AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Designing Payments to Induce Low Carbon Sustainable Aviation Fuel Production in U.S. Croplands

Fahd Majeed[1]* (fmajeed2@illinois.edu), Madhu Khanna[1,2] (khanna1@illinois.edu), Ruiqing Miao[3] (rzm0050@auburn.edu)
1 DOE Center for Advanced Bioenergy and Bioproducts Innovation; 2 Department of Agriculture and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL; 3 Department of Agricultural Economics and Rural Sociology, Auburn University, Auburn, AL

Selected Paper prepared for presentation at the 2024 Agricultural & Applied Economics Association Annual Meeting, New Orleans, LA; July 28-30, 2024

Copyright 2022 by authors. All rights reserved. Readers may make verbatim copies of this document for non-commercial purposes by any means provided that this copyright notice appears on all such copies

Abstract

Sustainable Aviation Fuels (SAFs) derived from cellulosic ethanol feedstocks (such as miscanthus, switchgrass, and corn stover) have the potential to provide substantial carbon mitigation benefits. However, significant variations in carbon intensities, high crop establishment and farming costs, uncertain biomass prices, risky yields, and long growing periods for some SAF feedstocks cast doubt on whether SAFs can be economically feasible at a large scale. Using a stylized integrated numerical simulation framework that links an economic model with a biogeochemical model, we examine the impact of various payment schemes on SAF feedstock cropping decisions of risk-averse, present-biased, and credit-constrained farmers in the rainfed agricultural region of the United States and the resulting aggregate carbon mitigation in the SAF production value chain and the spatial distribution of feedstock at various biomass price levels without incentive payments. In calculating carbon intensities, we conduct lifecycle analysis assessments for the entire value chain for SAF production. We estimate the effect of soil carbon mitigation and show that the intensities of SAFs from cellulosic ethanol feedstocks vary spatially and by crop. SAF sourced from miscanthus has the lowest carbon intensities across feedstocks, followed by switchgrass and corn stover. SAF sourced from miscanthus has the lowest carbon intensities in the lower Midwest, switchgrass in the Mississippi delta states, and corn stover across the Midwest. When farmers do not receive incentives, they require high biomass payments to produce SAF feedstocks. At high biomass prices, risk-averse, present-biased, or credit-constrained farmers prefer to grow feedstocks such as switchgrass and harvest larger quantities of corn stover over less carbon-intensive miscanthus. Carbon-based payments incentivize farmers to grow cellulosic ethanol feedstocks at lower biomass prices and choose feedstocks with the lowest carbon intensity. Upfront lump-sum carbon mitigation payments can incentivize risk-averse, impatient, and credit-constrained farmers to grow miscanthus, displacing up to 75 Mil. Mg CO2e Yr^{-1}. Annual carbon mitigation payments can also incentivize up to 175 Mil Mg CO2e Yr^{-1} through a spatial mix of feedstock choices. We also find that when farmers do not receive payment for the soil carbon sequestration they provide, they choose to harvest higher levels of corn stover, reducing the carbon mitigation benefit of SAFs.

Designing Payments to Induce Low Carbon Sustainable Aviation Fuel Production in U.S. Croplands

1.1 Introduction

Conventional petroleum-based aviation fuel (aviation fuel), with a carbon intensity of 80 to 95 grams of carbon dioxide per megajoule (gCO2eMJ^{-1}), is consumed at 320 million liters a day and accounts for more than 2% of global anthropogenic greenhouse gas (GHG) emissions. Sustainable Aviation Fuels (SAFs) are biomass-derived aviation biofuels sourced from plants, animals, or waste material and, depending on the source, could lower carbon emissions by 20–98% relative to conventional aviation fuel. The Sustainable Aviation Fuel (SAF) Credit, created under the Inflation Reduction Act of 2022, offers a $1.25 per gallon credit for a fifty percent reduction in lifecycle greenhouse gas emissions and an additional $0.01 per gallon for each subsequent percent reduction in greenhouse gas emissions. Under the SAF Credit, SAF production is expected to grow to 18 and 75 billion liters in 2025 and 2040, respectively, representing a 5% and 19% share of overall aviation fuel consumption. However, significant variations in carbon intensities of SAF sources and lack of development in SAF production value chains cast doubt on whether such a target can be reached. Further, whether SAF Credit incentivizes adequate SAF production or is the most efficient method of mitigating carbon per dollar spent is uncertain.

Cellulosic ethanol feedstocks (bioenergy crops) such as corn stover and bioenergy crops have the potential to provide substantial carbon mitigation benefits, first, through the production of low-carbon fuels such as cellulosic ethanol, which can be converted to SAF and, second, via carbon mitigation through soil carbon sequestration. These feedstocks, however, vary in terms of their carbon intensities, production costs, and risks due to differing and spatially varying input requirements, yields, and soil carbon sequestration effects. For instance, corn stover is a low-cost but low-yielding source of biomass readily available to farmers planting corn. However, harvesting stover removes soil carbon that would have otherwise remained sequestered in the ground. Farmers may reduce soil carbon loss by adopting more conservation tillage practices, adopting cover crops, or changing to conservative rotation choices, which may affect stover production. In contrast, bioenergy crops like miscanthus and switchgrass provide spatially varying carbon mitigation benefits through relatively high annual yield over the mature period of the crop, substantial soil carbon sequestration through the crop's life, and their ability to grow on lower-quality land. However, long establishment periods with high upfront costs and uncertain yields due to weather variations reduce incentives for risk-averse, impatient, and credit-constrained farmers to produce these carbon-mitigating bioenergy crops. Further, it is unsure whether increased carbon emissions due to the expansion of croplands for ethanol production, indirect land use change (ILUC), as well as impermanence of soil carbon will mitigate some of the additional carbon mitigation benefits of SAF production from cellulosic ethanol feedstocks.

Previous research shows that upfront subsidies for bioenergy crops to reduce establishment costs can incentivize the adoption of bioenergy crops by risk-averse decision-makers but have not yet considered directly incentivizing the spatially varying carbon mitigation that these feedstocks provide, which makes them appealing in the first place. Additionally, annual payments linked to carbon mitigation benefits through lifecycle displacement may produce higher carbon mitigation in cases where farmers are less credit-constrained or risk-averse. Furthermore, feedstocks that have the lowest cost for biomass feedstock cultivation, for instance, may not necessarily be the areas with the highest carbon mitigation potential due to spatial differences in high sequestration and high yield areas, spatial differences in high miscanthus and switchgrass yield areas, and payment for carbon mitigation benefits of corn stover. Earlier research finds heterogeneity in emission reduction potential from various sources and sites. Providing payments based on emission reduction would take advantage of spatial variability in carbon mitigation potential, yields, and costs by creating differing incentives for feedstocks in different locations and increasing the production of cellulosic ethanol where the carbon intensity of biofuel produced and the overall cost of production is lowest.

This research examines the impact of various payment schemes on SAF feedstock cropping decisions of risk-averse, present-biased, and credit-constrained farmers in the rainfed agricultural region of the United States. First, we examine farmer cropping decisions regarding the production of SAF feedstocks (miscanthus, switchgrass, and corn stover harvesting), along with tillage, rotation, and cover cropping decisions and the resulting aggregate carbon mitigation in the SAF production value chain and the spatial distribution of feedstock at various biomass price levels without incentive payments. Second, we examine how payment scheme design affects SAF feedstock adoption's magnitude and spatial distribution. We consider the effect of a SAF Credit style payment, annual and upfront payments based on carbon mitigation, and payments based on feedstock production. Third, we consider whether farmer risk-aversion, time-discounting, and access to credit affect the potential of adopting SAF feedstocks.

We undertake this analysis using a stylized integrated numerical simulation framework that links an economic model with a biogeochemical model, DayCent, to analyze farmers' cropping decisions while accounting for spatial and temporal heterogeneity in crop yields and carbon intensities across the rainfed region of the United States. In calculating carbon intensities, we conduct lifecycle analysis assessments for the entire value chain for SAF production and estimate the effect of soil carbon mitigation. The representative farmer maximizes their expected utility and chooses land allocations to conventional crops and bioenergy crops and whether to harvest a portion of corn stover from areas under corn production, switch rotation and tillage to more carbon-mitigating practices, and establish cover crops. We can capture additionality and ILUC effects by simulating the model without and again with incentive payments. We conduct our analysis for a fifteen-year cropping cycle at the county level for an exogenous degree of risk-aversion, time-preferences, and credit-constraints at exogenous biomass prices under differing soil carbon payment schemes.

1.2 Theoretical Framework

In the theoretical framework, we consider the effect of annual and upfront carbon mitigation payments and when farmers only paid for all their carbon mitigation or only part of it (i.e., only for Aviation fuel displacement).

1.2.1 Model Setup

We assume that a representative farmer has one unit of homogenous land[1] where a portion (i.e., $x_e \in [0,1]$) can be allocated to a bioenergy crop, e, and the remaining land to conventional crops (e.g., corn and soybeans), c (i.e., $x_c = 1 - x_e$).[2] We consider two periods, an establishment period and a mature period, to reflect that the perennial bioenergy crop requires an establishment period before it matures. We also assume that each period is of equal length, such that conventional crops can be planted and harvested during each period. The bioenergy crop provides carbon mitigation services from Aviation fuel displacement, l, and soil carbon sequestration, b. The former varies with bioenergy crop yield, while the latter is constant per unit of land irrespective of yield.[3] The farmer receives a payment at a price p^g per unit of carbon mitigated (through either displacement or soil carbon sequestration). Further, the farmer receives a biomass payment at a price p^b per unit of biomass yield. We consider two

---

[1] For simplicity we do assume land to be of homogenous quality.

[2] For simplicity we do not consider corn stover production in the theoretical framework model. However, it is included in the numerical simulation. See section 1.3 for details.

[3] For simplicity we do not consider soil carbon sequestration variation over the life of the crop in the conceptual model. In the numerical simulation, however, we do consider temporal variation over the life of the bioenergy crop.

payment schemes, where farmers may receive carbon mitigation payments as either annual payments, A, where the payment is made in the year the farmer mitigates that carbon, or upfront payments, U, in the establishment period for the value of the entirety of carbon mitigated. Further, we consider providing payment only for carbon mitigated through Aviation fuel displacement.

In the bioenergy crop establishment period, the farmer incurs a cost, w, per unit of land for establishment. We denote I to be a credit-constraint index such that the farmer may have access to credit ($I = 0$) or be credit-constrained ($I = 1$). If the farmer has access to credit, she can borrow the total amount of the establishment costs w, and she must pay it back with interest i in the mature period. Farmers do not harvest biomass, receive revenue, or mitigate carbon during the establishment period.[4] Under annual carbon mitigation payments, the establishment period profit for bioenergy crops per unit of land is $\pi_1^{Ae} = -Iw$. In the mature period, the farmer harvests the bioenergy crop, incurring a fixed cost f^e per unit of land and variable cost v^e per unit of biomass yield, and pays back establishment costs w with an interest rate i if they could borrow in the establishment period. Additionally, we assume that one-unit yield from the bioenergy crop generates l^e units of carbon mitigation through fossil fuel displacement and that one unit of land growing bioenergy crops produce b^e units of carbon mitigation through soil carbon sequestration. We express the farmer's profit per unit of biomass over variable costs as $r^e = p^b - v^e + p^g l^e$. Under annual carbon mitigation payments, mature period profit for bioenergy crop per unit of land is, therefore,$\pi_2^{Ae} = r^e(y^e + \epsilon^e) + p^g b^e - f^e - (1 - I)w(1 + i)$, with y^e being the mean yield for bioenergy crops and ϵ^e being the stochastic term associated. We assume that $E(\epsilon^e) = 0$ and $Var(\epsilon^e) = \sigma^e$.

---

[4] For simplicity we do not consider soil carbon change in the establishment period. However, in the numerical simulation in section 1.3, we do account for establishment period soil carbon effects.

The conventional crop completes one lifecycle during each period. For the conventional crop, we denote its price per unit of yield, fixed cost per unit of land, and variable cost per unit of yield as p^c, f^c, and v^c, respectively. We denote the profit per unit of land from conventional crops as $\pi^c = r^c(y^c + \epsilon^c) - f^c$, where r^c is defined to be $p^c - v^c$, y^c is conventional crop mean yields and ϵ^c is the stochastic term associated with the yield. We assume that $E(\epsilon^c) = 0$ and $Var(\epsilon^c) = \sigma^c$. Moreover, we denote the covariance between bioenergy crops and conventional crop yields as $Cov(\epsilon^e, \epsilon^c) = \sigma^{ec}$.

