Abstract

Despite the potential for cover cropping to enhance soil carbon sequestration and improve soil productivity, as well as numerous incentive programs, its adoption has remained low. We develop a framework that links an economic model with a biogeochemical model to analyze the incentives for utility-maximizing farmers, with varying risk and time preferences, to adopt cover cropping across spatially heterogeneous counties in the rainfed region of the United States, depending on the extent to which they internalize its net private benefits. We compare the cost-effectiveness of three types of incentive payments: practice/cost-share-based, price-premium-based, and carbon-based, in inducing carbon mitigation through cover crop adoption under various levels of internalization of the potential private benefits of cover cropping. We find that farmers' lack of internalization of potential private benefits can explain the low rates of adoption of cover cropping and the ineffectiveness of existing program payment rates in inducing adoption. We quantify the program payments needed to induce widespread adoption under each of the three policies, and show that these need to be much higher than offered by existing programs. Our analysis shows that building farmer awareness of the potential private benefits of cover cropping can be a mechanism to lower the program costs of mitigating carbon emissions with cover cropping.

Keywords: Agricultural Policy, Carbon Mitigation, Climate-Smart Practices, Corn, Cover Crops.

JEL codes: Q12, Q15, Q18.

Incentivizing Cover Crop Adoption: Effectiveness of Alternative Policy Approaches

1. Introduction

Growing interest in carbon removal strategies that utilize land as a sink for carbon leads to attention to climate-smart crop production practices that can enhance soil carbon sequestration (Bonnie et al. 2021; Elder 2021; Braun 2021; Yarmuth 2022). Cover crops grown between harvest and planting of conventional crops have the potential to sequester substantial carbon on cropland (Poeplau & Don, 2015; Eagle et al., 2012). Studies have estimated the technical potential for carbon sequestration with cover crops to be between 50 and 126 million metric tons of carbon dioxide per year (million Mg CO_2 per year)[1,2] on 167 million acres of corn and soybean in the US Midwest; this could reduce 8% to 21% of the emissions from agriculture (Jaglo et al., 2023; Eagle et al., 2012).[3] While cover crops provide external benefits, they also have the potential to improve soil health, which can lead to higher soil productivity and profitability for farmers in the long term.

Several practice-based conservation programs have been established to incentivize cover crop adoption by providing cost-share payments and paying for conservation benefits. Funding for these programs increased substantially through the Inflation Reduction Act (Yarmuth 2022). The federal 40B tax credit offered a tax credit for producing Sustainable Aviation Fuel (SAF) from corn and soybean produced with climate smart practices, such as cover cropping, with the magnitude of the tax credit scaling with the carbon intensity reduction. The USDA's Partnerships for Climate-Smart Commodities program sought to develop supply chains and market-based opportunities to offer premium prices for commodities produced with climate-smart practices[4]. Additionally, numerous voluntary carbon credit programs that are either practice-based or carbon performance-based have been set up by the private sector to pay farmers for carbon offsets through cover cropping.

Despite the potential private and public benefits of cover cropping and the presence of market and policy incentives, the adoption of cover crops has grown at a slow rate over the last two decades and was less than 5% of US cropland in 2022 (Zulauf et al. 2024). This has led to a growing body of literature examining the impacts of cover cropping on farm outcomes. Studies show that, in addition to imposing upfront planting costs and the cost of termination, their adoption can have a negative impact on conventional (cash) crop yields in the first few years (Raimbult et al. 1991; Qin et al. 2021; Deines et al. 2023; Qin et al. 2023). However, cover crops also have the potential to provide various private benefits for farmers during the period of adoption and in future periods (Rejesus et al. 2021; Plastina et al. 2020). There is considerable evidence that cover crops can improve soil health and potentially increase conventional crop yield in the long term (Qiu et al. 2024; Blanco 2023; Ma et al. 2023; Olson et al. 2014).[5] Moreover, cover crop adoption may reduce conventional crop yield risk, leading to more predictable returns (Aglasan & Rejesus, 2022; Won et al., 2023; Larson et al., 2001; Campbell et al., 2021; Ma et al., 2023). It may also reduce the need for fertilizer application and costs for erosion repair and weed control (Myers et al., 2019; Blanco, 2023; Bergtold et al., 2017).

Evidence on the direction and magnitude of these impacts is mixed and varies with the choice of cover crop, the method and timing of planting and termination, and location (Rejesus et al., 2021). The lack of generalizable and definitive evidence of the benefits of cover cropping for a farmer can lead to varying beliefs about them and differing extents to which a farmer may consider them when making their adoption decisions. This is supported by farmer surveys, which indicate that farmers differ in their awareness of these private benefits (SARE, 2023; Campbell et al., 2021) and that farmer perceptions about the benefits of cover cropping influence their adoption decisions (Sawadgo et al. 2021; Plastina et al. 2020; Myers et al. 2023; Dunn et al. 2016). Myers et al. (2023)

find that most non-adopters were unaware of the potential for long-term benefits and believed that adopting cover crops would reduce crop yield. Even with full internalization of the benefits, the incentives to adopt cover cropping will vary with farmers' risk and time preferences, which will affect the willingness to trade-off future yield gains with current costs and yield reduction and the value associated with the risk-reducing benefits of cover cropping.

This raises several questions that are addressed in this paper. How does the cover crop adoption decision vary with the farmer risk and time preferences and the extent of internalization (or awareness) of these private benefits from cover cropping? With given risk and time preferences, how does the adoption pattern vary spatially with heterogeneity in costs and private benefits of cover cropping to the extent that the latter is considered by a farmer? How does the extent of internalization of these private benefits with cover cropping by farmers affect the cost-effectiveness of alternative types of policies to induce widespread cover cropping and the payment needed in carbon equivalent terms for the external benefits of cover cropping?

We address these questions by developing a stylized framework to examine the economic incentives for an expected utility-maximizing farmer to adopt cover cropping with varying risk and time preferences and perceptions about the private benefits of cover crop adoption, with and without any policy or carbon credit market incentives. We analyze the extent to which there is under-adoption, not only due to the absence of compensation for the external benefits of cover cropping but also because farmers may not even be internalizing the potential private benefits of cover cropping. We analyze the implications of internalizing the various private benefits of cover crop adoption one at a time to isolate the key factor that could change their incentives to adopt cover crops and how this varies with the farmer's risk and time preferences.

We then apply this framework to examine the cost-effectiveness of three policy instruments

88 in inducing cover crop adoption and their carbon mitigation outcomes under various assumptions
89 about the extent to which farmers internalize the private benefits of cover cropping and farmer risk
90 and time preferences. These policy instruments serve as proxies for real-world payment programs
91 (to be described in the next section) to incentivize cover cropping and include annual cost-share
92 payments based on the cost of adopting cover crops or uniform payments per unit of land for
93 growing cover crops (*Practice-Based* payments), performance-based payments linked directly to
94 carbon mitigation provided by cover crops (*Carbon-Based* payment), and a yield-based uniform
95 price premium for conventional crops produced with cover crops (*Price-Premium-Based*
96 payment). Both cost-share based and adoption-based *Practice-Based* payments reduce the direct
97 costs of adopting cover crops (Sawadgo et al., 2021; Harkins et al., 2022), while *Carbon-Based*
98 and *Price-Premium-Based* payments increase the revenue from farming with cover cropping.
99 Since the yield and soil carbon sequestration impacts of cover cropping are expected to vary
100 spatially and over time, we link the economic model with a biogeochemical model, DayCent, to
101 analyze the spatial heterogeneity in the share of acres on which a utility-maximizing representative
102 farmer in each county will decide to plant cover crops. We consider varying levels of
103 internalization of the private benefits of cover cropping and farmer risk and time preferences. This
104 analysis also considers the stochasticity in conventional crop yields and prices at the county level.
105 It thus incorporates the underlying risks associated with conventional crop production that can also
106 vary spatially. We assess the aggregate carbon mitigated on cover cropped acres and compare the
107 effectiveness of alternative policies in mitigating carbon by incentivizing cover crops.
108 A few studies have used crop-budgeting approaches to analyze the profit impacts of cover
109 cropping and shown that it can have negative impacts on expected short-term profits in the absence
110 of any policy incentives (Schnitkey et al., 2024; Plastina et al., 2018). We extend these studies by

examining the extent to which the view of cover cropping as a long-term investment in improving soil health and reducing the riskiness of crop production can affect farmer adoption incentives depending on their risk and time preferences and awareness of the various impacts of cover cropping. Several studies have examined the maximum technical potential for cover crop adoption based on estimates of the total amount of land area under row crops with various rotation practices that are potentially available to plant cover crops and estimated its implications for carbon mitigation (Burnett et al., 2024; Jaglo et al., 2023; Kladivko et al., 2014; Eagle et al., 2012). We build on these studies by examining the economic incentives to adopt cover crops and the costs of achieving varying levels of carbon mitigation with cover crops.

We also extend studies that have examined the marginal costs of the abatement of carbon emissions with cover crops across various regions in the US (Burnett et al. 2024; Jaglo et al. 2023). Unlike these studies, which assume uniform sequestration rates and costs within a region and use cost-share payments offered by the Environmental Quality Incentives Program (EQIP) as a proxy for cover cropping costs, we consider not only the policy payout costs of adoption but the full costs and benefits of adoption for farmers and for carbon mitigation and heterogeneity in these at a fine spatial scale and with various risk and time preferences.

