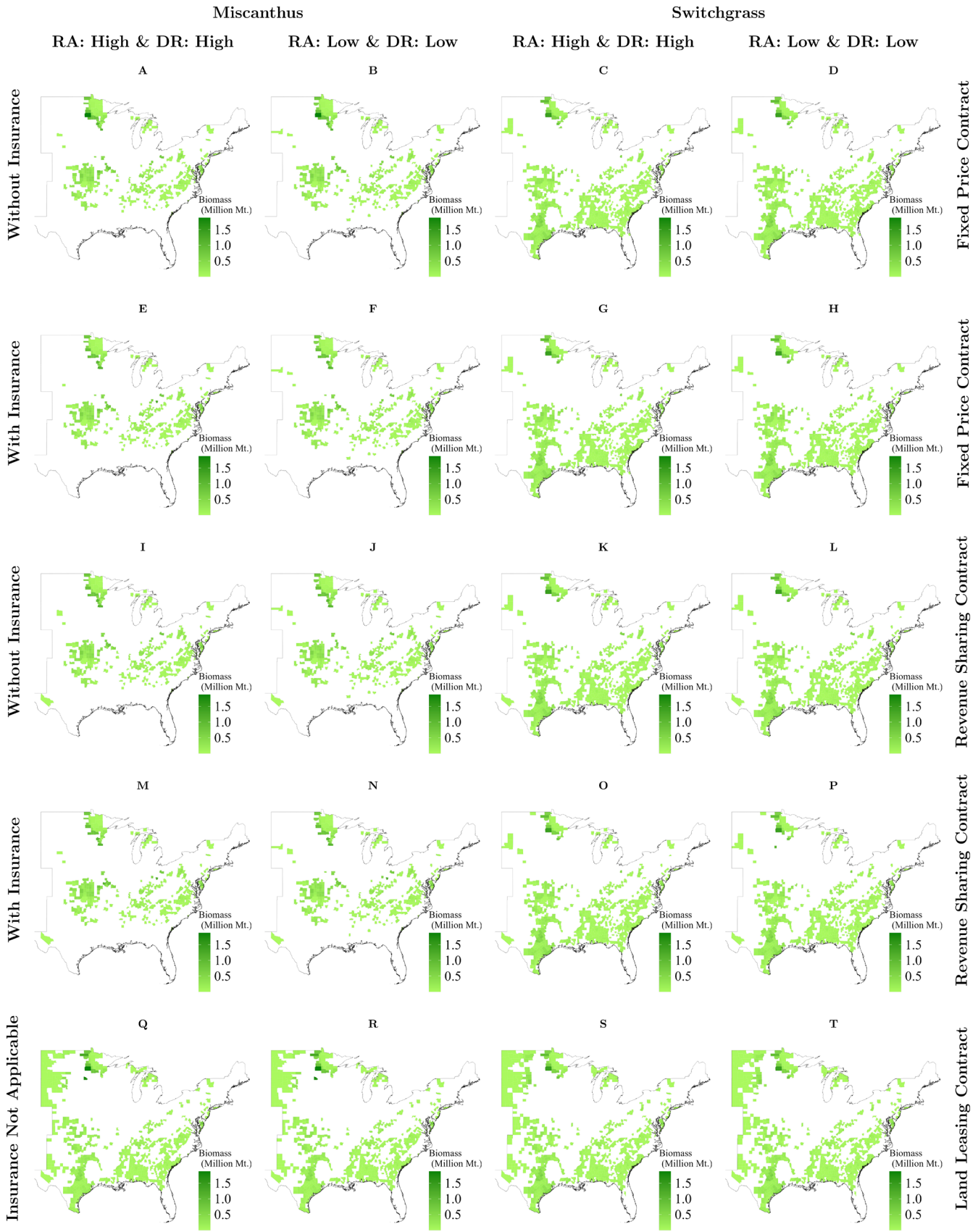

FIGURE 4 | County-level biomass production under different contract types and farmers' risk and time preferences. Note: The first two columns of maps are for miscanthus, and the last two columns are for switchgrass. The first two rows of maps are under fixed-price contract, the third and fourth rows 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. High and low risk aversion parameters are 0.00005 and 0.00001, respectively; and high and low discount rates are 17% and 12%, respectively.