1.2.2 Farmer's decision problem: utility maximization and first-order conditions

In sum, under the annual payment scheme, the profits for the establishment period and mature period can be given as $\pi_1^A(x_e) = x_e\pi_1^{Ae} + x_c\pi^c$ and $\pi_2^A(x_e) = x_e\pi_2^{Ae} + x_c\pi^c$, respectively. The farmer maximizes his expected utility by choosing x_c and x_e:

$$\max_{x_c,x_e} E[u(\pi_1^A) + \beta u(\pi_2^A)] \text{ s.t. } x_c + x_e = 1, \tag{2.1}$$

where $u(\cdot)$ is a utility function with properties $u''(\cdot) \le 0 \le u'(\cdot)$ and $\beta \in [0,1]$ is a discount factor. Without loss of generality, we let the utility function take the form of a Constant Absolute Risk-aversion (CARA), $u(\pi) = -e^{-\lambda\pi}$, where λ is the farmer's risk-aversion parameter and $\lambda = -u''(\cdot)/u'(\cdot)$. Assuming an interior solution, we can write the first-order condition of Eq. 2.1 as,

$$H^A(x_e) \equiv E[u'(\pi_1^A)\partial\pi_1^A/\partial x_e + \beta u'(\pi_2^A)\, \partial\pi_2^A/\partial x_e] = 0. \tag{2.2}$$

If we denote x_e^* as the internal solution to the first-order condition, we then have $\partial H^A/\partial x_e|_{x_e=x_e^*} < 0$ as shown in Appendix A.1. So for any exogenous parameter η (where η represents the variable of interest, e.g. p^g $\lambda, \beta,$ or I), we can conclude that the sign of $\partial x_e^*/\partial\eta$ will be the same as the sign of $\partial H^A/\partial\eta$, we, therefore, need only observe the sign of $\partial H^A/\partial\eta$ to determine the sign of $\partial x_e^*/\partial\eta$. Using a first-order Taylor series expansion given in Appendix A.2, we can rewrite the first-order condition as

$$H^A(x_e) = \underbrace{u'(\bar{\pi}_1^A)\left[M_1^A - \lambda\Omega_1^{\mathrm{A}}\right]}_{Term\ 3.1} + \underbrace{\beta u'(\bar{\pi}_2^A)\left[M_2^A - \lambda\Omega_2^{\mathrm{A}}\right]}_{Term\ 3.2} = 0, \tag{2.3}$$

where $M_1^A \equiv -Iw - (r^c y^c - f^c)$ and $M_2^A \equiv (r^e y^e + p^g b^e - f^e - (1-I)w(1+i)) - (r^c y^c - f^c)$ are the marginal mean profit of x_e in the establishment period and the mature period, respectively. We can check that $\mathrm{M}_1^{\mathrm{A}} \leq 0$, while the sign of $\mathrm{M}_2^{\mathrm{A}}$ depends on the difference in expected returns of the two crops. Additionally, $\Omega_1^{\mathrm{A}} \equiv -(1-x_e)(r^c)^2\sigma^c$ and $\Omega_2^{\mathrm{A}} \equiv x_e(r^e)^2\sigma^e - (1-x_e)(r^c)^2\sigma^c + (1-2x_e)(r^e r^c)\sigma^{ec}$ are proportional to the marginal effect of x_e on the variance of profits in the two periods, respectively. We can check that $\Omega_1^{\mathrm{A}} \leq 0$, while the sign of Ω_2^{A} depends on the yield variances and covariance of the two crops. $Term$ 3.1 and $Term$ 3.2 are the marginal utility of x_e in the establishment period and mature period, respectively. An increase in x_e reduces the establishment period net income variance through more bioenergy crop production and less conventional crop production. If we assume the farmer's risk-aversion does not exceed M_1^A/Ω_1^A such that $\lambda \leq M_1^A/\Omega_1^A$, $Term$ 3.1 will be negative due to the incurred establishment cost and forgone income from conventional crops. We present an explanation of M_2^A and Ω_2^{A} in Appendix A.3. As $H^A(x_e) = 0$, $Term$ 3.2 will be positive when $\lambda \leq M_1^A/\Omega_1^A$. We present in Appendix A4 the conditions on λ for when $\lambda \leq M_1^A/\Omega_1^A$.

Policymakers may choose to provide to the farmers in the establishment period the sum of the discounted mean payment for carbon mitigation over the crop's lifespan. The setup and first-order conditions under the upfront payment scheme are similar to those under the annual payment scheme, except carbon mitigation payments only occur now in the establishment period (see Appendix A.5 for details). Using a first-order Taylor series expansion given in Appendix A.2, we can rewrite the first-order condition as

$$H^U(x_e) = \underbrace{u'(\bar{\pi}_1^U)[M_1^U - \lambda\Omega_1^{\mathrm{U}}]}_{Term\ 4.1} + \underbrace{\beta u'(\bar{\pi}_2^U)\left[M_2^U - \lambda\Omega_2^{\mathrm{U}}\right]}_{Term\ 4.2} = 0, \tag{2.4}$$

where $M_1^U \equiv \beta p^g(l^e y^e + b^e) - Iw - (r^c y^c - f^c)$ and $M_2^U \equiv \left(r_u^e y^e - f^e - (1-I)w(1+i)\right) - (r^c y^c - f^c)$, such that $r_u^e = p^b - v^e$, are the marginal mean profit of x_e in the establishment period and the mature period, respectively. The sign of both M_1^U and M_2^U depend on the difference in expected returns of the two crops in each period. However, expected returns in the establishment period, M_1^U, will be positive if carbon mitigation payments exceed the establishment cost and expected returns from conventional crops. Additionally, $\Omega_1^U \equiv -(1-x_e)(r^c)^2\sigma^c$ and $\Omega_2^U \equiv x_e(r_u^e)^2\sigma^e - (1-x_e)(r^c)^2\sigma^c + (1-2x_e)(r_u^e r^c)\sigma^{ec}$ are proportional to the marginal effect of x_e on the variance of profits in the two periods, respectively. As with the annual payment scheme, we can check that $\Omega_1^U \leq 0$, whereas the sign of Ω_2^U depends on the yield variances and covariance of the two crops. $Term$ 4.1 and $Term$ 4.2 are the marginal utility of x_e in the establishment period and mature period, respectively. The sign of $Term$ 4.1 may be positive if carbon payments are enough to offset the establishment period establishment costs and the mean and variance of returns from conventional crops such that $\beta p^g(l^e y^e + b^e) > Iw + (r^c y^c - f^c) + \lambda(1-x_e)(r^c)^2\sigma^c$. As $H^U(x_e) = 0$, we know that if $Term\ 4.1 > 0$, then $Term\ 4.2 < 0$, and vice versa.

1.2.3 Effect of carbon mitigation payments on marginal utility

To see how x_e will be affected by carbon mitigation payments under an annual payment scheme. We solve first for $\partial H^A/\partial p^g$ under the CARA functional form and find

$$\frac{\partial H^A}{\partial p^g} = \underbrace{\beta u'(\bar{\pi}_2^A)\left[\frac{\partial \mathrm{M}_2^\mathrm{A}}{\partial p^g} - \lambda \frac{\partial \Omega_2^\mathrm{A}}{\partial p^g}\right]}_{Term\ 5.1} \underbrace{-\lambda \frac{\partial \bar{\pi}_2^A}{\partial p^g}\beta u'(\bar{\pi}_2^A)\left[\mathrm{M}_2^\mathrm{A} - \lambda\Omega_2^\mathrm{A}\right]}_{Term\ 5.2}, \tag{2.5}$$

where $\partial \mathrm{M}_2^\mathrm{A}/\partial p^g = l^e y^e + b^e$, $\partial \Omega_2^\mathrm{A}/\partial p^g = 2x_e l^e r^e \sigma^e + (1-2x_e) r^c l^e \sigma^{ec}$, and $\partial \bar{\pi}_2^A/\partial p^g = x_e(g^e y^e + b^e)$. Appendix A.6 and B.1.7 show the algebra to obtain Eq. 2.5. $Term$ 5.1 is the marginal impact of p^g on the marginal utility of x_e in the mature period caused through the channel affecting mean return and the variance of the returns, whereas $Term$ 5.2 is the marginal impact caused through the channel affecting the marginal utility of mature period mean returns, $u'(\bar{\pi}_2^A)$. $Term$ 5.1 will be positive if the change in mean returns is greater than the risk factor multiplied by the change in the risk of returns, such that $\partial \mathrm{M}_2^{\mathrm{A}}/\partial p^g \geq \lambda\, \partial \Omega_2^{\mathrm{A}}/\partial p^g$. We discuss in detail in Appendix A.8 the signs of the components of $Term$ 5.1. The sign of $Term$ 5.2 is negative as the marginal utility of $x_e$in the mature period is positive under Eq. 2.5. If $Term$ 5.1 is negative or equal to zero, such that $\partial \mathrm{M}_2^{\mathrm{A}}/\partial p^g \leq \lambda\, \partial \Omega_2^{\mathrm{A}}/\partial p^g$, then $\partial H^A/\partial p^g$ will be negative, implying that an increase in the carbon price will lead to a smaller x_e. If $Term$ 5.1 is positive, such that $\partial \mathrm{M}_2^{\mathrm{A}}/\partial p^g > \lambda\, \partial \Omega_2^{\mathrm{A}}/\partial p^g$, then the sign of $\partial H^A/\partial p^g$ and change in x_e will be undetermined, being negative if $|Term\ 5.1| \geq |Term\ 5.2|$, and negative otherwise.

Next, we solve for $\partial H^U/\partial p^g$ to see the impact of the carbon price on the marginal utility of x_e under an upfront payment scheme (see Appendix A.9 for setup and derivation of $\partial H^U/\partial p^g$). We find that,

$$\frac{\partial H^U}{\partial p^g} = \underbrace{u'(\bar{\pi}_1^U)\left[\frac{\partial \mathrm{M}_1^{\mathrm{U}}}{\partial p^g}\right]}_{Term\ 6.1} \underbrace{-\lambda \frac{\partial \bar{\pi}_1^U}{\partial p^g} u'(\bar{\pi}_1^U)[\mathrm{M}_1^{\mathrm{U}} - \lambda \Omega_1^{\mathrm{U}}],}_{Term\ 6.2} \qquad (2.6)$$

where $\partial \mathrm{M}_1^{\mathrm{U}}/\partial p^g = \beta(g^e y^e + b^e)$. $Term$ 6.1 is the marginal impact of p^gon the marginal utility of x_e in the establishment period caused through the channel affecting mean return and the variance of the returns, whereas $Term$ 6.2 is the marginal impact caused through the channel affecting the establishment period marginal utility of mature period mean profit, $u'(\bar{\pi}_1^U)$. $Term$ 6.1 is positive as it is not affected by the variance of payments for carbon mitigation through fossil fuel displacement due to policymakers paying farmers in advance for their expected carbon mitigation. The sign of $Term$ 6.2 depends on the magnitude of carbon mitigation payments and may be negative if $\beta p^g(l^e y^e + b^e) > Iw + (r^c y^c - f^c) + \lambda(1 - x_e)(r^c)^2 \sigma^c$ and positive otherwise.

We also want to see how $\partial H^A/\partial p^g$ and $\partial H^U/\partial p^g$ change occurs when farmers are paid only for carbon mitigation through fossil fuel displacement, not soil carbon sequestration. We consider this in Appendix

A.10 where we show that as b^e only contributes to mean returns through $\mathrm{M}_1^{\mathrm{U}}$ and $\mathrm{M}_2^{\mathrm{A}}$ and not the riskiness of returns through Ω_1^{U}or Ω_2^{A}, the mean returns decrease, but riskiness remains unchanged. Not paying for soil carbon sequestration would decrease the expected returns but not decrease the relative riskiness of the bioenergy crop. However, higher carbon prices based on only fossil fuel displacement would be required to keep expected returns at the same level. This would lead to increased return riskiness relative to carbon mitigation payments based on fossil fuel displacement and soil carbon sequestration.

1.2.4 Effect of other exogenous parameters on marginal utility

We also want to see how x_e will change as $\lambda, \beta,$ and I under annual and upfront payment schemes. We , we differentiate H^A and H^U with respect to λ, β and I and discuss our results.

First, we differentiate H^A and H^U with respect to λ (Appendix A.11-12). In both cases, we see an increase in risk-aversion makes risky returns within each period less preferable. The sign and magnitude of which term will depend on the relative riskiness and expected returns.

Next, we differentiate H^A and H^U with respect to β (Appendix A.13), and find $\partial H^A/\partial\beta = u'(\overline{\pi}_2)\left[M_2^A - \lambda\Omega_2^{\mathrm{A}}\right]$, and $\partial H^U/\partial\beta = u'(\overline{\pi}_2)\left[M_2^U - \lambda\Omega_2^{\mathrm{U}}\right]$. Under the assumption $\lambda \leq M_1^A/\Omega_1^A$, $\partial H^A/\partial\beta > 0$ while the sign of $\partial H^U/\partial\beta$ is ambiguous.

Next, we consider the effect of having access to credit and borrowing to pay for the establishment cost on H^A and H^U (Appendix A.14). We find that being able to borrow based on future returns will increase expected profits in the establishment period and lower them in the mature period. Upfront payments perform a similar function by increasing establishment period profit; instead, annual payments increase only mature period profits. Farmers who borrow to fund establishment may not experience a significant establishment period marginal utility change of increasing x_e under an upfront payment scheme but may experience a larger mature period marginal utility change of increasing x_e under an annual scheme. In this case, upfront payments and borrowing from credit will be substitutes. Farmers with access to credit may prefer larger mature period returns through annual payments for carbon mitigation than larger establishment period returns through upfront payments.

1.3 Numerical Simulation

A representative farmer in a county owns L acres of cropland. The farmer allocates the cropland between one conventional annual crop rotation and tillage (c) such that $x_C \in [0,1]$ is the share of land farmers allocate to the conventional crop and one perennial bioenergy crop (e) where farmers dedicate $1 - x_C$ share of land to the bioenergy crop. $\bar{T}$ is land tenure, and t depicts the discrete years during this period such that $t \in \{1,2..\bar{T}\}$. Conventional crops complete one lifecycle each year, while bioenergy crops complete one lifecycle during the fifteen-year cycle. We can separate the bioenergy crop lifecycle into an establishment period and a maturity period, with $\hat{t}$ being the number of years in the establishment period.

Bioenergy crops and corn stover provide carbon mitigation services from lifecycle conventional aviation fuel displacement, l per unit of biomass yield, which varies with feedstock yield, and from belowground soil carbon sequestration, b^{Harv} per unit of land, which may vary temporally over the crop lifecycle. Farmers can also affect soil carbon sequestration by switching rotation and tillage from what they would have chosen without carbon mitigation payment, b^{Switch}, per unit of land. Farmers receive carbon mitigation payment p^g per unit of carbon mitigated. Further, farmers harvesting cellulosic feedstocks receive a biomass payment of p^b per unit of biomass yield.