Additionally, we compare policy costs under alternative types of policy instruments and examine the policy incentives needed to induce varying levels of adoption of cover crops. This adds to the existing empirical literature analyzing the effect of existing policy incentives in driving cover crop adoption (Plastina et al. 2024; Park et al. 2023; Connor et al. 2022; Rejesus et al. 2021; Rosenberg et al. 2024; Aglasan et al. 2024). A growing body of literature infers the drivers of cover crop adoption by using survey data on socio-demographic farm and farmer characteristics as proxies for underlying costs and benefits of cover cropping (Myers and Watts 2015; Arbuckle

and Roesch-McNally 2015; Lee and McCann 2019; Sawadgo et al. 2021a; Canales et al. 2024). We extend these studies by directly analyzing the role that various types of costs and benefits appear to be playing in influencing adoption.

Our stylized analysis provides several new insights into the barriers to cover crop adoption and the type and extent of policy incentives needed to achieve more widespread adoption and carbon mitigation benefits. It shows that a lack of farmer awareness or willingness to consider the long-term yield benefits of cover cropping as a climate-smart practice, coupled with high risk-aversion and present-bias, are key barriers to adoption. We also find, counter-intuitively, that the aggregate costs of carbon abatement do not vary much across the practice-based, carbon-based, and yield-based policies considered here or with the risk and time preferences of farmers; instead, these costs vary substantially with the extent of internalization of the private benefits of cover cropping across all types of policies. Moreover, the choice of policy instrument can lead to substantial variation in the spatial pattern of the cover cropping induced and thus lead to regional variations in program payments.

The rest of the paper is organized as follows. Section 2 reviews the existing policies to incentivize cover crops to provide a context for the stylized policy analysis in this paper. Section 3 outlines a stylized modeling framework to simulate incentives for adopting cover crops by a utility-maximizing farmer. Section 4 details the data sources and model calibration used in our simulation model. Section 5 presents the results of our simulation, and Section 6 concludes by discussing the policy implications of efforts to induce cover crop adoption.

2. Policy Review

We briefly review the existing policy and market landscape for incentives for cover crop adoption to provide context and support the policy choices considered in our analysis. Existing

157 incentives for cover crop adoption from federal programs are primarily through the EQIP and in
158 the form of cost-share payments to offset a percentage of the estimated cost of the practice,
159 generally up to 75% (Coppess 2023a and 2023b). Campbell et al. (2021) report that cost-share
160 payments offered to farmers for cover crops ranged from $15 to $75 and averaged $45 per acre.
161 Other programs, such as the Conservation Stewardship Program (CSP), offer practice-based
162 payments to expand or continue climate-smart practices. Payments for cover crops in Illinois
163 ranged between $5.59 and $10.31 per acre for various cover crop configurations, with a typical
164 payment of $8.25 per acre. Additionally, state-level programs in Delaware, Illinois, Indiana,
165 Iowa, Kansas, Maryland, Missouri, Ohio, and Virginia offer various types of payments for cover
166 crop adoption (Jaglo et al., 2023). The largest of these programs is a cost-share program in
167 Maryland, paying farmers an equivalent of $45 to $95 per acre. Most programs in the Midwest
168 provide payments equivalent to $5 to $25 per acre.[6] In addition, the USDA's Climate-smart
169 Commodities Partnership program seeks to develop market-based supply chains that would
170 provide a premium price per unit output of commodities produced using climate-smart practices.
171 Cover crop production was also being incentivized by the 40B Sustainable Aviation Fuel
172 (SAF) Tax Credit established under the Inflation Reduction Act, which made corn and soybean-
173 based SAF eligible for the tax credit if these feedstocks are produced with climate-smart
174 practices that reduce the carbon intensity of SAF below 50% of that of petroleum jet fuels (IRS,
175 2024).[7] This tax credit offered a sliding scale of carbon-based payment per ton of CO_2 ranging
176 between $150 and $200;[8] however, how much will be passed through to the farmers was unclear.
177 Lastly, a growing number of voluntary private market programs are in place that seek to
178 monetize the farmer-provided carbon offsets that are in demand by companies seeking to achieve
179 net zero goals (Plastina et al.,2019; Wongpiyabovorn et al., 2022; Mishra et al., 2021). The

payment mechanism and amount vary across programs. Some programs pay farmers per acre for adopting a climate-smart practice.[9] Others offer payments based on the quantity of carbon reduced through these practices.[10] Carbon payment for some programs is fixed (with most programs offering payments ranging from \$20 to \$30 per Mg CO_2);[11] for others, payment may be linked to the value of the carbon credit sale.[12]

Our analysis considers the effectiveness of stylized versions of these policies. We consider *Practice-Based* payments that range from \$0 to \$85 per acre per year of cover crop planted at intervals of \$5 per acre. We also consider price premiums on conventional crops grown with a cover crop under *Price-Premium-Based* payments, which range from 0 to 15 percent (%) per bushel (bu.) of corn and soybeans and vary in intervals of 1%. Lastly, we analyze the effects of *Carbon-Based* payments based on the units of carbon mitigated in the year those units are mitigated. Carbon payment is set exogenously and ranges from \$0 to \$150 per metric ton of carbon dioxide mitigated (per Mg CO_2) at intervals of \$10 per Mg CO_2. We assume all payments will be constant over the planning period. Our analysis considers the potential of only one policy instrument in incentivizing cover crop adoption at a time.

3. Conceptual Framework

We simulate the economic incentives for the adoption of cover crops on cropland by a risk-averse, present-biased, expected-utility-maximizing representative farmer in a county. The farmer is assumed to grow a conventional crop r, and choose the share of L acres of cropland to plant with cover crops ($c1$) or not ($c0$), each year (t) over a given period $\bar{T}$. The cover crop adoption choice is represented by h, such that $h \in H \equiv \{c0, c1\}$. The farmer can assign a percentage of their land to each of these two choices such that each $x_h \in [0,1]$ is the portion of land dedicated to that choice, where $\sum^H x_h = 1$. The profit per unit of land at time t for each of these choices is $\pi_{h,t}$. The

farmer's overall utility is given by $V = \sum_{t=1}^{\overline{T}} \beta^{t-1} E\left[u\left(\sum^{H} L x_h \pi_{h,t} \,|\lambda\right)\right]$ where $u(\cdot)$ is the annual utility function that takes the form of a Constant Absolute Risk-Aversion (CARA) with properties $u''(\cdot) \leq 0 \leq u'(\cdot)$ and $\beta = 1/(1 + \gamma)$ is the discount factor, with $\gamma \in [0,1]$ as the discount rate. Finally, λ is the measure of risk-aversion.[13] The farmer maximizes their expected utility,

$$\max_{x_h} V = \sum_{t=1}^{\overline{T}} \beta^{t-1} E\left[u\left(\sum^{H} L x_h \pi_{h,t} \,|\lambda\right)\right], \quad s.t. \sum^{H} x_h = 1. \tag{1}$$

The yields and prices of conventional crops are stochastic, with distributions known to the farmer and the yields and prices realized at harvesting. Conventional crop yield is represented as $y^r + \epsilon^y$ where y^r is the mean yield, and ϵ^y is the associated stochastic term such that $E(\epsilon^y) = 0$ and $Var(\epsilon^y) = \sigma^y$. Prices offered for conventional crops are represented as $p^r + \epsilon^p$ where p^r is the mean price and ϵ^p is the associated stochastic term such that $E(\epsilon^p) = 0$ and $Var(\epsilon^p) = \sigma^p$. Without cover crops ($c0$), annual profit per unit of land from each conventional crop is calculated using yields, prices, and fixed and variable costs (f^r and v^r, respectively) and is depicted by $\pi_{c0,t} = (p^r + \epsilon^p - v^r)(y^r + \epsilon^y) - f^r$.

Cover crop planting involves a cost of establishing and terminating the cover crop, denoted by f^{CovCr}, per unit of land per year. We assume that the farmer expects a loss of yield from adopting cover crops and an increase in the long-term (*Long-Term-Yield* benefit) if they internalize that benefit. Cover crops also temporally reduce the yield risk of conventional crops (*Yield-Risk-Reduction* benefit). We represent the percentage change in conventional crop mean yield (due to farmer and long-term yield benefits) and yield riskiness relative to those without cover crop adoption at time t as $Y_{M,t}^{Loss}$ $Y_{M,t}^{LT}$ and $Y_{R,t}^{}$, respectively. We also assume that growing cover crops reduces the cost of inputs per unit land for conventional crops (*Cost-Saving* benefit),

denoted by S^r. Farmers may, however, vary in their awareness of the various costs and benefits of cover cropping. We denote K_R, K_S, and $K_{Y,t}$ as the binary parameters that represent whether or not farmers are aware of *Yield-Risk-Reduction*, *Cost-Saving*, and *Long-Term-Yield* benefits of cover crop adoption, respectively. In each case, these terms equal 0 when farmers do not have knowledge of the private benefits and 1 when they do. *Long-Term-Yield* benefits, $K_{Y,t}$, only apply in the long-term and equal 0 in the short-term. The perceived returns from conventional crops with cover crop ($c1$) configurations under no policy (NP) payments can then be written as

$$\pi_{c1,t}^{NP} = (p^r + \epsilon^p - v^r)\Big(\big(1 + \big(1 - K_{Y,t}\big)Y_{M,t}^{Loss} + K_{Y,t}Y_{M,t}^{LT}\big)y^r + \big(1 + K_R Y_{R,t}\big)\epsilon^y\Big) + K_S S^r - f^{CovCr} - f^r. \quad (2)$$

As there are multiple sources of risk in our model, we note that the loss or an increase in mean yields through $Y_{M,t}$ will implicitly decrease and increase the overall riskiness of returns by increasing the effect of price risk, ϵ^p.