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with unit production cost for switchgrass ($46.7/MT to $47.5/MT) being close to that for miscanthus.

3.3 | Farmers' Welfare Changes and Contract

Farmers' NPV of expected utility is used to measure 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, termed welfare gains throughout this article. Tables 2 and 3 show that, for farmers who enter a contract to produce bioenergy crops, their welfare increases by up to 7% when compared with growing conventional crops. For both bioenergy crops, the land-leasing contract brings farmers the highest welfare gains. 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.

3.4 | 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 bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare gains, and average production cost under each contract type to meet the biomass demand for producing three billion gallons of SAF.

3.4.1 | On Contract Terms

For both miscanthus and switchgrass, the presence of 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. The reason is that bioenergy crop insurance covers yield risk and increases farmers' expected utility from growing a bioenergy crop. As a result, in the presence of bioenergy crop insurance, farmers are willing to switch to bioenergy crop production even under a lower contract term. Figure 1 shows that the difference between a pair of black and gray curves of the same line type is slightly smaller for miscanthus than for switchgrass, indicating

TABLE 4 | Impact of bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare gains, and average production cost to meet the biomass demand from producing three billion gallons of SAF (%).

	Risk aversion parameter	High	High	Low	Low
	Discount rate	High	Low	High	Low
Impact on miscanthus (%)					
Fixed-price contract	Fixed price	−4.17	−4.36	−4.28	−4.46
	Bio. crop acreage	0.41	−1.72	−0.26	−1.29
	Welfare gains	0.19	4.11	1.01	3.6
	Production cost	−0.12	−0.17	−0.14	−0.17
Revenue-sharing contract	Revenue sharing	−4.54	−4.77	−4.64	−4.85
	Bioenergy acreage	0.31	−0.17	−1.39	0.15
	Welfare gains	−4.37	−2.68	−2.98	−3.1
	Production cost	−0.26	−0.16	−0.26	−0.19
Impact on switchgrass (%)					
Fixed-price contract	Fixed price	−5.64	−5.9	−5.76	−6.05
	Bio. crop acreage	−0.34	−0.29	−0.74	−0.83
	Welfare gains	0.53	−0.75	−0.51	−1.86
	Production cost	−0.08	−0.08	−0.09	−0.09
Revenue-sharing contract	Revenue sharing	−5.69	−6	−5.75	−5.89
	Bioenergy acreage	−0.84	−0.82	0.00	−0.42
	Welfare gains	0.62	−0.99	−1.12	−0.95
	Production cost	−0.04	−0.04	−0.04	−0.1

Note: High risk aversion indicates a risk aversion parameter at 0.00005, and low risk aversion indicates 0.00001. High and low discount rates are 17% and 12%, respectively. Bioenergy crop insurance is yield insurance with a 75% coverage level and an 80% premium subsidy rate.

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that for miscanthus, bioenergy crop insurance has a smaller impact on reducing the contract terms required to meet a given demand from SAF production. Specifically, by comparing the contract terms with and without bioenergy crop insurance in Table 2, one can see that when the target feedstock quantity is for three billion gallons of SAF, the availability of bioenergy crop insurance decreases fixed price by about $3.5/MT and revenue share by about 1.6 percentage points for miscanthus across various risk aversion and discount rate scenarios. For switchgrass, the corresponding reductions are about $4.7–4.9 per metric ton and 2 percentage points, respectively (see Table 3). Table 4 shows that for miscanthus, bioenergy crop insurance reduces the contract terms required for three billion gallons of SAF by marginally above 4%. For switchgrass, this reduction is about 6%. Although these impacts may appear small in percentage points, they actually indicate large magnitude of changes in biorefineries' biomass procurement cost. For instance, under the high risk-aversion parameter and high discount rate scenario, to induce sufficient biomass for three billion gallons of SAF from miscanthus, the required fixed price in the presence of bioenergy crop insurance is $82.32/MT, a $3.58/MT reduction when compared with that in the absence of the insurance. As producing three billion gallons of SAF requires about 66.2 million MTs of miscanthus, this $3.58/MT reduction in fixed price indicates $237 million of procurement cost reduction for biorefineries.