We consider two bioenergy crops; miscanthus and switchgrass. To reduce the dimensionality of the simulation, we assume that the representative farmer in a county only chooses one bioenergy crop between the two. Let e denote the bioenergy crop such that $e \in E \equiv \{misc, swit\}$. In the bioenergy crop establishment period, the farmer incurs a cost, w_t^e, per unit of land to establish the bioenergy crop for each year. The farmer can borrow the establishment cost if they have access to credit and pay back the annuity interest rate i, $A(w_t^e, .. w_{\hat{t}}^e, i)$, in the mature period. The farmer harvests the bioenergy crop, where the yield y_d^e is stochastic with distributions known to the farmer and yields realized at harvesting and is distinct for each land type. Miscanthus crop is harvested only in the mature period, while switchgrass produces harvestable yield in the establishment period. Under annual carbon mitigation payments, the farmer receives the value of carbon mitigated in the year farmers mitigate it. For bioenergy crops, returns per unit of crop d in year t is

$$\pi_{t,d}^{A,e} = \begin{cases} -Iw_t^e + p^g b_{d,t}^e, t \leq \hat{t}, d = misc \\ -Iw_t^e + (Jp^g l^e + p^b - v^e) y_d^e + p^g b_{d,t}^e - f^e, t \leq \hat{t}, d = swit \\ (Jp^g l^e + p^b - v_d^e) y_d^e + p^g b_{d,t}^e - f_d^e - (1 - I) A\left(w_t^e, .. w_{\hat{t}}^e, i\right), \quad t > \hat{t}, \end{cases} \tag{1.1}$$

where I is an indicator of whether the farmer has access to credit ($I = 1$) or not ($I = 0$), f_d^e is the fixed cost, v_d^e a variable cost, and p^b the payment per unit of biomass, p^g is the payment per unit of carbon mitigated, $l^e$is the lifecycle carbon mitigated in a year per unit of biomass, $b_{d,t}^e$ is the total soil carbon sequestration such that $b_{d,t}^e = b_t^{e,Harv} + b^{e,Switch}$, and J is an indicator of whether the farmer is paid for fossil fuel displacement or not ($J = 1$) or not ($J = 0$).

Alternatively, farmers may receive a lump sum upfront payment in the first year of planting bioenergy crops, the total value of carbon mitigated as given by $G = \left[\sum_{t=1}^{\overline{T}} \beta^{t-1} b_t^e + \sum_{t=\hat{t}}^{\overline{T}} \beta^{t-1} l^e E[y_d^e]\right]$. For bioenergy crops, profit per unit of land type d in year t under upfront carbon payments is

$$\pi_t^{U,e} = \begin{cases} p^g G - Iw_t^e - f^e, \quad t = 1, \\ -Iw_t^e - f^e, 1 < t \leq \hat{t}, d = misc \\ -Iw_t^e + (p^b - v^e) y_d^e - f^e, 1 < t \leq \hat{t}, d = swit \\ (p^b - v_d^e) y_d^e - f_d^e - (1 - I) A\left(w_t^e, .. w_{\hat{t}}^e, i\right), \quad t > \hat{t}, \end{cases} \tag{1.2}$$

where the farmer then maximizes his utility using $\pi_t^{U,e}$ instead of $\pi_t^{A,e}$. Returns per unit of land from bioenergy crops are denoted by π_t^e where $\pi_t^e = \pi_t^{A,e}$ or $\pi_t^e = \pi_t^{U,e}$ depending on the payment setup.

We consider two types of rotation for conventional crops, corn-corn (cc) or corn-soybean (cs) rotation, and two types of tillage, conventional tillage (ct) or reduced/no-tillage (nt). To reduce the dimensionality of the simulation, we assume that the representative farmer in a count can choose one conventional crop rotation and tillage combination out of eight. Let c denote the conventional crop rotation and tillage combination, and we have $c \in C \equiv \{(cc, ct), (cc, nt), (cs, ct), (cs, nt)\}$. The yields and prices of corn grain and soybeans are denoted by y_c^{corn}, $y_c^{soybean}$, p^{corn}, and $p^{soybean}$, respectively. The yields and prices of conventional crops are stochastic, with distributions known to the farmer and the yields and prices realized at harvesting. The fixed and variable costs of producing corn, soybeans, and corn stover are represented by f_c^{corn}, $f_c^{soybean}$, v_c^{corn}, $v_c^{soybean}$ respectively, where fixed costs (denoted by f_c^{corn}, and $f_c^{soybean}$) are per unit of land and variable costs (denoted by v_c^{corn}, and $v_c^{soybean}$) are per unit of yield produced. Conventional crop returns per unit of land for corn grain and soybeans under rotation-tillage-cover crop combination in set C can then be written as $\pi_c^{corn} = (p^{corn} - v_c^{corn}) * y_c^{corn} - f_c^{corn} + p^g b^{Switch}$ and $\pi_c^{soybean} = \left(p^{soybean} - v_c^{soybean}\right) * y_c^{soybean} - f_c^{soybean} + p^g b^{Switch}$. For corn-soybean rotation, we assume that half of the land is used for corn and half for soybeans. Overall, conventional crop returns without stover harvest is

$$\pi_c^{crop} = \begin{cases} \frac{1}{2}\pi_c^{\text{corn}} + \frac{1}{2}\pi_c^{\text{soybean}}, c \in \{(cs, ct), (cs, nt)\} \\ \pi_c^{\text{corn}}, c \in \{(cc, ct), (cc, nt)\}. \end{cases} \tag{1.3}$$

Additionally, farmers produce corn stover as a by-product of corn from any conventional crop choice. It may be harvested for biomass only if the farmer deems it profitable. The farmer receives a biomass price, p^b per unit of biomass produced through stover. The fixed and variable costs of producing corn stover for crop c are represented by f_c^s and v_c^s respectively, where fixed costs are per unit of land and variable costs are per unit of yield produced. Further, farmers who harvest stover and establish cover crops will see a reduction in stover yield, where $YldLoss^{stover}$ is the percentage loss in stover yield. We assume that one-unit stover yield generates l_c units of lifecycle carbon mitigation. We also assume that one unit of land harvesting stover will produce b_c^{Harv} units of carbon mitigation through soil carbon sequestration. Additional returns from corn stover per unit of land for land under corn grain in set *C* can then be written as $\pi_{\text{CCr}}^{\text{stover,corn}} = (Jp^b - v_c^s + p^g l_c) y_c^s (1 - CCr * YldLoss^{stover}) + p^g b_c^{Harv} - f_c^s$. As corn-soybean rotations will only produce half the corn. We denote returns from harvesting stover from corn from a rotation-tillage combination as

$$\pi_{\text{c,CCr}}^{\text{stover}} = \begin{cases} \frac{1}{2}\pi_{\text{CCr}}^{\text{stover,corn}} & , c \in \{(cs,ct),(cs,nt)\} \\ \pi_{\text{CCr}}^{\text{stover,corn}} & , c \in \{(cc,ct),(cc,nt)\}. \end{cases} \tag{1.4}$$

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

$$h_{\text{c,CCr}} = \begin{cases} 1, & E\left[\pi_{\text{c,CCr}}^{\text{stover}}\right] \geq 0 \\ 0, & E\left[\pi_{\text{c,CCr}}^{\text{stover}}\right] < 0. \end{cases} \tag{1.5}$$

The farmer chooses land allocations by maximizing her expected utility over one lifecycle of the bioenergy crop spanning the fifteen-year cycle. Land allocation share $x_C \in [0,1]$ denotes the total land the farmer assigns to a conventional crop on cropland. The remaining share of the land $(1 - x_C)$ is dedicated to bioenergy crops. The total acreage available for cultivation to the farmer is L. Additionally, α is an exogenous limit in the percentage share of land of the total bioenergy crop planted such that $1 - x_c \leq \alpha$. The representative farmer works under various exogenous risk-aversion, discount rate, and credit-constraint assumptions. We depict the farmer risk-aversion factor by λ. The farmer's discount rate is $\gamma \in [0,1]$ such that the discount factor $\beta = 1/(1 + \gamma)$. For any given conventional crop choice and bioenergy crop combination and cover crop choice, the farmer chooses x_C to maximize the following problem:

$$V_{e,c,CCr} = \max_{x_C} \sum_{t=1}^{\overline{T}} \beta^{t-1} E\left[u\left(L\left[x_C\left[\pi_{\mathrm{c}}^{crop} + h_c \pi_{\mathrm{c,CCr}}^{stover}\right] + (1 - x_C)\pi_t^e\right] | \beta, \lambda, I\right)\right] \tag{1.6}$$

$$\text{s.t. } x_C \leq 1,\ 1 - x_C \leq \alpha.$$

The farmer then chooses the conventional crop rotation and tillage, and bioenergy crop choice, and whether to harvest corn stover by selecting the highest expected utility, $V_{e,c,CCr}$ from all eight possible conventional and bioenergy crop combinations where $c \in C$, and $e \in E$, and $CCr \in \{0,1\}$. We solve at various exogenous biomass price levels p^b and carbon prices p^g, under various assumptions about the farmer’s risk and time preferences and her credit constraint situation.

1.4 Methods and Materials

1.4.1 Crop Yields

We simulate county-level yields of bioenergy crops (miscanthus and switchgrass) and conventional crops (corn and soybean) with the potential corn stover harvesting using the biogeochemical model DayCent. All crop yields are stochastic and obtained under 30 years of randomized weather conditions. We simulate conventional crop yields under eight permutations of two rotation types (corn-corn and corn-soybean), two tillage types (conventional and no-tillage), and two corn stover removal choices (with and without corn stover removal).

We perform our analysis for 2,168 counties on or to the east of the 100th meridian within the continental U.S. that produce corn or soybean and have simulated bioenergy and conventional crop yields using DayCent. Counties that produce corn or soybeans are determined based on pixel-level satellite data on land use from 2008 to 2015 by Jiang et al.(Jiang, Guan, Khanna, Chen, & Peng, 2021). In the numerical simulation, we consider corn-soybean and continuous corn rotations in counties where satellite data show soybean cultivation and consider only continuous corn in counties where satellite data shows no soybean cultivation. We apply a 25% penalty on corn yields for conservation tillage in our primary analysis following Chen et al. (2021), who show that yield under conservation tillage is not statistically different from conventional tillage; however, a yield penalty could arise when farmers adopt conservation tillage but do not change other management practices. We assume that the stover removal rate is 30% for conventional till and 50% for no-till, as determined by Hudiburg et al. (2016), to have low impacts on corn yield.

We separate the bioenergy crop lifespan into an establishment and a mature period. In the mature period, the farmer harvests the bioenergy crop annually. We assume that miscanthus reaches its mature period after two years of establishment. In contrast, switchgrass reaches the mature period within the first year.(Miao & Khanna, 2017a) Conventional crops are planted and harvested annually over the life of the bioenergy crop. Following Skevas et al. (2014), we set a limit for each county the land that can be converted to bioenergy crops at 25% to allow for the possibility of other unknown behavioral factors that may affect land use and prevent extreme changes in land use. Nitrogen application rates are those assumed by the DayCent model for bioenergy crops and row crops based on public databases (USDA), published historical data, and recommended fertilization rates. Additionally, we take potassium and phosphorus application rates from Dwivedi et al. (2015). We model the reduced need for fertilizer from Swanson et al. (2018).

1.4.2 Carbon mitigation benefits

The calculation of carbon benefits from replacing fossil fuels is the difference in grams of CO_2 for the same amount of energy produced between sustainable aviation fuel from cellulosic ethanol feedstocks and conventional aviation fuel lifecycles. We calculate the lifecycle carbon emission intensity through a lifecycle analysis for each biomass source. Our lifecycle analysis for the carbon intensity of sustainable aviation fuel (hereafter aboveground LCA) produced (Appendix B.2) includes feedstock production, processing, conversion to ethanol, and the conversion of ethanol into sustainable aviation fuel using carbon mitigation parameters from Dwivedi et al. (2016) and GREET. Establishing bioenergy crops may incur initial soil carbon losses followed by an accrual period toward a new soil carbon equilibrium (Chen et al., 2021). We simulate the change in soil carbon levels for each year of the planting period for miscanthus and switchgrass and eight permutations of rotation, tillage, and corn stover removal under conventional crops using the DayCent model. To determine payments for the additional soil carbon sequestration with feedstock production that a unit of land provides, we need to determine the change in soil carbon sequestration for each feedstock choice relative to an initial rotation and tillage choice with no carbon payments. In response to the carbon payment, farmers may switch from a conventional crop to a bioenergy crop or begin harvesting corn stover while keeping their existing crop rotation and tillage choice or by changing tillage and/or rotation to increase stover harvest or to mitigate more soil carbon. We determine an initial rotation and tillage choice with conventional crops without carbon payments. We then determine the soil carbon change relative to the initial rotation and tillage choice when a farmer harvests corn stover harvest or switches to a bioenergy crop through carbon payments at the county level. The calculation of soil carbon effects for each cropping choice is detailed in Appendix B.4.

1.4.3 Crop returns

We calculate bioenergy crop costs at the county level for each year in the establishment and mature periods with input quantities from the Iowa State Extension and input prices from the National Agricultural Statistics Service (NASS).(Hoque, Artz, & Hart, 2020) In the establishment period, the farmer incurs a cost per unit of land to establish the energy crop. In the mature period, the farmer harvests the bioenergy crop annually and incurs costs associated with harvesting (Appendix B.5).

Farmers receive a biomass price per unit of biomass yield each year they harvest biomass. Farm gate biomass price at 13% moisture is set exogenously from \$0 to \$150 per metric ton (\$ Mg^{-1}) of biomass at intervals of \$10 and is assumed constant over time. We select a biomass price of \$40 \$ Mg^{-1} to illustrate the effect of carbon payments when biomass payments cannot incentivize high adoption. We also show how results differ when farmers receive no biomass price (\$0 Mg^{-1}) and a higher biomass price (\$60 Mg^{-1}).