Policy instruments: We consider three policy instruments to incentivize cover crop adoption beyond the privately optimal level in the absence of any policy (or *No-Policy instrument*). First, farmers may receive uniform *Practice-Based* payments per acre (p^{acre}) of land adopted under cover crops. In this case, the perceived per-acre returns from conventional crops with cover crop ($c1$) configurations under *Practice-Based* payments can be written as

$$\pi_{c1,t}^{Practice} = \pi_{c_1,t}^{NP} + p^{acre}. \quad (3a)$$

Farmers may receive a *Price-Premium-Based* payment based on conventional crop yield ($p^{premium} \geq 0$) where $p^{premium}$ is the additional percentage payment per unit of conventional crop yield. Returns from conventional crops with cover crop ($c1$) configurations under *Price-Premium-Based* payments can be written as

$$\pi_{c1,t}^{PricePremium} = \pi_{c_1,t}^{NP} + p^{premium}(p^r + \epsilon^p)\left(\left(1 + \left(1 - K_{Y,t}\right)Y_{M,t}^{Loss} + K_{Y,t}Y_{M,t}^{LT}\right)y^r + \left(1 + K_R Y_{R,t}\right)\epsilon^y\right). \quad (3b)$$

In the case of *Price-Premium-Based* payments, an increase in payments ($p^{premium}$) will increase the effect of both ϵ^p and ϵ^y on the overall riskiness of returns.

We represent the carbon mitigated by cover crops, through soil carbon sequestration and fertilizer reduction, by g units of carbon per year per unit of land. Farmers receive annual *Carbon-Based* incentive payments per unit of carbon mitigated (p^{ghg}). The returns from conventional crops with cover crop ($c1$) under *Carbon-Based* payments are represented as

$$\pi_{h=c1,t}^{Carbon} = \pi_{c1,t}^{NP} + p^{ghg} g. \quad (3c)$$

Under baseline and each policy instrument, farmers maximize eqn. (1) by choosing the portion of land on which to adopt cover crops (x_h for each $h \in \{c0, c1\}$) in a county with exogenous parameters for payments in each of the three policy instruments ($p^{acre}, p^{ghg}, p^{premium}$), farmers knowledge of private benefits (K_S, $K_{Y,t}$, K_R), and farmer risk and discount factors (λ, β).

Under each policy instrument and risk and discount factors, we assume a farmer will adopt cover crops if their expected utility with non-zero cover crop adoption (i.e., $x_{c1} > 0$) is greater than without cover crops (i.e., $x_{c1} = 0$). As such, farmers can be incentivized to adopt cover crops through payments that are large enough to make their expected utility with non-zero cover crop adoption at least as high as their expected utility without cover crops under each policy instrument. The level of payment needed under each policy may differ across counties due to spatial heterogeneity in carbon benefits, private benefits, and effects of cover crop adoption on yield and yield riskiness. The payment level needed to incentivize cover crop adoption will differ

261 across policy instruments and counties, depending on the degree of heterogeneity of these cover
262 crop parameters at the county level.

263 **4. Data and Model Calibration**

264 We simulate cover crop adoption choices for 2,153 counties east of the 100th meridian (i.e.,
265 the rainfed region) within the continental US. These counties are included because they produce
266 corn or soybeans, for which we simulate stochastic crop yields using 52-year (1972-2024)
267 historical county level crop yields from the USDA , accounting for 166.7 million acres of
268 cropland. As we simulate yield simulates risk at the county-level, we adjust yield variance using
269 parameters from Scott et al. (2014) and Cooper et al. (2012) to make our analysis reflect farm-
270 level riskiness. We model the effect of adopting cover crops on corn and soybean yield and risk
271 following Ma et al. (2023) and Qin et al. (2021), and detail, along with other cover crop effects
272 in Table 1.[14] For further details on crop yields, see Appendix A.1. Nitrogen application rates in
273 our model are based on public databases (USDA, 2016). Cropland acreage for counties included
274 in our model is determined based on pixel-level analysis using the USDA Cropland Data Layer
275 (CDL) for the years 2019-2023. Land is considered usable if i) in the past four years it grew corn
276 or soybean at least once ii) it is marked in 2023 as cropland (i.e. not marked as urban land), and
277 iii) in the years the land is not marked as corn or soybean, it is marked as idle. Further, we
278 consider the county level share of corn-soybean rotations and continuous corn land based on
279 pixel level cropland usage. A pixel is considered to be of continuous-corn rotation if there is no
280 soybean grown on it in the past four years, and corn-soybean otherwise.

281 As there is no consensus on the magnitude of soil carbon sequestration potential of cover
282 cropping, we estimate the mean annual change in soil carbon from establishing cover crops using
283 the two methods, one described by Poeplau et al. (2015) and the other using USDA's COMET

model. We provide additional details for the soil carbon effects of cover crop adoption in Appendix A.2. We also consider the carbon-mitigating impact of cover crops on conventional crop farm management through reduced fertilizer use following Swanson et al. (2018), using carbon mitigation parameters from Dwivedi et al. (2016) and the GREET life cycle model (Wang 2001). We assume that farmers choose to terminate their crops using tillage, the least cost method under conventional tillage.

Farmers plant and harvest conventional crops annually. We assume that farmers do not change their rotation and cover crop adoption decisions during the modeling period, taken as seven years to account for short-term and long-term yield effects (Zhang and Blevins 1996; Olson et al. 2014; Ma et al. 2023). We calculate conventional crop costs for each rotation at the county level using quantities and prices provided by state extension-service budgets. Reduction of farm management costs through fertilizer, diesel use, weed management, and erosion management are taken from Myers et al. (2019). We provide details on the spatial distribution of conventional crop costs in Appendix A.3. Costs to establish cover crops are from Schnitkey et al. (2016) and are converted to 2024 values using the St Louis Fed's GDP deflator. We assume cover crop production costs to be uniform across the rainfed region. We provide details on the calculation of cover crop costs in Appendix A.4.

We also consider the prices for conventional crops (corn and soybean) to be stochastic and estimate price distributions at the national level using 52-year (1972-2024) national-level harvest prices (NASS) and futures prices (Chicago Board of Trade) to reflect the riskiness of conventional crop prices and corresponding to crop yields from the same years. We then normalize these price distributions to the state level using the national and state prices (NASS) ratio. We describe these methods in detail in Appendix A.5. We assume a joint yield-price

distribution where the farmer knows the distribution of conventional crop prices and yields for all crops estimated for their county to reflect their stochastic nature. We obtain random draws by constructing a yield-price distribution for each county by a copula approach (a modeling process that estimates joint distributions of multiple stochastic variables) following Miao and Khanna (2017b), as detailed in Appendix A.6. The joint yield-price distribution consists of crop yields linked to cover crop adoption choices, and conventional crop prices.

We use the 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. We assume the farmers have 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 (*Low-Risk-Averse*) and 50% for high risk-aversion (*High-Risk-Averse*). Following Miao and Khanna (2017b), we set the discount rate at 2% for a low discount rate (*Low-Discount*) and 10% for a high discount rate (*High-Discount*). High discount rates indicate less willingness to wait for future returns. They will lower the value the farmer assigns to future conventional crop returns relative to present returns. For ease of discussion, we refer to the "*High-Risk-Aversion* and *High-Discount*" farmer profile as the "*High-Constraint*" and refer to "*Low-Risk-Aversion* and *Low-Discount*" as the "*Low-Constraint*" profile. Our simulation considers permutations of farmer profiles of risk-aversion (*High-Risk-Averse, Low-Risk-Averse*), discount rate (*High-Discount, Low-Discount*), and the extent to which private benefits are internalized by the farmer (no private benefits, *Yield-Risk-Reduction*, *Cost-Saving*, and *Long-Term-Yield* benefits, and all three benefits (*All-Private* benefits)). We also consider in our analysis a no-policy instrument (*No-Policy-Instrument*) and exogenously varying policy payments under

three policy instruments (*Practice-Based*, *Price-Premium-Based*, and *Carbon-Based*). For each permutation, we aggregate the total carbon mitigated and area under various cropping practices across the rainfed US and examine the spatial distribution of adoption of cover crops. A flow diagram of the numerical simulation model is shown in Figure A.1. Additionally, in Table 1, we present a summary of the data listed above, with additional details and spatial distributions in the Appendix.

5. Simulation Results

5.1. Economic Incentives for Cover Crop Adoption

We find that when farmers disregard the private benefits of cover cropping and in the absence of any policy incentives, there is no adoption of cover cropping in the rainfed region, regardless of risk and time preferences (Figure 1 (a-d)). This lack of adoption is mainly due to the additional cost of cover crop adoption and the reduction of conventional crop returns due to yield loss from cover crop adoption in the near term. Even when farmers account for *Yield-Risk-Reduction* benefits (Figure 1 (e-h)) or *Cost-Saving* benefits (Figure 1 (i-l)), there is no adoption of cover crops. It is only when farmers consider potential revenue changes from *Long-Term-Yield* benefits are their incentives for adoption in some counties. With *Long-Term-Yield* benefits, however, there is an increase in conventional crop yield riskiness due to the effect of increased yield on other sources of riskiness in the model (for example, price riskiness); thus incentives to adopt cover crops are relatively higher in the *Low-Risk-Averse* farmer profiles. Additionally, as yield increases in the long-term, farmers with high discount rates adopt cover crops on fewer acres relative to those with low discount rates; adoption is therefore lower under the *High-Constraint* farmer profile (Figure 1 (m)) relative to the *Low-Constraint* farmer profile (Figure 1 (p)) as farmers value future benefits and lower riskiness of cover crop adoption less in the former

and more in the latter profile. Farmers adopt cover crops on about 3 and 47 million acres (2% and 28% of total cropland) in the *High-Constraint* and *Low-Constraint* farmer profiles, respectively. In the counties where farmers adopt cover crops when they consider *Long-Term-Yield* benefits, they generally adopt them on less than 25% of cropland in a county under the *High-Constraint* and between 25-75% of cropland in a county under the *Low-Constraint* farmer profiles, respectively.