3.4.2 | On Land Intensity

Table 4 shows that in most scenarios the bioenergy crop insurance will slightly decrease the land intensity for producing three billion gallons of SAF under both fixed-price contract and revenue-sharing contract. One possible reason for this land-intensity-reducing effect is that the availability of bioenergy crop insurance brings land with high risk but high mean yield into biomass production.[15] Nevertheless, the impact magnitude is smaller than 2% (see Table 4) across all scenarios, 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).

3.4.3 | On Farmers' Welfare Gains

The presence of bioenergy crop insurance affects farmers' welfare gains when they switch from growing conventional row crops with insurance to bioenergy crops via two channels. On the one hand, bioenergy crop insurance provides indemnity payment when yield is low, and thus increases farmers' welfare gains. On the other hand, the insurance reduces the contract terms (i.e., fixed price and revenue share) required to produce a given amount of biomass (see Table 4), and thus lowers the welfare gains of farmers who switch to bioenergy crops. The overall effect of bioenergy crop insurance on the welfare gains under a contract depends on the relative magnitude of these two opposing forces. The results show that for miscanthus, the presence of bioenergy crop insurance enlarges farmers' welfare gains under the fixed-price contract while lowering the welfare gains under the revenue-sharing contract. For switchgrass, however, the results are mixed: the welfare gains can be either enlarged or lowered under the same type of contract, depending on farmers' risk and time preferences (see Table 2).

3.4.4 | On Average Production Cost

Results show that the presence of bioenergy crop insurance slightly reduces the average production cost of bioenergy crops to meet the feedstock demand from three billion gallons of SAF (see Table 4). For miscanthus, the bioenergy crop insurance reduces biomass production cost by 0.12%–0.17% under the fixed-price contract and 0.16%–0.26% under the revenue-sharing contract. For switchgrass, the magnitude of the impact is even smaller. Under the fixed-price contract, switchgrass production cost decreases by 0.08%–0.09%, while under the revenue-sharing contract, the cost decreases by 0.04%–0.1%. The reason for the small effects is twofold: first, bioenergy crop insurance does not affect the geographical distribution of producing counties very much (see Figure 4); and second, the variation of production costs in the sample is not large.

4 | Sensitivity Analyses

Four sets of sensitivity analyses are conducted to examine how the main results are affected by changes in key parameters of the simulation. Specifically, the first set of sensitivity analyses involves increasing the land share that can be devoted to bioenergy crop production from 25% to 40%. This is of interest because land availability is a key constraint on bioenergy crop production and may significantly affect the simulation results. The corresponding results are presented in Tables S1–SI3 in the online Supporting Information (SI). As expected, when the portion of land allowed to be devoted to energy crops increases in each county, the contract terms required to induce sufficient biomass for three billion gallons of SAF decrease. For miscanthus, a comparison between Tables S1 and 2 shows that the biomass price under the fixed-price contract decreases by about $3/MT, the revenue share under the revenue-sharing contract decreases by about 1.2 percentage points, and the land lease rate under the land-leasing contract decreases by $46/acre. For switchgrass, the three corresponding changes are: $7/MT, 2.8 percentage points, and $58/acre (see Table SI2 in the online SI). This finding indicates that the land-leasing contract term is much more sensitive to the land portion allowed for energy crops than are the contract terms of the fixed-price contract and revenue-sharing contract. This pattern can be partially explained by the shapes of the supply curves between contract terms and SAF production depicted in Figure 1. For the fixed-price contract and revenue-sharing contract, the supply curves are in the shape of a logarithmic curve, and at the three billion gallons of production level, the biomass supply is quite sensitive to the contract terms. This indicates that to produce sufficient feedstock for three billion gallons of SAF, the contract terms cannot decrease much even when the land portion allowed for bioenergy crops increases significantly. In contrast, for the land-leasing contract, the supply curves are largely linear, and the biomass supply is not quite sensitive to the contract term, resulting in a considerable decrease in land lease rate when the land portion allowed for bioenergy crops increases from 25% to 40%. Correspondingly, under the fixed-price contract and revenue-sharing contract,

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the bioenergy crop acreage, farmers' welfare gains, and average production cost are affected only minimally by the land portion increase, while under the land-leasing contract they are affected by a larger, but still modest, magnitude.