Farmers also receive an annual carbon payment based either on the carbon price per unit of carbon mitigated in the year (hereafter referred to as annual payment) or a lump-sum upfront payment of all the carbon mitigated over the life of the crop (hereafter referred to as upfront payment). The carbon price is set exogenously from \$0 to \$150 per metric ton of carbon mitigated (Mg^{-1} CO_2) and is assumed constant over time (Appendix B.8). We assume that soil carbon sequestered during the lifespan of the crop will be permanent and do not consider the mechanisms of soil carbon loss over time or due to replanting. Our analysis, therefore, provides an upper bound to the profitability of incentivizing soil carbon sequestration through carbon mitigation payments. Further, accurate soil carbon sequestration measurement is cost-prohibitive and varies spatially (McCarl and Murray, 2002). We consider cases of carbon payment that take into account only the aboveground LCA (annual aboveground payment and upfront aboveground payment). Further, we assume that the entire carbon payment will go to the farmer and not to other agents in the value chain (e.g., processing plants or transporters). Our analysis, therefore, provides an upper bound to a farmer’s expected payment from carbon mitigation policies. We discuss these underlying assumptions for carbon mitigation payments in more detail in Appendix B.7.

We then generate annual returns over the life of the crop for each SAF feedstock at exogenously given biomass and carbon mitigation prices (formally detailed in Appendix B.9). Biomass from stover harvest sells for the same price as bioenergy crops. It provides carbon mitigation benefits from fossil fuel displacement and (mostly negative) changes in soil carbon sequestration from stover harvest and (ambiguous) changes to soil carbon sequestration from changes in tillage and rotation. The net returns from any given rotation and tillage choice of conventional crops include the returns from corn grain and soybeans (cost and stochastic prices of conventional crops detailed in Appendix B.10 and Appendix B.11), as well as returns from the possible harvest of corn stover along with associated carbon mitigation payments (calculation of corn stover returns are described in Appendix B.12 and conventional crop net return calculations and equations are presented in Appendix B.13).

A joint yield-price distribution is assumed where the farmer knows the distribution of conventional crop prices and yields for all crops estimated for their county to calculate stochastic returns. We model the joint distributions using the copula approach (a modeling process that first describes and then replicates the dependence structure between multiple stochastic variables) following Miao and Khanna (2017a), Yan (2007), and Du and Hennessy (2012). The joint yield-price distribution consists of crop yields linked to eight conventional crop rotations, tillage, corn stover harvest choices, two bioenergy crop choices, and prices for corn and soybean. We use these joint yield-price distributions, associated carbon mitigation benefits, spatially varying input costs, biomass, and carbon mitigation payments to calculate stochastic returns for each crop option as described in the numerical simulation for a fifteen-year planting period at exogenously varying biomass and carbon mitigation prices. We assume the farmers maximize their utility using a Constant Absolute Risk-aversion (CARA) utility function. We follow Hennessy, Babcock, and Hayes (1997) to set the Absolute Risk-aversion (ARA) parameter to imply a risk premium of 10% for low risk-aversion and 50% for high risk-aversion simulations. As there is no consensus on discount rates, we use two rates of 2% (low discount rate) and 10% (high discount rate), following Miao and Khanna(Miao & Khanna, 2017b). These rates are similar to those used by the Environmental Protection Agency (EPA) for determining the social cost of carbon

(US Environmental Protection Agency, 2022, n.d.) and allow a comparison of carbon mitigation prices to the social cost of carbon. High discount rates indicate less willingness to wait for future returns. They will lower the value the farmer assigns to future bioenergy crop returns relative to present returns. Further, farmers with access to credit to pay for the costly establishment of bioenergy crops borrow to pay for the establishment costs and pay it back with interest in the mature period.

We use stochastic returns to simulate land allocation to cover crop adoption, rotation, and tillage change across the eight permutations of risk-aversion (high and low) and time-discounting (high and low), with and without access to credit (yes and no) under an exogenously varying carbon mitigation payment price. For ease of discussion, we refer to the farmer profile of high time-discounting, high risk-aversion, and credit-constrained as the high constraint scenario and the low time-discounting, low risk-aversion, and not credit-constrained as the low constraint scenario. For each permutation, we can aggregate the total carbon mitigated and area under various cropping practices across the rainfed U.S. and examine the spatial distribution of adoption of conservation cropping practices.

1.5 Simulation Results

1.5.1 No Payment for Carbon Mitigation

Without carbon mitigation payments, biomass production for sustainable aviation fuels only occurs when the biomass price at the farm-gate is above \$40 Mg^{-1}. High discount rates, high risk-aversion, and credit-constraints discourage miscanthus production due to the crop's long establishment period, riskiness, and high establishment cost. For example, under the high-constraint scenario (Figure 1.1-3 (a)), at biomass prices of \$40 and \$80 per metric ton (Mg^{-1}), miscanthus is not adopted. Instead, farmers opt to grow switchgrass, providing .9 and 9.9 Billion gallons of SAF (Bil Gal Yr-1) and mitigating 0.7 and 161.8 million metric tons of carbon (M Mg CO_2). Spatially, under the high-constraint scenario, switchgrass is grown in a few counties in the south at biomass prices of \$40 (Figure 1.4 (c)) and across the rainfed region at 80 Mg^{-1} (Figure 1.4 (d)). Conversely, in the low-constraint scenario (Figure 1.1-3 (h)), miscanthus provides 3.9 and 14.8 Bil Gal Yr-1 and mitigating 0.1 and 208.6 M Mg $CO_{2.}$ Farmers also grow switchgrass, providing .02 and 0.65 Bil Gal Yr-1 and mitigating 0.4 and 9 M Mg CO_2. In the low-constraint scenario, miscanthus (Figure 1.4 (e, f)) is grown in the Midwest. In contrast, switchgrass is grown in a few counties in the southern states (Figure 1.4 (g,h)).

Farmer risk preferences affect SAF from corn stover harvest less than bioenergy crops. For example, at biomass prices of \$40 and \$80 Mg^{-1}, stover provides 0 and 3.75 Bil Gal Yr-1 and mitigating 0 and 18.8 M Mg CO_2 in the high constraint scenario (Figure 1.1-3 (a)). Similarly, in the low constraint scenario (Figure 1.1-3 (h)), corn stover provides 0 and 3.71 Bil Gal Yr-1 and mitigating 0 and 18.3 M Mg CO_2. Corn stover provides negative soil carbon sequestration, which is offset by aviation fuel displacement. For illustration, in the high constraint scenario, 0 and 8.31 M Mg CO2 of soil carbon are removed, and 0 and 27.1 M Mg CO2. are mitigated through aviation fuel displacement at biomass prices of \$40 and \$80 Mg^{-1}, respectively (with similar numbers for the low constraint scenario). Corn stover harvest is concentrated in the Midwest and some in the southern states (Figure 1.4 (i,j)).

1.5.2 Annual Payments for Carbon Mitigation

We illustrate the effect of annual carbon mitigation payment when biomass price is \$40 Mg^{-1} on feedstock adoption, SAF production, and carbon mitigation. Annual carbon mitigation incentivizes comparable bioenergy feedstock adoption under all scenarios (Figure 2.1-3 (a-h)). Additionally, without carbon payments, annual payments do not significantly change feedstock choice or the spatial patterns from what farmers would have grown at higher biomass prices. For example, miscanthus is not adopted under the high-constraint scenario (Figure 2.1-3 (a)) with annual carbon payments of \$20 and \$60 Mg-1 $CO2_{.}$ Farmers, however, grow switchgrass, providing 5.7 and 10.9 Bil Gal Yr-1 and mitigating 89.3 and 164.1 M Mg CO_2. Under the low-constraint scenario (Figure 2.1-3 (h)), farmers grow a mix of bioenergy crops, where miscanthus provides 5.2 and 14.4 Bil Gal Yr-1 and switchgrass provides .045 and 0.93 Bil Gal Yr-1 and mitigating 73.2 and 218 M Mg CO_2. Annual carbon payments also have little effect on the spatial pattern of where biomass feedstocks are adopted, significantly increasing adoption in areas where farmers grow these crops in our simulation under higher biomass prices. For example, under annual carbon mitigation payments of $20 Mg-1 and $60 Mg-1 CO2, switchgrass is grown in a few counties in the southern states and throughout the rainfed `region, most significantly in the Midwest respectively under the high-constraint scenario (Figure 2.4 (c-d)). Further, annual payments increase miscanthus and switchgrass production around the Midwest and southern states under the low-constraint scenario (Figure 2.4 (e-f)).

Significantly higher annual payments are required to incentivize corn stover harvest (Figures 2.1-3 (a-h)), with carbon mitigation payments of $20 Mg-1 and $60 Mg-1 CO2 providing 0 and 0.39 Bil Gal Yr-1 and mitigating 0 and 3 M Mg CO_2.with adoption being similar across farmer risk preference scenarios. At carbon mitigation payments of $100 Mg-1 and $150 Mg-1 CO2, corn stover provides 1.6 and 4.5 Bil Gal Yr-1 and mitigates 10.9 and 23 M Mg CO2, with adoption being similar across farmer risk preference scenarios. Corn stover harvests occur primarily in the Midwest at low payments and across the northern and Delta regions at higher payments under all risk-aversion scenarios (Figure 2.4 (g,h)).

We present the effect of an annual carbon payment based on no biomass price ($0 Mg-1, Figures A1.1-3) and a higher biomass price ($80 Mg-1 Figures A1.4-6). We show that while higher carbon prices are required to incentivize adoption, the spatial pattern of adoption is similar to that presented above. In the case of high biomass prices, higher carbon prices are needed to incentivize further adoption as SAF feedstocks are produced throughout the rainfed region.

1.5.3 Upfront Payments for Total Lifecycle Carbon Mitigated

We consider the effect of an upfront carbon mitigation payment based on a carbon price of \$40 Mg^{-1} C on feedstock adoption, SAF production, and carbon mitigation. Under upfront payments, carbon mitigation payments are most effective in increasing carbon mitigation under high constraint scenarios, where they incentivize farmers to substitute away from switchgrass and increase their miscanthus production; however, overall bioenergy crop adoption and carbon mitigation is generally lower than from annual payments. For example, under the high-constraint scenario (Figures 3.1-3 (a)), upfront carbon payments of \$20 and \$60 Mg^{-1} CO_2 increase miscanthus to provide 3.0 and 3.6 Bil Gal Yr-1 and mitigate 42.6 and 60.5 M Mg CO_2 and no switchgrass adoption. Under the low-constraint scenario (Figures 3.1-3 (h)), upfront carbon payments increase miscanthus adoption to provide 1.3 and 4.5 Bil Gal Yr-1, mitigate 19.4 and 63.1 M Mg CO2, and no switchgrass adoption. As farmers who harvest corn stover are paid annually regardless of payment scheme, upfront payments also similarly increase corn stover production to that under annual payments (Figure 3.1-3 (a-h)), with adoption being similar across farmer risk preference scenarios.

Upfront carbon payments differ in where biomass feedstocks are adopted, with each feedstock being adopted in regions that provide significant carbon mitigation regardless of farmer risk preferences. For example, with carbon mitigation payments of \$20 Mg^{-1} and \$60 Mg^{-1} CO2, farmers produce mostly miscanthus in the Midwest (Figure 3.4 (a, d)), switchgrass (Figure 3.4 (b, e)) in the Delta region in the south, and stover in the Midwest (Figure 3.4 (c, f)) in the low-constraint and high-constraint scenarios.

We present the effect of upfront carbon payments based on no biomass (\$0 Mg-1, Figures A2.1-3) and a higher biomass price (\$80 Mg-1 Figures A2.4-6). We show that while higher carbon prices are required to incentivize adoption, the spatial pattern of adoption is similar to that presented above. In the case of high biomass prices, higher carbon prices are required to incentivize further adoption as SAF feedstocks are produced throughout the rainfed region.

1.5.4 Payments For Aboveground Carbon Displacement Only

When farmers are paid only for carbon mitigation from aviation fuel displacement (and are not paid for the soil carbon sequestration they provide), they first plant fewer bioenergy crops at the same carbon price than if they were paid for aviation fuel displacement and soil carbon sequestration (we also compare dollar per Mg CO2 mitigated across all payment schemes in section 1.5.5). For example, with a biomass price of $40 Mg-1 and a carbon price of $20 Mg^{-1} CO2 in the high-constraint scenario (Figure A3.1-3 (a)), an upfront payment for only aviation fuel displacement incentivizes 5.79 Bil Gal Yr-1 mitigating 43.6 M Mg CO_2 from bioenergy crops relative to. 5.7 Bil Gal Yr-1 mitigating 43.6 M Mg CO_2 when farmers are also paid for soil carbon sequestration. A similar trend holds in the low-constraint scenario (Figure A3.1-3 (h)) and for upfront payments (Figure A4.1-3 (a,h)).

Second, payments for aviation fuel displacement only incentivize farmers to harvest more stover than under payment, including carbon mitigation from soil carbon sequestration. However, this is because farmers producing corn stover are not penalized for the soil carbon loss they cause. This results in higher carbon intensities for the SAF produced through corn stover. For example, with a biomass price of $40 Mg-1 and a carbon price of $60 and $100 Mg^{-1} CO2 in the high-constraint scenario (Figure A3.1-3 (a)), an upfront payment for only aviation fuel displacement incentivizes 0.8 and 3.27 Bil Gal Yr-1 mitigating 3.7 and 16.2 M Mg CO_2 from corn stover relative to. 0.39 and 1.63 Bil Gal Yr-1 mitigating 2.4 and 10.9 M Mg CO_2 when farmers are paid for soil carbon sequestration (Figure 2.1-3 (a)). Similar results hold across farmer risk profiles and under upfront and annual payments.