When farmers consider *All-Private* benefits (Figure 1 (q, t)), the extent of adoption of cover varies with farmer risk-aversion and discount rate. Cover crop adoption covers 66 and 164 million acres (40% and 98% of total cropland) in the *High-Constraint* and *Low-Constraint* farmer profiles. When farmers have high risk-aversion but low discount rates, or when they have low-risk-aversion but high discount rates, their adoption patterns are between those in the *High-Constraint* (i.e., high risk-aversion and high discount rate) or *Low-Constraint* (i.e., low risk-aversion and low discount rate) cases. These farmers differ in the intensity of cover cropping and the number of counties in which they adopt cover crops. For example, when farmers have a *High-Risk-Aversion* and *Low-Discount* profile (Figure 1 (r)) and consider *All-Private* benefits, cover crop adoption occurs on 126 million acres (75% of total cropland) in 2,051 of the 2,163 counties (94% of counties in the model) in the rainfed region. Of these, 494 counties (23% of counties in the model) have low county-level adoption rates (i.e., adoption of cover crops on 0% to 75% of cropland at the county level). When farmers have a *Low-Risk-Aversion* and *High-Discount* profile (Figure 1 (s)), cover crop adoption occurs on 144 million acres (86% of total cropland) in 1936 counties (89% of counties in the model); however, only 195 counties (9% of counties in the model) have low county-level adoption rates. These results indicate that low discount-rates may encourage low-level adoption in a relatively larger number of counties, while

low risk-aversion may encourage relatively higher rates of adoption (i.e., adoption of cover crops on more than 75% of cropland at the county level) in relatively fewer counties. A similar pattern holds under *Long-Term-Yield* benefits (Figure 1 (n, o)).

We analyze the sensitivity of outcomes to more conservative yield effects (with lower expected yield loss from cover cropping and lower yield gain in the long-term, thus reducing the implicit risk effects of yield loss and yield gain in the model) as indicated by Qin et al. (2021) relative to the findings in Ma et al. (2023)). We find that lowering the long-term yield benefits of cover cropping lowers the private benefits of adoption and eliminates any adoption in the absence of any policy incentives. This indicates the importance of the expectation of future yield effects in driving the adoption of cover cropping.

5.2. Incentives for Cover Crop Adoption under Alternative Policy Instruments

Next, we consider the effect of the three alternative policy instruments on farmers' adoption decisions under various assumptions about the extent to which farmers internalize the private benefits. We show the land on which cover crops will be adopted and the carbon mitigation achieved at various payment levels under each policy instrument.

Adoption with No Internalization of Private Benefits under Alternative Policy instruments: Under *Practice-Based* payments, farmers who consider no private benefits only adopt cover crops at payments higher than $30 per acre (shown by the red curves in Figure 2 (a-d)). The incremental cost of incentivizing farmers increases as more land is converted to cover crops. Annual payment rates of $35, $45, and $75 per acre result in 22, 126, and 167 million acres (12%, 75%, and 100% of total cropland), respectively, of cover crop adoption in the *High-Constraint* farmer profile. The perceived conventional crop yield penalty of adopting cover crops implicitly reduces the conventional crop yield riskiness, leading to lower adoption in the *Low-*

Risk-Averse farmer profiles. For example, farmers adopt cover crops on 15, 122, and 166 million acres (9%, 73%, and 100% of total cropland), respectively, of cover crop adoption in the *Low-Constraint* farmer profile at the same payment rates. The slight difference in adoption rates indicates that risk and time preferences do not significantly influence cover crop adoption decisions when farmers do not consider its private benefits.

Under *Price-Premium-Based* payments, farmers who consider no private benefits (red curves in Figure 2 (e-h)) start to adopt cover crops when payments exceed 8% of crop revenue, with 165 million acres adopted at 14%. Under *Practice-Based* (red curves in Figure 2 (i-l)) do not adopt cover crops even at 100% of the cost of adopting cover crops. Under *Carbon-Based* payments, farmers adopt cover crops at payments exceeding \$50 per Mg CO_2, with approximately 116 to 167 million acres adopted (red curves in Figure 2 (m-p)) at carbon payments between \$80 and \$140 per Mg CO_2.

Adoption with Internalization of Private Benefits under Alternative Policy instruments: We consider the effect of incentive payments under alternate policy instruments on farmers' adoption decisions when farmers consider private benefits. Without loss of generality, we report our results based on *Practice-Based* payments and note that these results are similar to those with other policy instruments unless specified.

When farmers consider only *Yield-Risk-Reduction* benefits, the cost to adopt cover crops is reduced slightly relative to farmers who internalize no benefits. Adoption increases relative to levels with no internalization of private benefits by 3.4, 6.4, and 0.9 million acres (2%, 4%, and 0.5% of total cropland) under *Practice-Based* payments of \$35, \$40, and \$50 per acre, respectively, in the *High-Constraint* farmer profile (blue dashed line compared to red line in Figure 2 (a) and Table A.1). The *Yield-Risk-Reduction* benefits of cover cropping are more

appealing to *High-Risk-Averse* farmers than *Low-Risk-Averse* farmers. For example, in the *Low-Constraint* farmer profile, additional adoption is lower than with *High-Constraint* profiles, with 1.7, 0.6, and 0.1 million acres added (less than 1% of total cropland) relative to not considering any private benefits under payments of $35, $40, and $50 per acre (blue dashed line compared to red line in Figure 2 (d) and Table A.1). In the presence of *Price-Premium-Based* payments farmers respond more to the *Yield-Risk-Reduction* benefits of cover crops than under other policy instruments. For example, in the *High-Constraint* profile, for farmers who consider *Yield-Risk-Reduction* benefits (blue dashed lines compared to red lines in Figure 2 (e) and Table A.1), adoption increases by 10.8, 5.1, and 3.7 million acres (6.5%, 5%, and 2% of total cropland) at payments of 8%, 9%, and 10% of crop revenue compared to farmers who do not consider any benefits. In the *Low-Constraint* profile (blue dashed lines compared to red lines in Figure 2 (h) and Table A.1), adoption increases by 3.1, 0.6, and 1.8 million acres (all less than 2% of total cropland) at the same payment levels.

When farmers consider *Cost-Saving* benefits only, *Practice-Based* payments needed to induce cover crop adoption are reduced by approximately $10-$15 per acre (purple dashed lines compared to red lines in Figure 2 (a-d) and Table A.1) relative to when they consider no benefits. Farmers start to adopt cover crops at payments above $15 per acre and can adopt up to 167 million acres at $60 per acre. In the *High-Constraint* farmer profile, adoption increases from 0 to 9.8 million acres (6% of total cropland) at payment levels of $20 per acre and from 0.8 to 120.3 million acres (71% of total cropland) at a payment of $30 per acre relative to no internalization. Here too, the perceived conventional crop yield penalty of adopting cover crops implicitly reduces the farmers return riskiness, leading to slightly lower adoption in the *Low-Risk-Averse* farmer profiles (purple dashed lines in Figure 2 (a-d) and Table A.1). For example, in the *Low-*

445 *Constraint* farmer profile (Figure 2 (d) and Table A.1), adoption increases from 0 to 5.7 million
446 acres and from 0.2 to 113 million acres (3.5% and 67% of total cropland respectively) at the
447 same payment levels relative to no internalization.

448 When farmers consider *Long-Term-Yield* benefits, some may adopt cover crops without
449 policy payments (see section 5.1 for a detailed breakdown). Compared to internalization of other
450 benefits, however, farmers respond to the risk-lowering effect of cover crops due to increased
451 long-term yield along with valuing future yield increase such that they adopt more cover crops in
452 the *Low-Constraint* farmer profile than in the *High-Constraint* profile. Farmers adopt cover
453 crops on 167 million acres at a payment of $60 per acre per year in the *High-Constraint* farmer
454 profile and $15 per acre per year in the *Low-Constraint* profile (green dashed lines in Figure 2
455 (a-d) and Table A.1). When farmers consider *All-Private* benefits (black lines in Figure 2 (a-d)),
456 adoption without payments under all farmer risk and time profiles extends to large parts of the
457 rainfed region (see section 5.1 for a detailed breakdown). Overall, the effect of risk increase due
458 to *Long-Term-Yield* benefits is greater than the risk reduction effects of *Yield-Risk-Reduction* or
459 the implicit risk reduction of adopting cover crops such that a $5 per acre payment incentivizes
460 up to 167 million acres in the *Low-Constraint* farmer profile for which a $50 per acre payment is
461 needed in the *High-Constraint* farmer profile.

462 Our sensitivity analysis compares cover crop adoption using more conservative yield effects
463 from Qin et al. (2021). Without loss of generality, we present results under *Practice-Based*
464 payments; however, these results also hold for other policy instruments. Under more
465 conservative yield effects, payments needed to incentivize cover crop adoption (Figure A.4) are
466 relatively lower than in the benchmark model (Figure 2). The impact of internalizing *Long-Term-*
467 *Yield* benefits is smaller in magnitude in this case, with *Cost-Saving* benefits having the most

significant effect in lowering costs (purple dashed line in Figure A.4 representing *Cost-Saving* with adoption at lower payments compared to the green dashed line representing *Long-Term-Yield* benefits). In the sensitivity analysis, the effects of *Yield-Risk-Reduction* are more prominent due to smaller expected and long-term yield effects and benefits that implicitly decrease and increase return riskiness (through other sources of risk in the model, for example, price riskiness). To illustrate, when farmers consider *Yield-Risk-Reduction* benefits only (dashed blue lines in Figure A.4) or *All-Private* benefits (black lines in Figure A.4), they adopt more cover crops when they are *Low-Risk-Averse* (Figure A.4 (b, d)) than when they are *High-Risk-Averse* (Figure A.4 (a, c)).