The second set of sensitivity analyses examines how the main results change if farmers only contract a share (80% in this study) of their expected yield under the fixed-price contract and revenue-sharing contract. Only contracting a share of expected yield could be appealing to farmers because it reduces the chance to rely on the spot market to offset production shortfalls. The results are presented in Tables SI4–SI6 in the online SI. As expected, when farmers only contract 80%, rather than 100%, of their expected yield, the contract terms and the acreage required to produce adequate feedstock under the fixed-price contract and revenue-sharing contract increase. For miscanthus, when compared with the results in Table 2, the fixed prices increase by \$6/MT to \$9/MT, and the revenue shares increase by 2–4 percentage points. For switchgrass, the increases in contract terms are in a similar range. For both miscanthus and switchgrass, the land acreage required increases by about 25%. Interestingly, for miscanthus (respectively, switchgrass), only contracting 80% of the expected yield decreases (respectively, increases) farmers' welfare gains when compared with contracting 100% of the expected yield. The reason is that although contracting a portion of expected yield reduces the probability of using the spot market to offset production shortfalls, it increases the chance to sell the production surplus in the spot market, which both involve transportation cost and price risk. Therefore, whether contracting a portion of expected yield would increase welfare gains depends on yield distributions of a specific crop. Nevertheless, the average production cost is only negligibly affected.

The third set of sensitivity analyses concerns yield of switchgrass in its establishment year. In the main analysis, switchgrass yield in the establishment year is assumed to be 50% of mature-year yield. As studies show that the establishment-year yield can be about 30%–50% of mature-year yield (e.g., Holman et al. 2011; Wright et al. 2011), this set of sensitivity analyses examines how a lower establishment-year yield (i.e., 30% of the mature-year yield) will affect the results (see Tables SI7 and SI8). A comparison between the results in Table 3 and those in Table SI7 shows that a reduction in the establishment-year yield from 50% to 30% of the mature-year yield has minimal effects on the contract terms, bioenergy crop acreage, welfare gains, and average production costs. For instance, under the scenario with high risk aversion, high discount rate, and without bioenergy crop insurance, such establishment-year reduction increases the fixed price from \$82.65/MT to \$84.48/MT, a 2.2% increase. The reason for this small increase is that the assumed 20-percentage-point decrease in the first yield only accounts for a small portion (about 2%) of total biomass generated by switchgrass in a lifespan.

Finally, the fourth set of sensitivity analyses investigate how the results are affected by a decrease in crop insurance premium subsidy rate. This set of analyses is relevant because premium subsidy is critical for crop insurance adoption (Tsiboe and Turner 2023) and has been shown to affect farmers' production decisions (Ghosh et al. 2023). Tables SI9–SI11 present the simulation results when the premium subsidy rate of crop insurance (for both conventional crops and, if applicable, bioenergy crops) is reduced from 80% to 55%, a common subsidy rate for insurance policies with 75% of coverage level. A comparison between Tables SI9–SI11 with Tables 2–3 indicates that the contract terms decrease considerably: the fixed prices are lowered by \$4/MT to \$6/MT for miscanthus and by \$5/MT to \$6/MT for switchgrass, a decrease of approximately 6%–8%. Similar magnitude of relative reduction is observed for revenue shares. An approximately 18%–20% reduction in land lease rate is observed for miscanthus and switchgrass, indicating that land lease rate is more sensitive to crop insurance premium subsidy rate than the fixed price and revenue share are. The underlying reason is still related to the shape of the supply curves of the biomass (see Figure 1): at the biomass target for three billion gallons of SAF, biomass production under the fixed-price and revenue-sharing contracts are much more sensitive to contract terms than that under the land-leasing contract. However, the impact of the reduction in crop insurance premium subsidy rate on bioenergy crop acreage and average production cost is largely negative but minimal. Finally, the welfare gains from switching to bioenergy crops are decreased by about one third due to the reduction in the premium subsidy rate across all scenarios for both miscanthus and switchgrass, resulting from the reduction in the contract terms required to produce adequate feedstock for three billion gallons of SAF.

5 | Concluding Remarks

A conceptual framework is developed 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, the study investigates the contract terms required to induce sufficient miscanthus or switchgrass production to meet a given feedstock demand from SAF. It analyzes bioenergy crop acreage, farmers' welfare gains, and average biomass production cost under each type of contract to generate sufficient feedstock for three billion gallons of SAF, and examines how these values may be affected by farmers' risk and time preferences as well as the presence of bioenergy crop insurance.