1.5.5 Costs to mitigate carbon under various payment schemes

Next, we compare the effectiveness of upfront and annual payment schemes in incentivizing aggregate carbon mitigation in high and low-constraint scenarios (Figure 4). Annual payments have the lowest cost per unit of carbon mitigated in the high and low constraint scenarios. In the high constraint scenario

(Figure 4 (a)), an expenditure of $8 Billion results in the highest carbon mitigation through annual payments (mitigating 145 million metric tons of carbon per year (M Mg CO2 Yr-1)), then through annual payments for aboveground sequestration only (105 M Mg CO2 Yr-1), with upfront payments incentivizing the lowest mitigation (75 M Mg CO2 Yr-1). These programs cost $55, 76, and 106 Mg-1 CO2 to mitigate carbon under each payment scheme. Similar results hold under low constraint scenarios (Figure 4 (h)) where an expenditure of $8 Billion results in the highest carbon mitigation through annual payments (210 M Mg CO2 Yr-1) followed by upfront payments (80 M Mg CO2 Yr-1) and cost $38 and 100 Mg-1 CO2 to mitigate carbon under each payment scheme. Additionally, upfront payments are most effective in incentivizing low-cost adopters with high time-discounting low risk-aversion (Figure 4 (b,d,f)). For example, in the credit-constrained scenario (Figure 4 (b)), an expenditure of $2.5 Billion results in carbon mitigation of 135 M Mg CO2 Yr-1 through upfront payments compared to 110 M Mg CO2 Yr-1 through annual payments, costing $18 and 22Mg-1 CO2 to mitigate carbon under each payment scheme.

1.6 Discussion and Conclusion

We show that the carbon intensities of SAF from cellulosic ethanol feedstocks are significantly lower than other sources of aviation fuel. However, the intensities vary spatially and by crop. SAF sourced from miscanthus has the lowest carbon intensities across feedstocks, followed by switchgrass and corn stover. SAF sourced from miscanthus has the lowest carbon intensities in the lower Midwest, switchgrass in the Mississippi delta states, and corn stover across the Midwest. When farmers are not incentivized to grow SAF feedstocks, they require high biomass payments (more than \$50 Mg^{-1}, with high adoption happening at prices above \$80 Mg^{-1}). When farmers are risk-averse, credit-constrained, or have low time-discounting, they grow switchgrass and harvest more corn stover over growing miscanthus, even in regions where miscanthus provides higher yield and higher carbon mitigation potential. This is due to high establishment costs and a long time to see positive returns. Carbon-based payments incentivize farmers to grow cellulosic ethanol feedstocks for SAF production at lower biomass prices and incentivize farmers to choose feedstocks with the lowest carbon intensity in that region. Upfront carbon mitigation payments can incentivize risk-averse, impatient, and credit-constrained farmers to grow miscanthus, displacing up to 75 Mil. Mg CO2e Yr^{-1}. Annual carbon mitigation payments can also incentivize up to 175 Mil Mg CO2e Yr^{-1} through a spatial mix of feedstock choices. We also find that a SAF Credit-style payment may not be sufficient to incentivize adequate bioenergy crop production. Our work shows the potential of bioenergy crops in SAF production as these crops provide soil carbon sequestration from biomass production (up to 230 Mil. Mg CO2 Yr^{-1}) in addition to carbon mitigation from aviation fuel displacement.

Previous research typically has not considered the implications of carbon mitigation payments when considering SAF production through cellulosic feedstock adoption for farmers who are risk-averse, impatient, or credit-constrained. Our work highlights the importance of and has several implications for, the payment program design in incentivizing bioenergy feedstocks. First, our results suggest that bioenergy feedstock adoption will require high biomass prices without carbon mitigation payments, especially in cases where farmers are risk-averse, impatient, or credit-constrained. Second, we find that the design of carbon payments plays a significant role in the quantity of biomass produced by each feedstock and the mitigation of aggregate carbon. The amount of biomass produced by each feedstock and aggregate carbon mitigated under various designs of carbon mitigation payments is also impacted by farmer risk-aversion, time-discounting, and credit-constraints. Specifically, we find that upfront payments drive more bioenergy crop adoption in high-constraint scenarios where farmers adopt significant amounts of miscanthus. In comparison, annual payments drive more bioenergy crop adoption overall in low-constraint and high-constraint scenarios where farmers adopt substantial amounts of miscanthus and switchgrass. Additionally, we find that upfront payments may be more effective than annual payments to incentivize adoption in farmers who are either credit-constrained or have high time-discounting but are not risk-averse. Policymakers may do well to include provisions that appeal to farmers with differing risk-aversion, credit-constraints, and time-discounting when designing payments that incentivize cellulosic ethanol feedstock for SAF production best. Third, we show that while corn stover has the potential to be adopted across a wide area in the rainfed U.S., the carbon mitigation potential is significantly smaller than that of bioenergy crops. Further, our research highlights the importance of accounting for soil carbon sequestration benefits. Payment schemes where farmers are not paid for their soil carbon effects result in less bioenergy crop adoption and higher corn stover adoption. Such payment designs do not account for the positive non-market effects that bioenergy crops provide through soil carbon sequestration. Additionally, such payment designs do not account for the negative soil carbon sequestration from sources like corn stover, which, when accounted for, results in higher carbon intensities for SAF sourced from corn stover.

We provide a comprehensive economic analysis of the potential of SAF production through U.S. agriculture. In doing so, we consider lifecycle carbon mitigation along the entire SAF value chain and soil carbon sequestration provided by producing SAF feedstock. Additionally, we design cost-effective (in terms of dollar per unit of carbon mitigated) policies to incentivize SAF production and carbon mitigation. Our study should interest economists, policy analysts, and those interested in programs that support sustainable aviation fuel production, carbon mitigation, or bioenergy production.

References

Chen, B., Gramig, B. M., & Yun, S. D. (2021). Conservation tillage mitigates drought-induced soybean yield losses in the US Corn Belt. *Q Open*, *1*(1), 1–29. https://doi.org/10.1093/QOPEN/QOAB007

Chen, L., Blanc-Betes, E., Hudiburg, T. W., Hellerstein, D., Wallander, S., Delucia, E. H., & Khanna, M. (2021). Assessing the Returns to Land and Greenhouse Gas Savings from Producing Energy Crops on Conservation Reserve Program Land. *Environmental Science & Technology*, *55*(2), 1301–1309. https://doi.org/10.1021/ACS.EST.0C06133

Du, X., & Hennessy, D. A. (2012). The planting real option in cash rent valuation. *Applied Economics*, *44*(6), 765–776. https://doi.org/10.1080/00036846.2010.522524

Hoque, M., Artz, G., & Hart, C. (n.d.). Estimated Cost of Establishment and Production of Miscanthus. Retrieved November 25, 2020, from https://www.extension.iastate.edu/agdm/crops/html/a1-28.html

Hudiburg, T. W., Wang, W., Khanna, M., Long, S. P., Dwivedi, P., Parton, W. J., … Delucia, E. H. (2016). Impacts of a 32-billion-gallon bioenergy landscape on land and fossil fuel use in the US. *Nature Energy*, *1*(1), 1–7. https://doi.org/10.1038/nenergy.2015.5

Jiang, C., Guan, K., Khanna, M., Chen, L., & Peng, J. (2021). Assessing Marginal Land Availability Based on Land Use Change Information in the Contiguous United States. *Environmental Science & Technology*, *55*(15), 10794–10804. https://doi.org/10.1021/acs.est.1c02236

McCarl, B., & Murray, B. (2002). Agricultural Soil Carbon Sequestration: Economic Issues and Research Needs. *Paper, Department of Agricultural*. Retrieved from http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/0875.pdf

Miao, R., & Khanna, M. (2017a). Costs of meeting a cellulosic biofuel mandate with perennial energy crops: Implications for policy. *Energy Economics*, *64*, 321–334. https://doi.org/10.1016/j.eneco.2017.03.018

Miao, R., & Khanna, M. (2017b). Effectiveness of the Biomass Crop Assistance Program: Roles of Behavioral Factors, Credit Constraint, and Program Design. *Applied Economic Perspectives and Policy*, *39*(4), 584–608. https://doi.org/10.1093/aepp/ppx031

Skevas, T., Swinton, S. M., & Hayden, N. J. (2014). What type of landowner would supply marginal land for energy crops? *Biomass and Bioenergy*, *67*, 252–259. https://doi.org/10.1016/j.biombioe.2014.05.011

US Environmental Protection Agency. (2022). *Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Re*.

US Environmental Protection Agency, C. C. D. (n.d.). *Social Cost of Carbon, December 2015*. Retrieved from https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.

Yan, J. (2007). Enjoy the Joy of Copulas: With a Package copula. *Journal of Statistical Software*, *21*(4), 1–21. https://doi.org/10.18637/jss.v021.i04

Figures

Figure 1.1: Area under feedstock production with no carbon payment under various biomass prices for differing farmer discount, risk, and credit constraint profiles

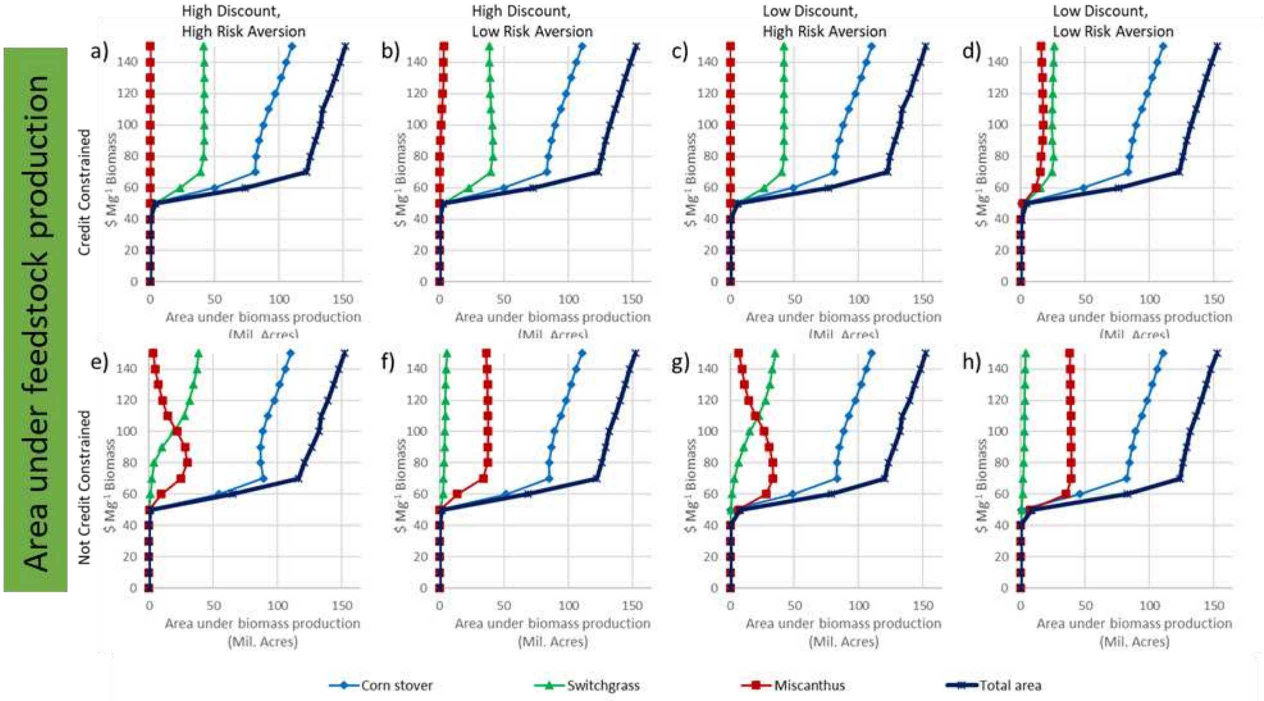


Figure 1.2: Sustainable Aviation Fuel production with no carbon payment under various biomass prices for differing farmer discount, risk, and credit constraint profiles

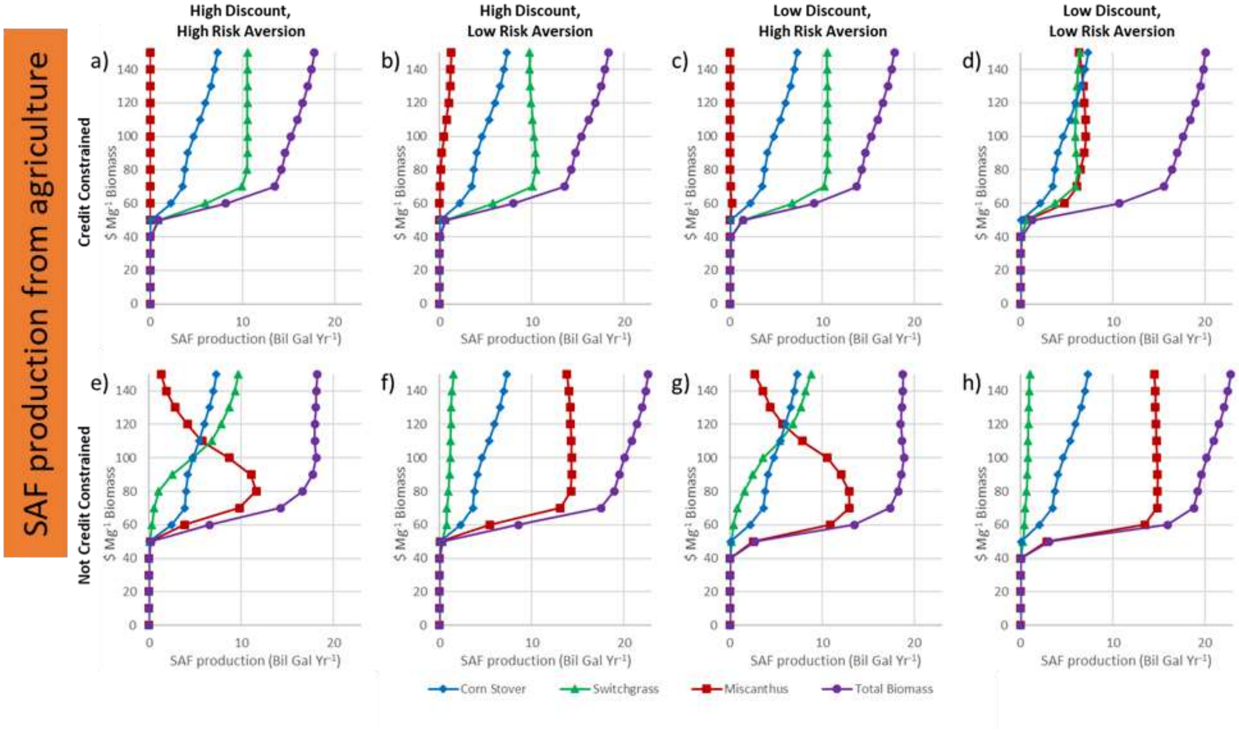


Figure 1.3: Sustainable Aviation Fuel production with no carbon payment under various biomass prices for differing farmer discount, risk, and credit constraint profiles