5.3. Cost-Effectiveness of Alternative Policy instruments

Next, we calculate the average cost per acre of cover cropping induced and the quantity of carbon mitigated (metric tons (Mg) of CO_2) with each policy instrument and compare the cost of abatement across policy instruments.

No Internalization of Private Benefits: When farmers do not internalize private benefits of cover cropping (Figure A.3 (a-d)), the cost to incentivize up to 125 million acres (75% of total cropland) ranges from $35 to $55 per acre per year across policy instruments. The lowest cost per acre is through *Practice-Based* payments (orange lines in Figure A.3 (a-d)), followed by *Carbon-Based* payments (green lines in Figure A.3 (a-d)), then *Price-Premium-Based* payments (yellow lines in Figure A.3 (a-d)). The aggregate cost of incentivizing cover crop adoption of approximately 125 million acres across policy instruments is approximately $6.5 billion annually.

Cover crop adoption on 125 million acres results in carbon mitigation of up to 70 million Mg CO_2 per year, with a mitigation cost ranging from $60 to $80 per Mg CO_2 across policy

instruments. The lowest carbon costs are through *Carbon-Based* payments (green lines in Figure 3 (a-d)), followed by *Practice-Based* payments (orange lines in Figure 3 (a-d)), and *Price-Premium-Based* payments (yellow lines in Figure 3 (a-d)).

The per acre cost to incentivize adoption beyond 125 million acres increases sharply. The cost of inducing the adoption of cover crops on 167 million acres (100% of total cropland) increases to about $80 per acre per year across *Practice-Based*, *Price-Premium-Based*, and *Carbon-Based* policy instruments (Figure A.3 (a-d)). This mitigates 93 million Mg CO_2 per year, with carbon mitigation costs rising to $140 per Mg CO_2 (Figure 3 (a-d) with little difference in payments needed across the alternative policy instruments (*Price-Premium-Based* payments have marginally lower per acre and Mg CO_2 costs).

With Internalization of Private Benefits:

When farmers do consider the private benefits of cover cropping, the cost difference between payment plans is smaller (the magnitude of which depends on which benefits they internalize) due to farmers needing fewer incentives to adopt cover crops as they internalize the monetary benefits of cover crops (Figure A.3 (a-t)). For example, when farmers consider the *Yield-Risk-Reduction* benefits of cover crops (Figure 3 (e-h)), the cost of mitigation is slightly lower than (by about $6 per Mg CO_2 to mitigate 70 million Mg CO_2 per year) the case when no private benefits are considered (Figure 3 (a-d)).

When the *Cost-Saving* benefits of cover crop adoption are considered, cover crop adoption has the overall potential to mitigate up to 103 million Mg CO_2 per year (this is higher than the 93 million Mg CO_2 potential when farmers do not internalize private cost-saving benefits and so do not mitigate carbon through reduced fertilizer use in conventional crop production). Carbon

mitigation costs up to \$60 per Mg CO_2 for mitigating 70 million Mg CO_2 per year and \$80 per Mg CO_2 for 103 million Mg CO_2 per year (Figure 3 (i-l)).

When farmers consider *Long-Term-Yield* benefits, the level of carbon mitigation and the cost to mitigate carbon depend on farmer risk and time preferences. For example, 1.7 million Mg CO_2 are mitigated yearly without incentives when farmers have *High-Constraint* profiles and 26.7 million Mg CO_2 in the *Low-Constraint* farmer profile (Figure 3 (m, p)). In the *High-Constraint* farmer profile, carbon mitigation costs up to \$30 per Mg CO_2 for mitigating 70 million Mg CO_2 per year and \$70 per Mg CO_2 for 93 million Mg CO_2 per year (Figure 3 (m)). In the *Low-Constraint* farmer profile, carbon mitigation costs up to \$20 per Mg CO_2 for mitigating 70 million Mg CO_2 per year and \$35 per Mg CO_2 for 93 million Mg CO_2 per year (Figure 3 (m)).

When farmers internalize *All-Private* benefits of cover cropping, 41.1 million Mg CO_2 per year are mitigated without policy payments when farmers have *High-Constraint* profiles. Carbon payments up to \$5 per Mg CO_2 can increase mitigation to 80 million Mg CO_2 per year and \$70 per Mg CO_2 for 103 million Mg CO_2 per year; however, most mitigation happens at lower costs (Figure 3 (q)). In the *Low-Constraint* farmer profile, 100 million Mg CO_2 per year are mitigated without incentives, and non-zero carbon payments can incentivize up to 103 million Mg CO_2 per year (Figure 3 (t)).

5.4. Spatial Pattern of Cover Crop Adoption

When farmers receive no incentive payments, internalization of *Long-Term-Yield* and *All-Private* benefits leads to cover crop adoption across most of the rainfed US but with lower within-county cropping intensity (see section 5.1 for more details). With *Long-Term-Yield* benefits, adoption occurs in the Delta region, upper Midwest, and eastern states (see Figure 1 (m-p)). With *All-Private* benefits considered, farmers with the *High-Constraint* profile adopt cover

crops in the Midwest (Figure 1 (q)), the Delta region and Great Plains region. With a *Low-Constraint* profile adoption would be viable across the rainfed region.

Next, we compare the spatial adoption patterns of cover crops under various alternative policy instruments at similar aggregate expenditure levels.[15] We present adoption patterns at three expenditure levels (*Low Aggregate Expenditure, Moderate Aggregate Expenditure, and High Aggregate Expenditure*) to represent annual expenditures of up to $1, 4, and 6.5 billion. In Figure 4, we present the aggregate abatement cost of mitigating carbon through cover crop adoption, and in Figure A.5 we present the aggregate cost of adoption for cover crops. Additionally, in Table 2, we present a summary of these results. We present the case where farmers do not internalize the private benefits of cover crop adoption and have a *High-Constraint* profile, with aggregate costs shown in Figure 4 (a) and Figure A.5 (a).

The spatial adoption pattern of cover crops when farmers do not internalize the private benefits of cover cropping varies by policy instruments. With *Practice-Based* payments, which are uniform for both low and high-yielding cropland and cropland, adoption occurs in lower-yield cropland in the Great Plains under *Low Aggregate Expenditure*, because the expected loss in revenue due to cover cropping is low relative to the payments. At *Moderate Aggregate Expenditure* payments, adoption expands to the lower Midwest region (Figure 5 (a-b)). With *Price-Premium-Based* payments, cover crop adoption occurs at *Low Aggregate Expenditure* in the Midwest (Figure 5 (d)). It expands to the upper Midwest and Great Plains areas at *Moderate Aggregate Expenditure* levels (Figure 5 (e)). This adoption pattern is due to the higher payments in the high-yield region of the Midwest, since payments are proportional to crop yields. With *Carbon-Based* payments, adoption under *Low Aggregate Expenditure* occurs in the southern states, specifically in the Texas/Oklahoma region and the Alabama/Georgia/northern Florida

559 region (Figure 5 (g)), followed by adoption in the lower Midwest at *Moderate Aggregate*
560 *Expenditure* (Figure 5 (h)). This adoption pattern is due to the southern states having high soil
561 carbon sequestration potential and lower loss in revenue due to relatively lower yields. With
562 *Carbon-Based* payments, farmers adopt cover crops in cropland with the highest carbon
563 sequestration potential at *Low Aggregate Expenditure*. Regardless of policy instrument, cover
564 crops are adopted throughout the rainfed US under the *High Aggregate Expenditure* scenario
565 (Figure 5 (c, f, i)).
566 With the internalization of *Yield-Risk-Reduction*, *Cost-Saving*, and *Long-Term-Yield*
567 benefits, the spatial pattern of cover crop adoption is similar to that when farmers do not
568 internalize the benefits of cover crops. Still, the area covered with the same amount of program
569 payments is much larger. With *All-Private* benefits internalized, all policy instruments with *Low*
570 *Aggregate Expenditure* can incentivize 100% adoption rates for *High-Constraint* farmers.
571 **Discussion and Conclusion**

There is considerable interest in understanding the reasons for the limited adoption of cover crops despite their potential to provide private benefits in addition to public environmental benefits. While many studies quantify these benefits and show that impacts vary with the type of cover crops, methods and timing of planting and termination, and geographic location, there is limited research analyzing the implications of the lack of internalization of the private benefits of cover cropping on adoption decisions by farmers. This paper developed a framework to analyze the effects of varying internalizations about the short- and long-term private benefits of cover cropping on the optimal share of land allocated to cover cropping by a representative utility-maximizing farmer with given risk and time preferences. We apply this framework to quantify the economically viable potential to mitigate carbon through cover crop adoption in the rainfed US and the effectiveness of alternative policies in mitigating carbon emission while incorporating spatial heterogeneity in the costs, benefits, and carbon sequestration effects of cover cropping.