We find that to meet the feedstock demand from three billion gallons of SAF, the contract terms for miscanthus under fixed-price contract, revenue-sharing contract, and land-leasing contract are \$74/MT to \$86/MT of biomass, 31%–36% of revenue share devoted to farmers, and about \$178/acre of rental payment, respectively. For switchgrass, however, these three groups of numbers are \$76/MT to \$83/MT of biomass, 31%–34% of revenue share, and about \$191/acre of rental payment, respectively. 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. The results

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show that miscanthus requires about 2.47–3.4 million acres of land to supply sufficient feedstock for three billion gallons of SAF, depending on contract types and farmers' risk and time preferences. Switchgrass would require 3.6–3.8 million acres of land to meet the same goal.

In terms of the impact of bioenergy crop insurance, the results show that to produce feedstock for three billion gallons of SAF by growing miscanthus, the presence of bioenergy crop insurance can decrease fixed price by approximately $3.5/MT and revenue share by 1.6 percentage points (about 4% decrease for both terms). For switchgrass, the corresponding reductions are about $4.7/MT to $4.9/MT and 2 percentage points (about 6% decrease for both terms). The findings show that bioenergy crop insurance has mixed effects on farmers' welfare gains and has minimal impact on bioenergy crop land intensity and average biomass production cost.

These findings provide direct insights for developing feedstock pathways and supporting policies associated with SAF. First, the 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 depending on specific policy goals.

Second, the present study shows the difference between two major bioenergy crops, miscanthus and switchgrass, regarding their contract terms, land requirement, farmers' welfare gains, and production cost when meeting the feedstock demand from three billion gallons of SAF, providing market players in the feedstock supply chain with information that can help them make crop choice decisions. The results also highlight the role of farmers' risk and time preferences in determining the contract terms for miscanthus and switchgrass, showing that the 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, the findings provide supporting evidence for existing survey studies showing that bioenergy crop insurance can be an important incentivizing factor for farmers to adopt bioenergy crops. The presence of bioenergy crop insurance can reduce the contract terms by 4% for miscanthus and by 6% for switchgrass, while it has minimal impact on land use and biomass production cost. The reduction should not be simply interpreted as a small percentage change in simulated contract terms. Instead, it quantifies the extent to which an insurance mechanism can substitute for contractual compensation for production risk. More broadly, our results suggest that the effectiveness of bioenergy crop insurance will depend on the contractual structure of the biomass supply chain. When farmers bear production risk as they do under a fixed-price contract or a revenue-sharing contract, insurance can substitute partially for the risk premium that must otherwise be included in contract payments. In contrast, under a land-leasing contract in which farmers do not bear production risk, bioenergy crop insurance will not affect the land rental rate. Thus, policymakers who are contemplating introducing subsidized bioenergy crop insurance should take into account the contractual arrangements through which biomass is procured.

Despite the insights provided, the present study has some limitations that can be addressed in future research. First, while focusing on contract terms, land-use intensity, direct biomass production costs, farmers' welfare gains, as well as bioenergy crop insurance's impact on these variables, the study does not consider the broader and indirect impacts of growing feedstock for three billion gallons of SAF. These impacts include, but are not limited to, the indirect land-use change caused by the biomass production, greenhouse-gas emissions associated with the indirect land-use change, and the welfare impact of potential bioenergy crop insurance premium subsidy. Examining these impacts can be a direction for future research. Second, 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.[16] 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 from, 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. Third, to obtain a 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. Finally, the study does not model insurance demand as it simply imposes a fixed crop insurance policy on conventional crops and bioenergy crops. In reality, however, farmers have the options to choose from various coverage levels and insurance types. Allowing explicit modeling of crop insurance demand could be a meaningful expansion of the current model for future research.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Endnotes

[1] According to Economic Research Service (ERS) (2026) and Whitt (2022), contracts are widely used for the production and marketing of agricultural commodities, accounting for about a third of the total value of US agricultural production over 1996–2024. Contracts are particularly popular for specialty crop and livestock production. For instance, in 2020, about 53% of fruit production was under contracts. For poultry and hogs, the percentages were 90% and 74%, respectively (Whitt 2022). Moreover, for crop production, marketing contracts are more prevalent than production contracts, whereas for livestock production the opposite is true. For instance, in 2020, the shares of total US sugar beets, peanuts, and cotton production under marketing contracts are 78%, 62%, and 32%, respectively, while the shares of these three crops under production contracts are negligible (Whitt 2022). Existing contracting practices provide useful precedents for bioenergy crop production and marketing.