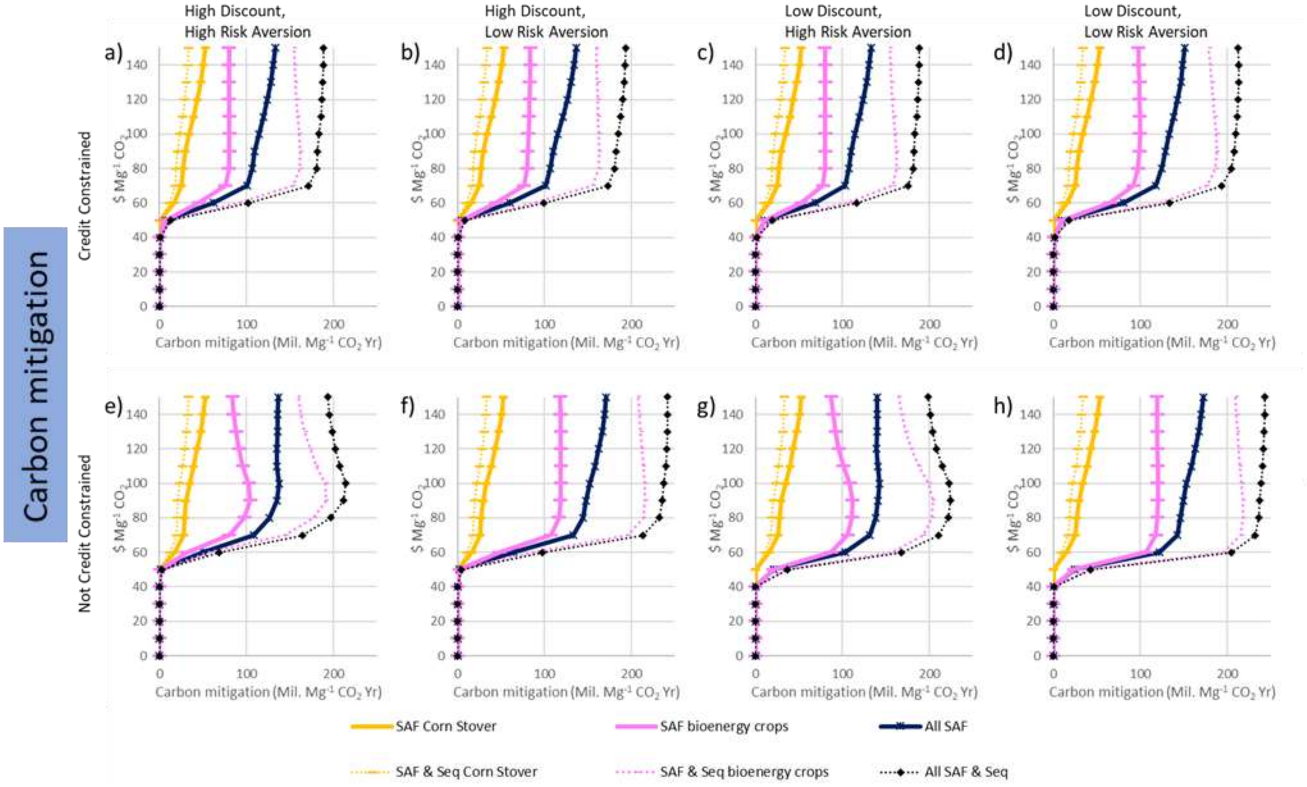


Figure 2.1: Area under feedstock production under annual carbon payment for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

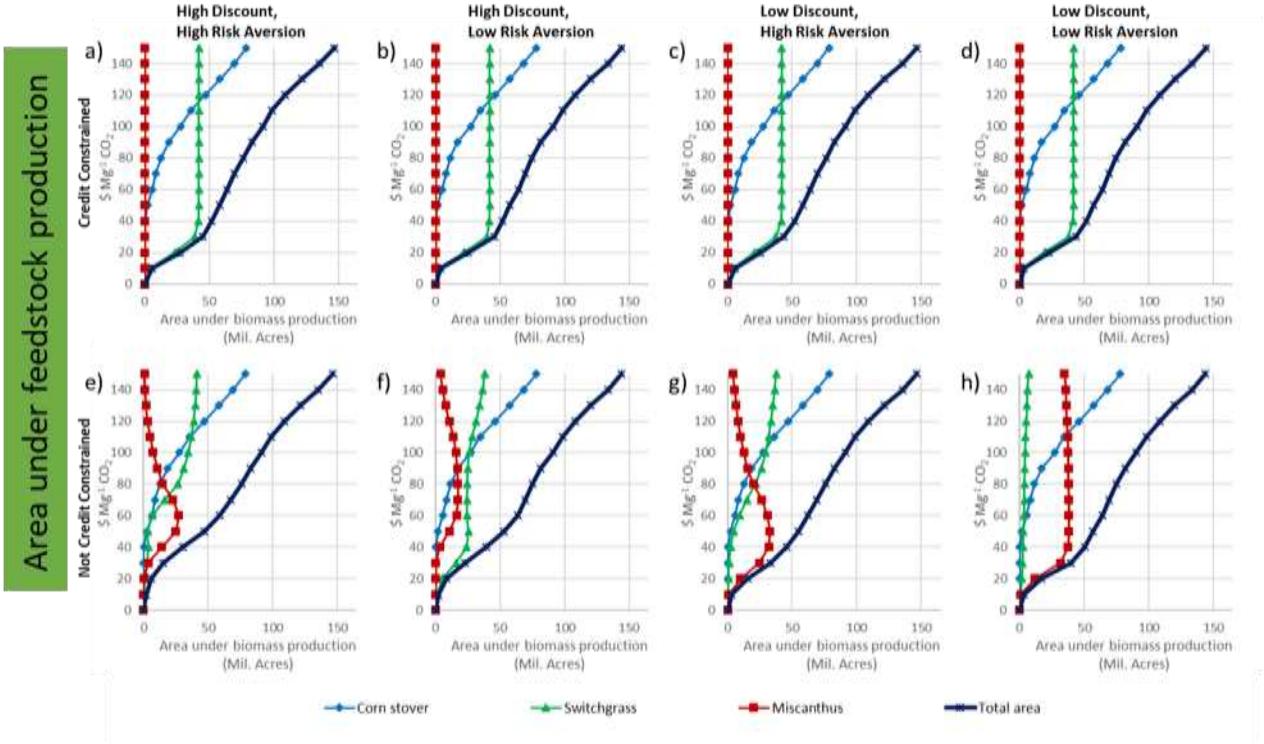


Figure 2.2: Sustainable Aviation Fuel production under annual carbon payment for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

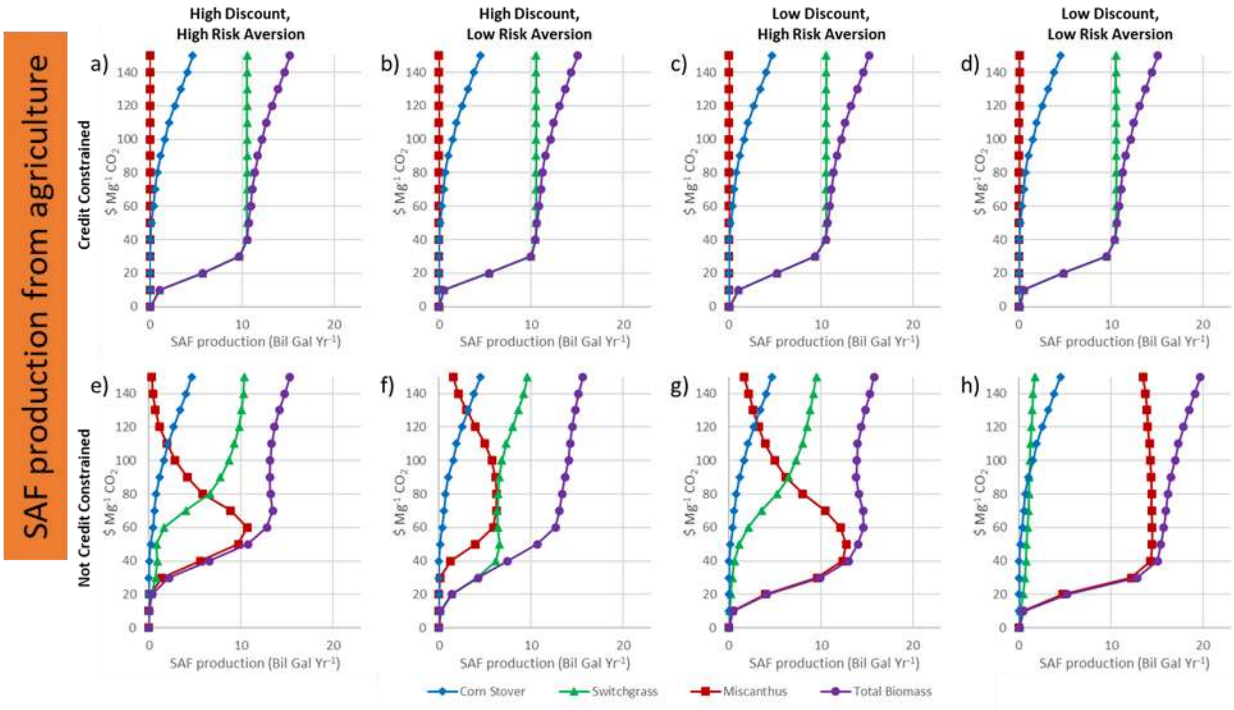


Figure 2.3: Carbon mitigation from SAF production under annual carbon payment for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

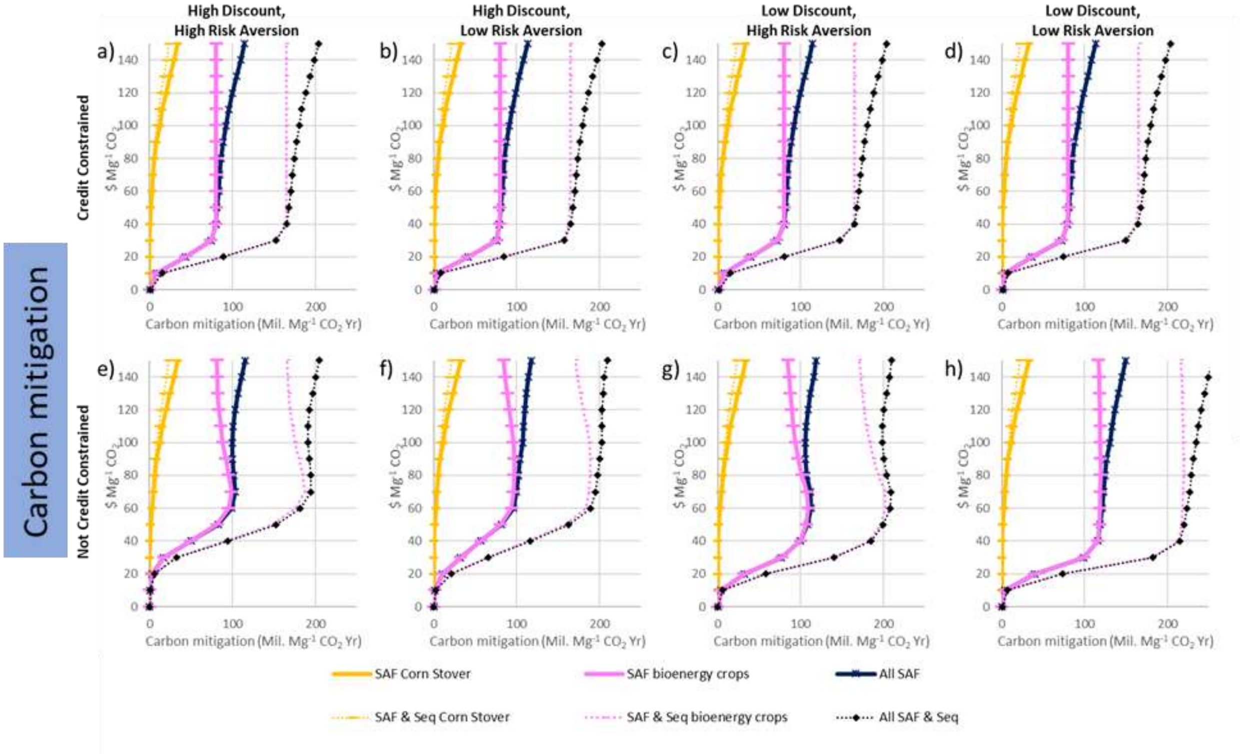


Figure 3.1: Area under feedstock production under upfront carbon payment for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