We show that a possible reason for the low observed adoption rates is the lack of internalization of the potential private benefits of cover crop adoption. Among the various benefits of cover cropping, consideration of potential long-term yield benefits would have the largest impact in inducing adoption, particularly by farmers with low risk-aversion and discount rates. Farmers who consider long-term benefits and have low discount rates are more likely to adopt cover crops than impatient ones because the potential for yield-increasing benefits occurs in the long-term. While the implicit and explicit yield risk reduction benefits of cover cropping could be expected to increase cover crop adoption by risk-averse farmers, this is the case only when farmers do not consider long-term yield benefits. This is because profit risks may increase with cover crop production, as an increase in long-term yields can increase the revenue risk of

595 conventional crops. Thus, farmers with low risk-aversion and low discount rates are more likely
596 to adopt cover crops if they fully internalize the benefits of cover cropping and to do so even in
597 the absence of any policy incentives.

598 We also find that the extent to which policy incentives will be needed to induce the adoption
599 of cover cropping varies with the extent of internalization of private benefits and the risk and
600 time preferences of farmers and by location. In the absence of any internalization of the private
601 benefits of cover cropping, the payments needed to induce any cover crop adoption are
602 substantially higher. More specifically, a minimum of $35 per acre is needed under *Practice-*
603 *Based*, 8% of corn and soybean returns is needed under *Price-Premium-Based*, and $60 per Mg
604 CO_2 is needed under *Carbon-Based* payments, in 2016 dollars.

605 Costs to incentivize up to 125 million acres and mitigate up to 70 million Mg CO_2 per year
606 under all policy instruments increased to $55 per acre per year and $90 per Mg CO_2 and imposed
607 an aggregate abatement cost of $5.6 billion annually when farmers do not internalize any private
608 benefits (Figure 4 (a-d), and Figure A.5 (a-d)). When farmers internalize the private benefits of
609 cover cropping, the aggregate abatement cost changes depending on which private benefits they
610 internalize. For example, it does not change significantly when *Yield-Risk-Reduction* is
611 considered by farmers (Figure 4 (e-h), and Figure A.5 (e-h)), but is reduced from $5.6 billion
612 annually to $3.5 billion under *Cost-Saving* (Figure 4 (i-l), and Figure A.5 (i-l)). When farmers
613 consider long-term yield benefits or all private benefits, farmer risk-aversion and time-
614 discounting have a significant effect as well, for example abatement costs $3 billion annually for
615 *High-Constraint* farmer profiles (Figure 4 (m), and Figure A.5 (m)) under *Long-Term-Yield*, and
616 $1 billion in *Low-Constraint* profiles (Figure 4 (p), and Figure A.5 (p)). Similarly, abatement
617 costs are $0.5 billion for *High-Constraint* farmer profiles when they consider *All-Private* benefits

(Figure 4 (q), and Figure A.5 (q)), and have no cost in *Low-Constraint All-Private* benefits (Figure 4 (t), and Figure A.5 (t)).

These payments are generally higher than those currently offered through federal, state, and voluntary private markets (which may offer up to 75% cost-share through EQIP, $25 through state programs in the Midwest, $10 per acre through CSP, or between $20 to $30 per Mg CO_2 across most voluntary programs offered between 2022 and 2024). This may explain why current incentive payments are largely ineffective in incentivizing cover crop adoption.

Our analysis also shows that cover cropping can significantly contribute to overall carbon mitigation and reduce emissions from the agriculture sector. However, the costs of inducing cover crop adoption increase sharply after adoption occurs on approximately 75% of cropland. Thus, the economically viable potential is less than its technical potential, particularly when farmers do not internalize the private benefits of cover cropping.

We also find that *Practice-Based* payments have lower costs in dollars spent per acre of cover crop adoption compared to other policy instruments when incentivizing adoption on up to 75% of cropland. In comparison, *Carbon-Based* payments have lower costs in terms of dollars spent per unit of carbon mitigated compared to other policy instruments. However, the difference in the cost per acre and the cost of carbon mitigation across alternative policies is small. Our analysis suggests that the small gains in the cost-effectiveness of mitigating carbon with carbon-based payments may not be sufficient to overcome the higher costs of implementing this policy relative to uniform practice-based payments.

Although the aggregate costs of alternative policies are similar, these policies differ in the locations where they incentivize adoption at low expenditures. *Practice-Based* payments incentivize adoption mainly in the Great Plains and the Eastern states where crop yields are low,

641 and payments can cover yield loss. However, the Great Plains and the Eastern states have lower
642 carbon sequestration benefits; thus, *Carbon-Based* payments incentivize cover crop adoption in
643 other regions, such as the southern states and the Midwest, where such practices have greater
644 potential to increase carbon sequestration. *Price-Premium-Based* payments incentivize cover
645 crop adoption in the Midwest, where conventional crops have the highest yields. Our findings
646 indicate that a mix of policy incentives may be more effective than a single instrument in
647 incentivizing cover crop adoption across the rainfed region.

648 Our research shows that if the private benefits of cover cropping are small (or farmers
649 believe them to be small), the costs of inducing the adoption of cover cropping for their external
650 benefits will be higher. This suggests a need for greater research on cover cropping practices to
651 reduce costs and adverse impacts on short-term yields while enhancing the gain in yields in the
652 long term. Ongoing research indicates that it is possible to optimize cover crop practices for
653 positive yield impacts and more significant synergies between private and public benefits (Qiu et
654 al. 2024). Larger investment in extension services to increase farmer awareness of the positive
655 outcomes of cover cropping can also increase adoption. Obtaining more accurate assessments of
656 the outcomes with cover cropping for farmers can enable more effective policy design.

657 Our analysis is intended to be stylized and based on several simplifying assumptions. We do
658 not consider variations in cover crop varieties, planting technology, and planting practices which
659 can affect outcomes. In analyzing the spatial pattern of cover crop adoption, we assume
660 uniformity in risk and time preferences and the level of internalization of the private benefits of
661 cover cropping. These may vary regionally based on location-specific knowledge. Lastly, we
662 assume that farmers make a long-term decision to adopt or not to adopt cover cropping and do
663 not consider the possibility of disadoption based on observed realizations with cover crop

664 adoption. We leave these considerations for future research to explore.

[1] Jaglo et al. (2023) estimate that up to 50 M Mg CO_2e per year from can be mitigated from soil carbon sequstration, N_2O reduction, and management practices.
[2] Eagle et al (2012) estimate 1.34, 0.12.0.42.and 1.92 Mg CO_2e Ha-1 per year as soil carbon sequestration, N_2O emissions, upstream emissions reduction, and total carbon mitigated respectively. They estimate 66 million hectares available for cover crops, resulting in a total mitigation of 126 M Mg CO_2 per year.
[3] Agriculture contributed approximately 596 M Mg CO_2 (9.4% of 6343 M Mg CO_2) according to https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#agriculture.
[4] Partnership for Climate-Smart Commodities Project https://www.usda.gov/climate-solutions/climate-smart-commodities/projects.
[5] We follow Ma et al. (2023) by designating year 1-3 of cover crop adoption as short term, and 4-7 and 8-15 as long-term.
[6] See, https://www.cleanwateriowa.org/cropinsurancediscount; and https://agr.illinois.gov/resources/landwater/cover-crops-premium-discount-program.html.
[7] US Department of the Treasury and IRS press release https://home.treasury.gov/news/press-releases/jy2307.
[8] We assume that 2.8 gallons of SAF can be made from one bushel of corn, and that corn yield is 165 bushels per acre (https://farm-energy.extension.org/corn-for-biofuel-production/) and that SAF produced from corn is eligible for the 50% tax credit.
[9] For example Bayer, TruTerra, (TCMAP), and LocusAg CarbonNOW) offer fixed per-acre payments for adopting climate-smart practices; some pay farmers $6 per acre per year for cover crop adoption. Bayer offers $6 per acre for cover crop adoption. https://www.bayer.com/en/us/news-stories/carbon-program-expands-eligibility, retrieved July 2024.
[10] These include, Ecosystem Services Market Consortium (ESMC), Soil and Water Outcomes Fund (SWOF), Indigo, Nori, Agoro, Bayer, Corteva, Nutrien, CIBO, Gradable, and TruTerra among others.
[11] TruTerra offers $30 per Mg CO_2 for soil carbon sequestration https://www.truterraag.com/articles/truterra-2024-programs-announcement-expanded-eligi; Indigo offers a minimum of $20 per credit, https://www.indigoag.com/carbon/for-farmers . Additionally, SWOF offers an average of $33 per acre, based on the field's carbon mitigation potential and practices adopted https://theoutcomesfund.com/.
[12] Agoro will pay farmers a lump sum based on the value of carbon once the carbon credit has been sold https://agorocarbonalliance.com/our-carbon-program/.
[13] In order to compute land allocation where farmers decide the percentage of land (at intervals of 5%) allocated to each of the eight permutation choices, restricting the model to choosing at most one permutation would require computing 8 combinations, two would require 540, four would require 72920, and all eight would require 759720 combinations. Additionally, we run our simulation model for a subset of counties allowing for more than two land allocations, and find farmers rarely allocating land to more than two permutation choices. We therefore, restrict our model to choosing at most two of the eight permutation choices such that $n(\{x_h > 0\}) \leq 2$, where n() is cardinality to reduce computational complexity.
[14] Qin et al. (2021) show that cover crop establishment leads to a short-term yield reduction. Olson et al. (2014) and Ma et al. (2023) show that cover crop establishment leads to improved soil health and Long-Term-Yield increases. Aglasan and Rejesus (2022) show that adopting cover crop leads to a drop crop insurance claims due to less risky yields and Ma et al. (2023) show a reduction in yield risk in the long-term when adopting cover crops.
[15] Since aggregate expenditure is an output of the discrete model, we cannot set it to be the same across all policy instruments. Instead in order to compare the spatial adoption pattern of the various policy instruments, we pick the most similar expenditure levels from our model.