[2] Although commercial production of cellulosic biomass for biofuels has remained limited, evidence shows that early biorefineries contracted biomass supply using 10-year fixed price contract (Fletcher 2014). Moreover, many existing studies related to cellulosic feedstock supply either implicitly assume the production is under a certain type of contract (e.g., Anand et al. 2019; Bocquého and Jacquet 2010; Miao and Khanna 2017a, 2017b; Majeed et al. 2026) or explicitly examine the contract terms and their impact on farmers' willingness to adopt bioenergy crops (e.g., Fewell et al. 2016; Jensen et al. 2007; Okwo and Thomas 2014; Yang et al. 2016). Thus, our analysis on the three stylized contract types is grounded in actual agricultural contracting practice and in existing cellulosic feedstock studies. Particularly, the fixed-price and revenue-sharing contracts considered in our study can be viewed as simplified variants of crop marketing contracts, as the farmer produces and delivers biomass under pre-specified pricing and delivery terms. The land-leasing contract, by contrast, is closer to a more vertically coordinated arrangement in which the biorefinery assumes complete control over production decisions and bears all risk.

[3] DuPont's former cellulosic ethanol facility in Nevada, Iowa was designed to produce 30 million gallons of cellulosic ethanol per year using corn stover grown within a 30-mile radius of the plant (U.S. Department of Energy (USDOE) 2015). Because miscanthus and switchgrass can yield five to seven times more biomass per acre than does corn stover, their use as feedstocks could substantially reduce the required feedstock catchment radius, potentially to around 10 miles. Khanna et al. (2008) document a transportation cost at $0.22 per ton per mile of distance between the farm gate and biorefinery. Gonzalez et al. (2011) assume the transportation cost to be $0.13 per ton per mile of loaded truck. Overall, these estimates suggest that transportation costs for a biorefinery using high-yielding bioenergy crops such as miscanthus and switchgrass could be relatively low considering the reduced catchment radius (e.g., $2–$3 per ton within a 10-mile radius), and are thus abstracted from the simulation. Assuming a positive transportation cost of delivering biomass from farm gates to biorefineries would obscure, but not obviate, the insights that the study provides.

[4] Considering that farmers may contract a level lower than the mean yield to avoid purchasing yield shortfalls in the spot market, in the sensitivity analysis section the contract quantity is reduced to be 80% of the mean yield.

[5] Conventional yield insurance requires standardized yield measurement and extensive historical yield data, which are well established for major row crops but largely absent for miscanthus and switchgrass. As a result, yield insurance is currently difficult to implement in practice, and the bioenergy crop insurance component in our model should be interpreted as a stylized risk-management mechanism rather than a mature commercial product. Nonetheless, the availability of detailed simulated yields over 30 years allows us to model the outcomes of yield insurance for these crops in the study.

[6] Here a no-till system is used to represent conservation tillage production because yields under other types of conservation tillage are not available to us.

[7] An enterprise unit is a crop insurance unit under which a farmer's all insurable acreage of a specific crop within the same county is combined (RMA 2021). Because the simulation is conducted at the county level, it is reasonable to assume that insurance coverage is based on enterprise units, consistent with aggregating all insured acreage of a crop within a county.