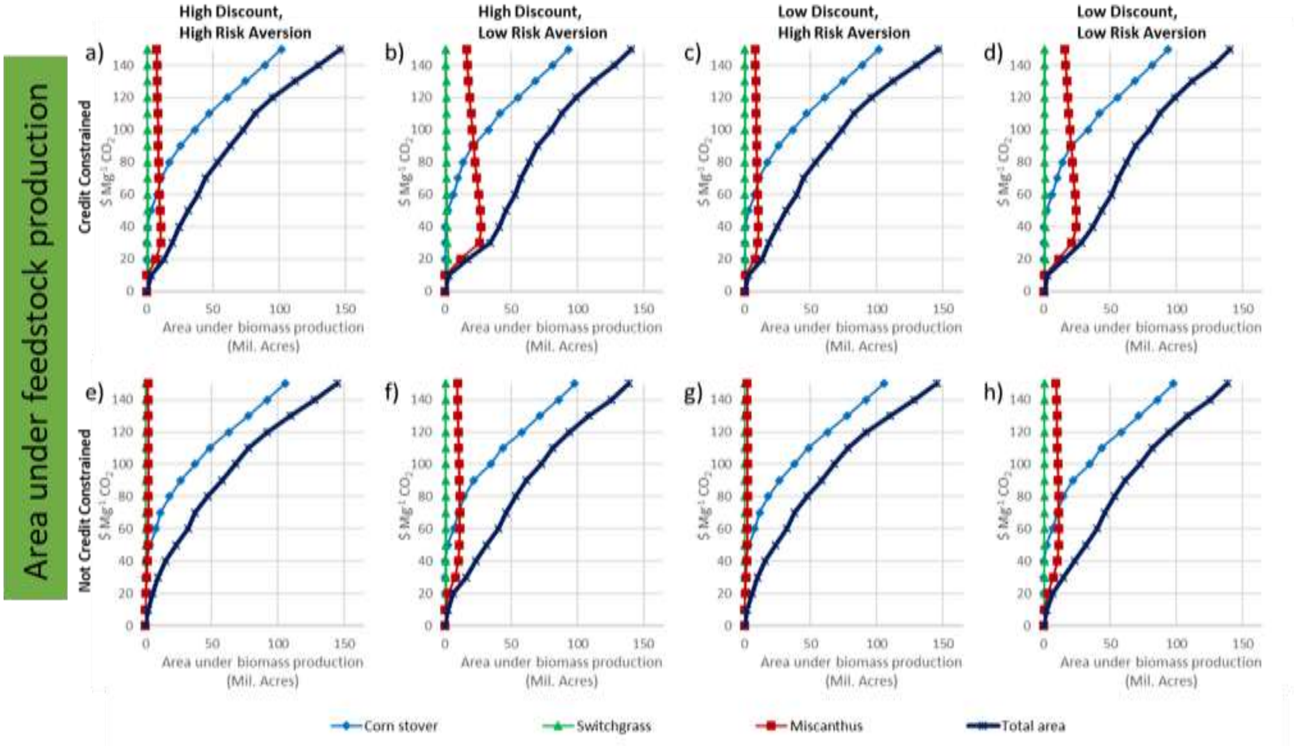


Figure 3.2: Sustainable Aviation Fuel production under upfront carbon payment for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

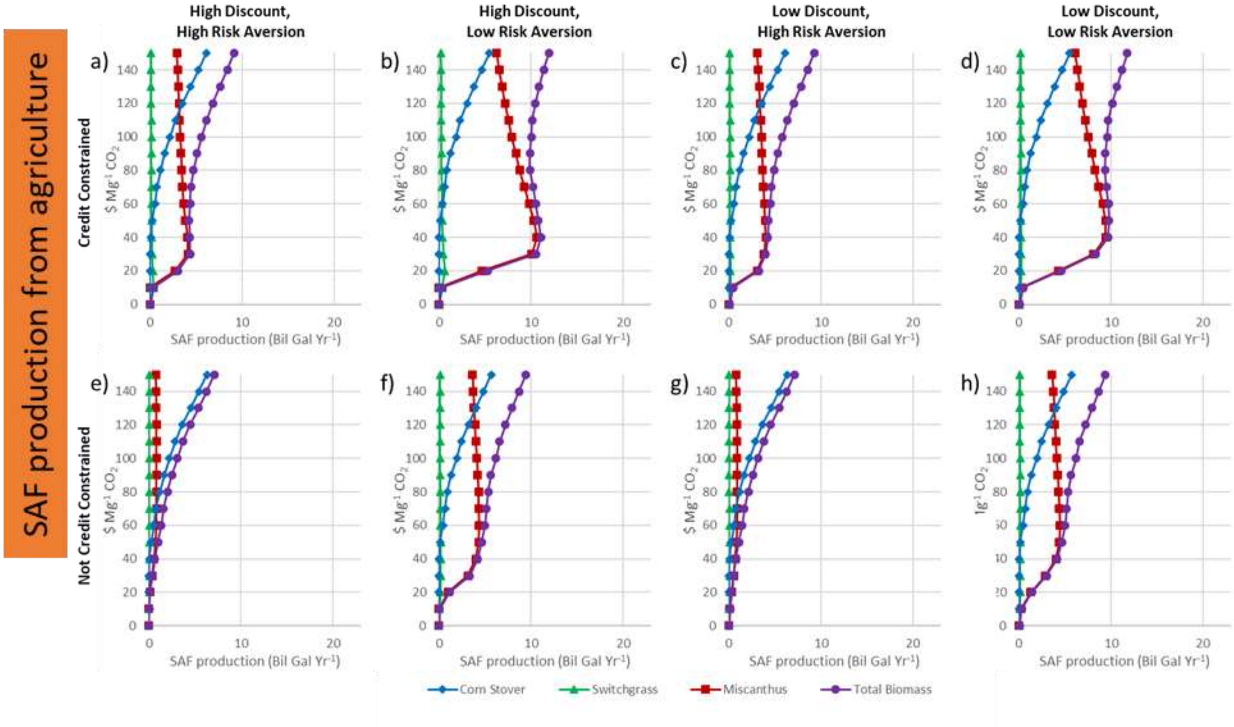


Figure 3.3: Carbon mitigation from SAF production under upfront carbon payment for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

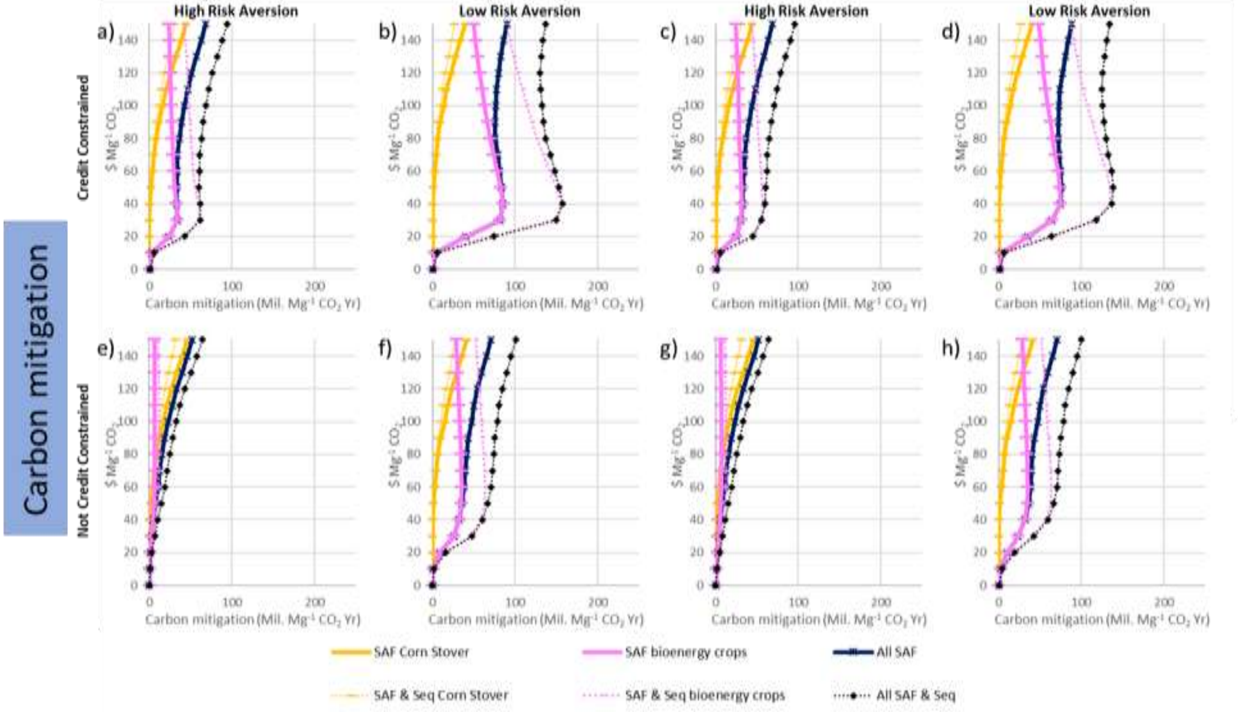
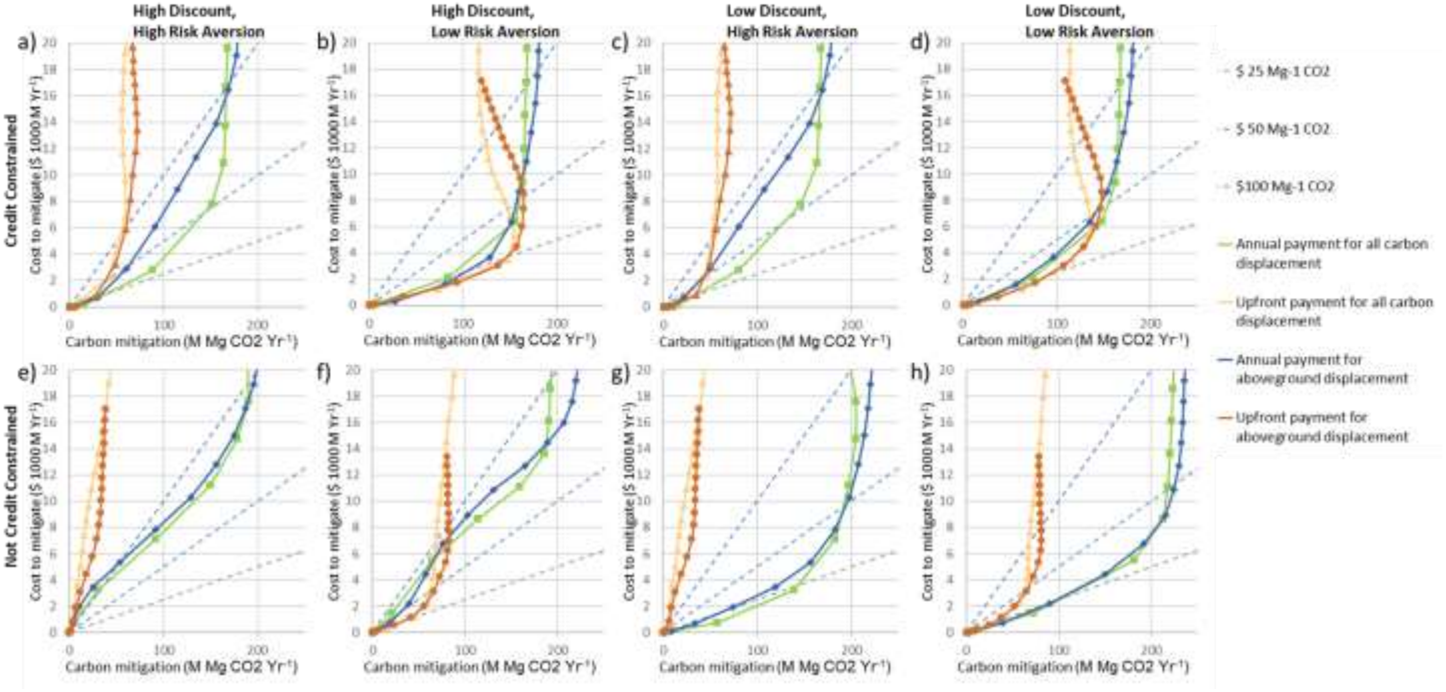


Figure 4: Carbon mitigation from SAF production at various expenditure levels for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1



Appendix

Appendix Figures

Figure A3.1: Area under feedstock production under annual carbon payment for aboveground displacement only for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