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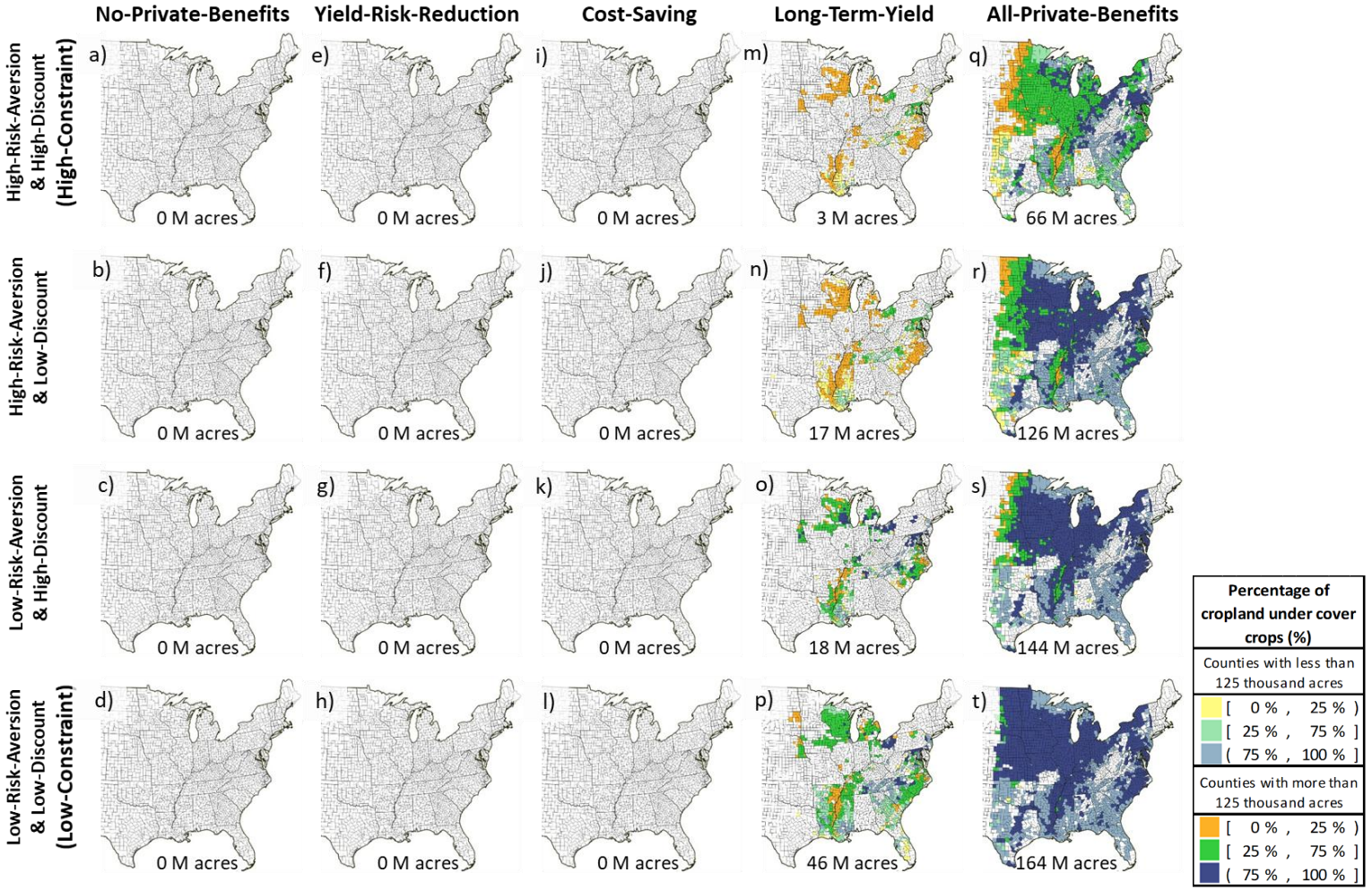
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Tables and Figures

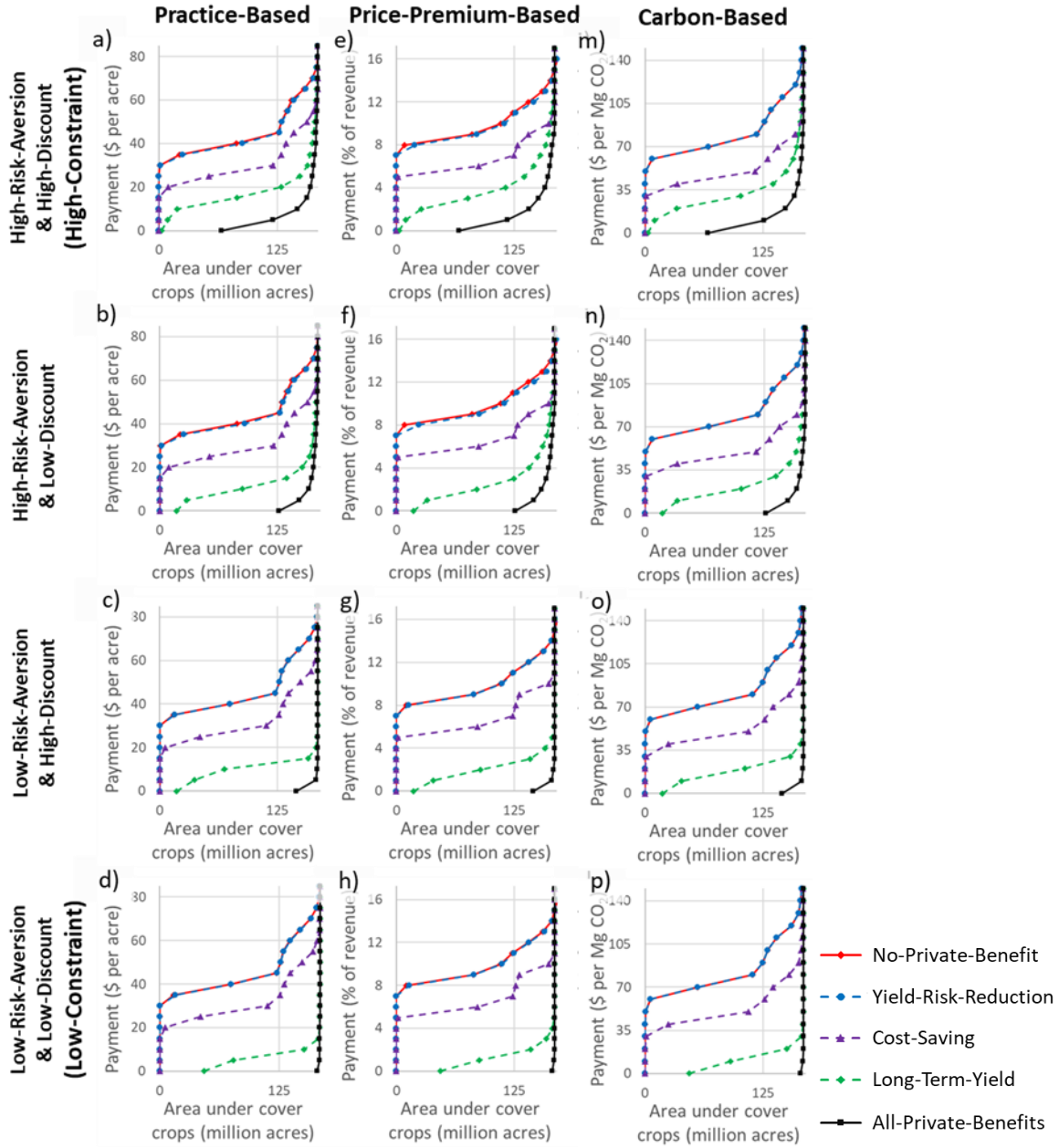
FIGURE 1. Cover Crop Adoption with Various Levels of Internalizations of Private Benefits and Farmer Risk and Time Preferences.



In this figure, we present the extent of cover crop adoption in acres as well as shares of cropland within each county without incentives under different internalizations of benefits, farmer risk, and time preferences when farmers are not incentivized to adopt cover crops.

Figures (a-d) show that cover crop adoption does not occur when farmers do not consider any private benefits. Figures (e-h) and (i-l) show that adoption does not occur when farmers consider only *Yield-Risk-Reduction* or *Cost-Saving* benefits. When farmers consider *Long-Term-Yield* benefits only, Figures (m-p) show they adopt some cover crops primarily outside of the Midwest in the delta and northern regions, the extent of which depends on farmer risk-aversion and time-discounting profiles. When farmers consider *All-Private* benefits, Figures (q-t) adopt cover crops on large portions of the rainfed US, the extent and intensity of which depend on farmer risk-aversion and time-discount profiles.

FIGURE 2. Cover Crop Adoption through Alternate Policy Instruments under different Internalizations of Benefits and Farmer Risk and Time Preferences.