[8] Many studies in the literature assume that miscanthus and switchgrass have lifespans of 15 years and 10 years, respectively (e.g., Anand et al. 2019; Brechbill et al. 2011; Chen et al. 2014; Haque et al. 2009; Jain et al. 2010; James et al. 2010; Majeed et al. 2026; Miao and Khanna 2017a, 2017b; Mooney et al. 2009; Perrin et al. 2008). While there is evidence that miscanthus and switchgrass can grow for longer than 15 or 10 years, a meta-analysis based on 1403 miscanthus yield observations and 2811 switchgrass yield observations over 2002–2019 in the United States shows that miscanthus and switchgrass yields usually peak in the 7th and 6th year respectively and then decrease in age thereafter (Sharma et al. 2022). We therefore believe that the 15-year and 10-year lifespans are reasonable assumptions for miscanthus and switchgrass, and we follow the same assumptions in the present study. Because a longer lifespan would spread the one-time establishment cost to more biomass and thus would reduce the total average production cost, we expect that a longer lifespan of miscanthus or switchgrass will lower the contract terms required to induce sufficient biomass for three billion gallons of sustainable aviation fuel.

[9] Sensitivity of simulation results to this conversion limit is explored in the Sensitivity Analyses section by increasing the limit from 25% to 40%.

[10] Detailed description about calibration and validation of DayCent yield simulation is described in Majeed et al. (2023, 2026).

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

[12] The ethanol yield gap between miscanthus and switchgrass is due to the differences in the composition of biomass between the two bioenergy crops. Data published by Idaho National Laboratory Bioenergy Feedstock Library show that miscanthus contains 40.79% of glucan, a complex carbohydrate that can be converted to ethanol, while switchgrass only contains 33.21% of it (Lee et al. 2023; U.S. Department of Energy (USDOE) 2022).

[13] The original values of these reference prices in the 2016 and 2024 Billion-Ton Reports are $60 per dry short ton in 2014 dollars and $70 per dry short ton in 2022 dollars, respectively. To ease comparison with the findings in the present study, we convert these two values into price per metric ton of biomass with 13% moisture rate in 2025 dollars based on GDP Implicit Price Deflator. The results are $76.5/MT and $74.2/MT, respectively.

[14] For better contrast and simplicity, in Figures 2 and 3 we include only four scenarios that are permutations of two cases of risk aversion and discount rate (i.e., high risk aversion high discount rate, low risk aversion low discount rate) and two cases of bioenergy crop insurance availability (i.e., with and without insurance).

[15] Overall, in the dataset the correlation coefficient between county-level yield mean and the county-level yield standard deviation on high quality land is 0.92 for miscanthus and 0.86 for switchgrass.

[16] Commercial production of miscanthus and switchgrass remains limited, and we are not aware of biorefineries currently offering a menu of contract options. However, in US grain markets, a single buyer (e.g., elevators or ethanol plants) commonly offers multiple contract types, such as hedge-to-arrive, basis, and minimum-price contracts (see ADM grain marketing for an example at https://admadvantage.com/grain-marketing/), providing a practical precedent for contract choice in bioenergy crop markets. Moreover, Yang et al. (2016) explicitly modeled farmers' and biorefineries' decision problems considering a menu of three contract options.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** aepp70129-sup-0001-Tables.docx. **Table SI1:** Sensitivity Analysis 1—contract terms required to induce adequate biomass production from miscanthus for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI2:** Sensitivity Analysis 1—contract terms required to induce adequate biomass production from switchgrass for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI3:** Sensitivity Analysis 1—impact of bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare gains, and average production cost to meet biomass demand from producing three billion gallons of SAF. **Table SI4:** Sensitivity Analysis 2—contract terms required to induce adequate biomass production from miscanthus for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI5:** Sensitivity Analysis 2—contract terms required to induce adequate biomass production from switchgrass for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI6:** Sensitivity Analysis 2—impact of bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare gains, and average production cost to meet biomass demand from producing three billion gallons of SAF. **Table SI7:** Sensitivity Analysis 3—contract terms required to induce adequate biomass production from switchgrass for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI8:** Sensitivity Analysis 3—impact of free bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare gains, and average production cost to meet biomass demand from producing three billion gallons of SAF. **Table SI9:** Sensitivity Analysis 4—contract terms required to induce adequate biomass production from miscanthus for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI10:** Sensitivity Analysis 4—contract terms required to induce adequate biomass production from switchgrass for three billion gallons of SAF as well as corresponding land intensity, farmers' welfare gains, and average biomass production cost. **Table SI11:** Sensitivity Analysis 4—impact of bioenergy crop insurance on contract terms, bioenergy crop acreage, farmers' welfare gains, and average production cost to meet biomass demand from producing three billion gallons of SAF.

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