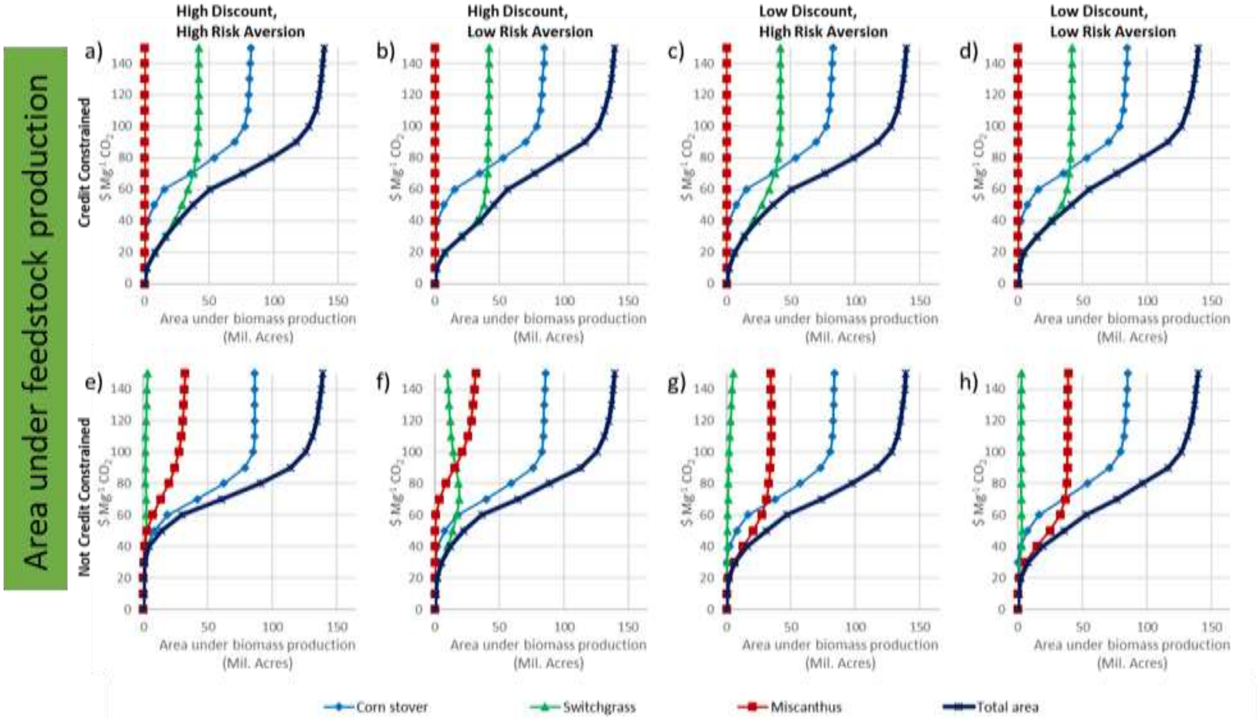


Figure A3.2: Sustainable Aviation Fuel production under annual carbon payment for aboveground displacement only for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

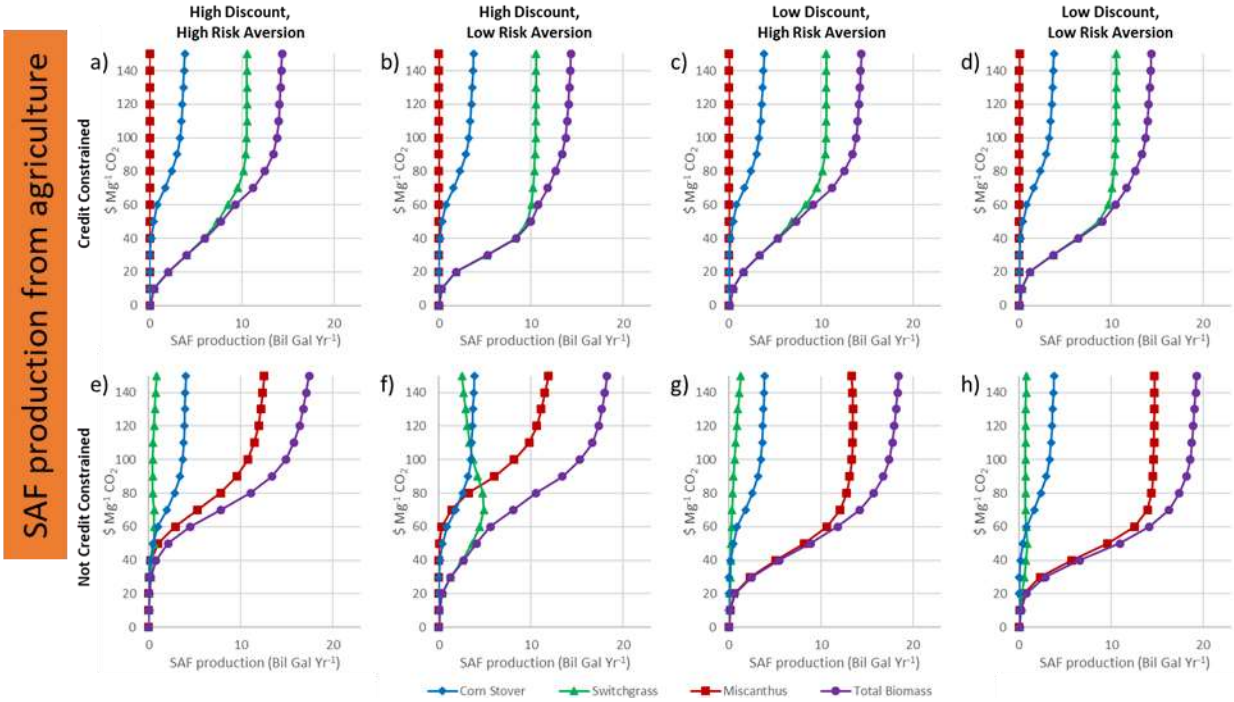


Figure A3.3: Carbon mitigation from SAF production under annual carbon payment for aboveground displacement only for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

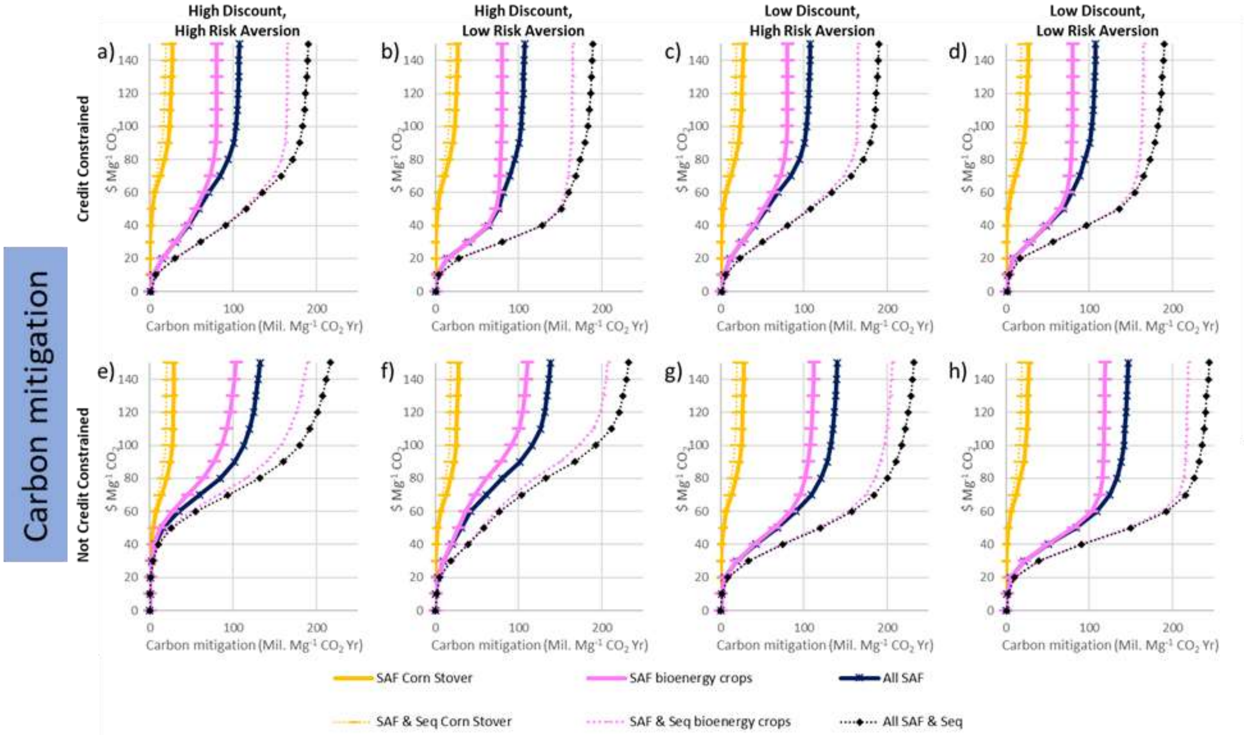


Figure A4.1: Area under feedstock production under upfront carbon payment for aboveground displacement only for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

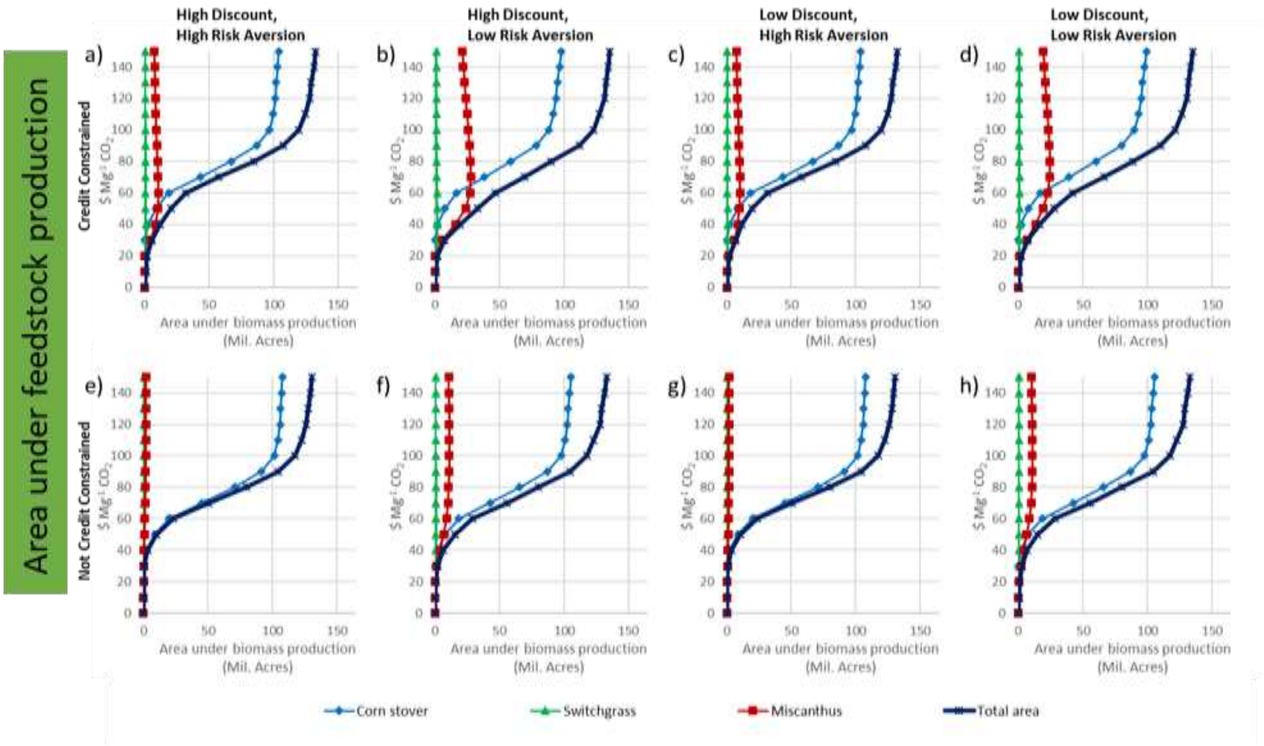


Figure A4.2: Sustainable Aviation Fuel production under upfront carbon payment for aboveground displacement only for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1

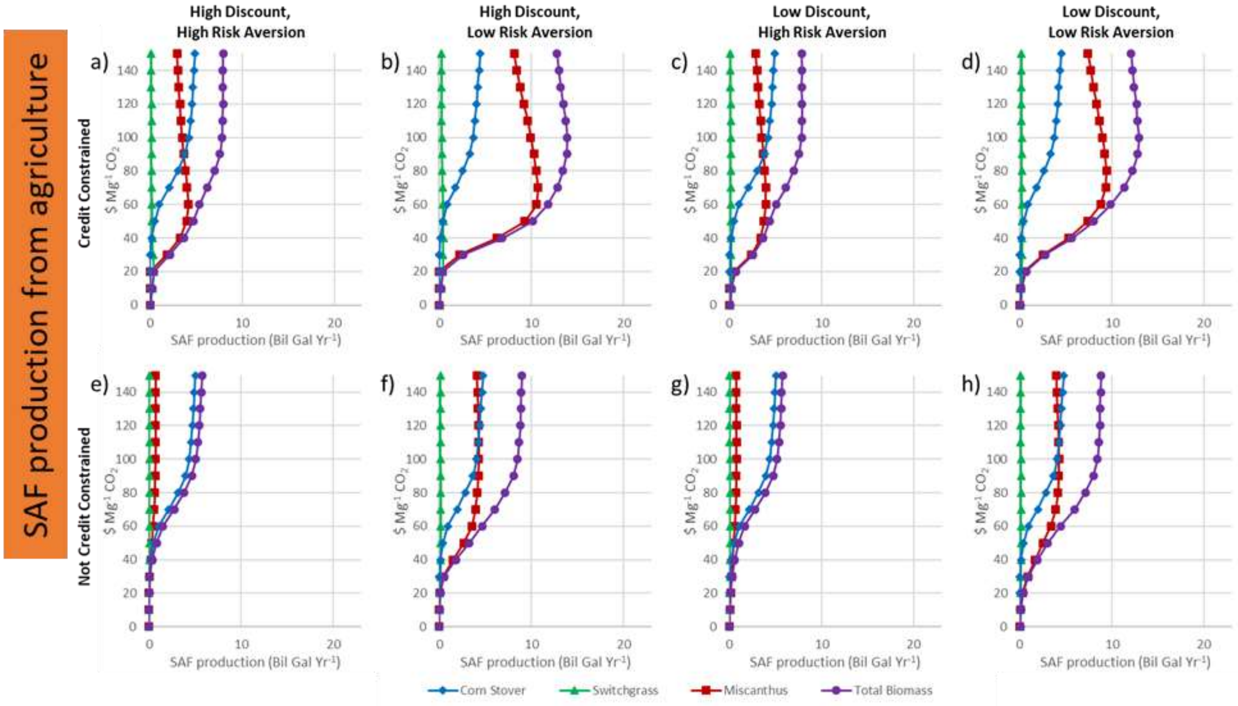


Figure A4.3: Carbon mitigation from SAF production under upfront carbon payment for aboveground displacement only for differing farmer discount, risk, and credit constraint profiles at a biomass price of $40 Mg-1