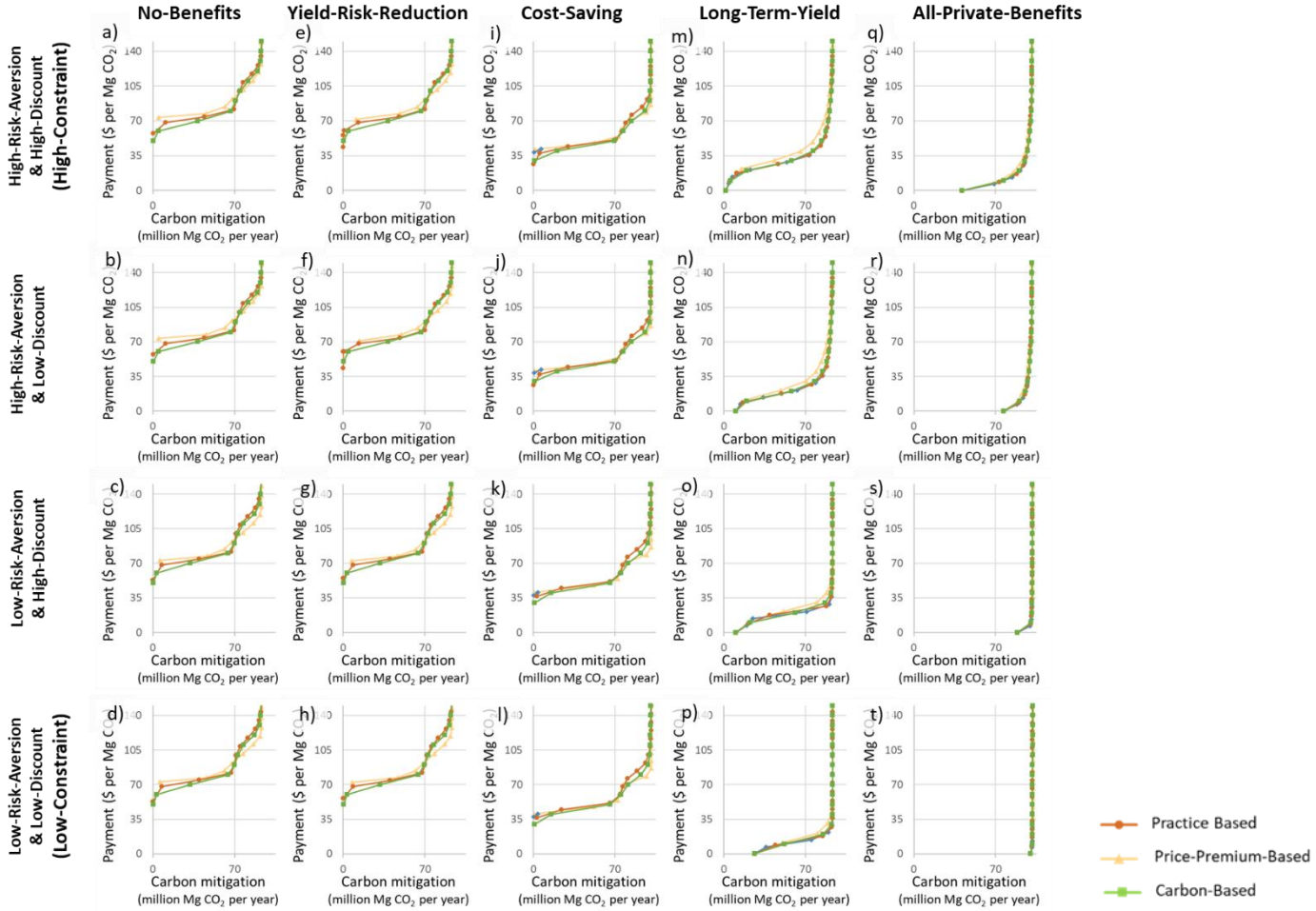


In this figure, we present the extent of cover crop adoption through alternate policy instruments under different internalizations of benefits, farmer risk, and time preferences.

We show cover crop adoption acreage under *Practice-Based* payments (Figures (a-d)), *Price-Premium-Based* payments (Figures (e-h)), and *Carbon-Based* payments (Figures (m-p)). In each case, red lines depict cover crop adoption when farmers consider no private benefits, blue dashed lines depict *Yield-Risk-Reduction* benefits only and purple dashed lines depict *Cost-Saving* benefits only. In each case, the cost to adopt cover crops is progressively lower. Farmers are, however, largely unaffected by risk-aversion and time-discounting under these internalizations. When farmers consider *Long-Term-Yield* benefits (green dashed lines) or *All-*

Private benefits (black lines), they adopt more cover crops under *Low-Constraint* (i.e., *Low-Risk-Aversion* and *Low-Time-Aversion*) farmer profiles (Figures (d, h, l, p)) than under *High-Constraint* (i.e., *High-Risk-Aversion* and *High-Time-Aversion*) farmer profiles (Figures (a, e, i, m)).

FIGURE 3. Carbon Mitigation through Cover Crops at Various Payment Levels under Alternate Policy Instruments and Different Internalizations of Benefits and Farmer Risk and Time Preferences.



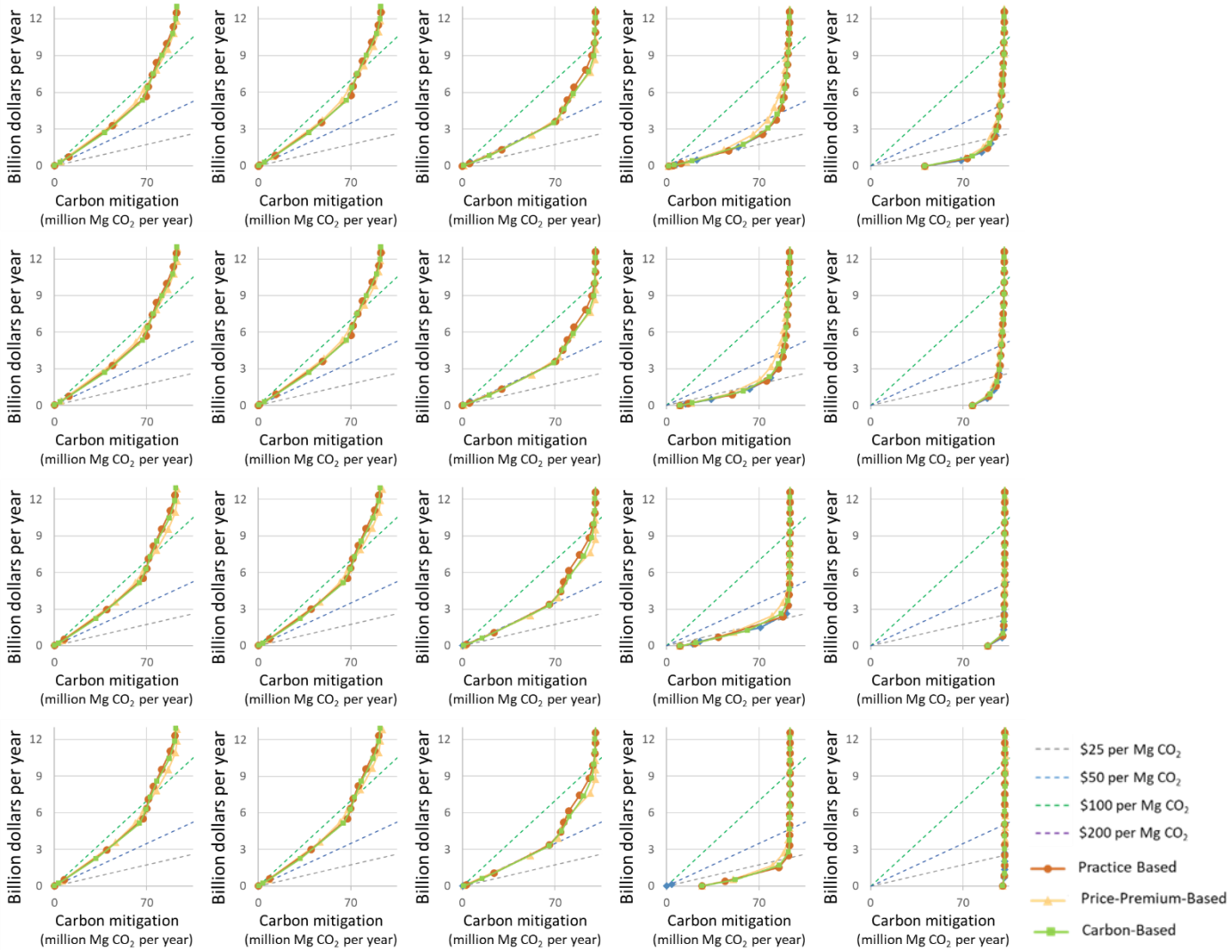
In this figure, we present the extent of carbon mitigation through cover crop adoption at various payment levels under alternate policy instruments under different internalizations of benefits, farmer risk, and time preferences.

Figures (a-d) depict carbon costs when farmers consider no private benefits to cover crop adoption. Carbon mitigation costs when farmers consider *Yield-Risk-Reduction* benefits only, *Cost-Saving* benefits only, *Long-Term-Yield* benefits only or *All-Private* benefits

are shown in Figures (e-h), (i-l), (m-p) and (q-t) respectively. In each figure, policy instruments are depicted by colored lines such that orange represents *Practice-Based* payments, yellow for *Price-Premium-Based* payments, and green for *Carbon-Based* payments.

When farmers consider no private benefits, Yield-Risk-Reduction, and Cost-Saving benefits only, (Figures (a-d), (e-h), and (i-l)), the lowest cost to mitigate up to 70 million Mg CO_2 per year is through *Carbon-Based* payments (green lines in Figures (a-d), (e-h), and (i-l)), followed by *Practice-Based* payments (orange lines in Figures (a-d), (e-h), and (i-l)), and *Price-Premium-Based* payments (yellow lines in Figures (a-d), (e-h), and (i-l)). Under *Long-Term-Yield* or *All-Private, the* benefits of cover crop adoption are significantly lower and do not vary considerably by payment.

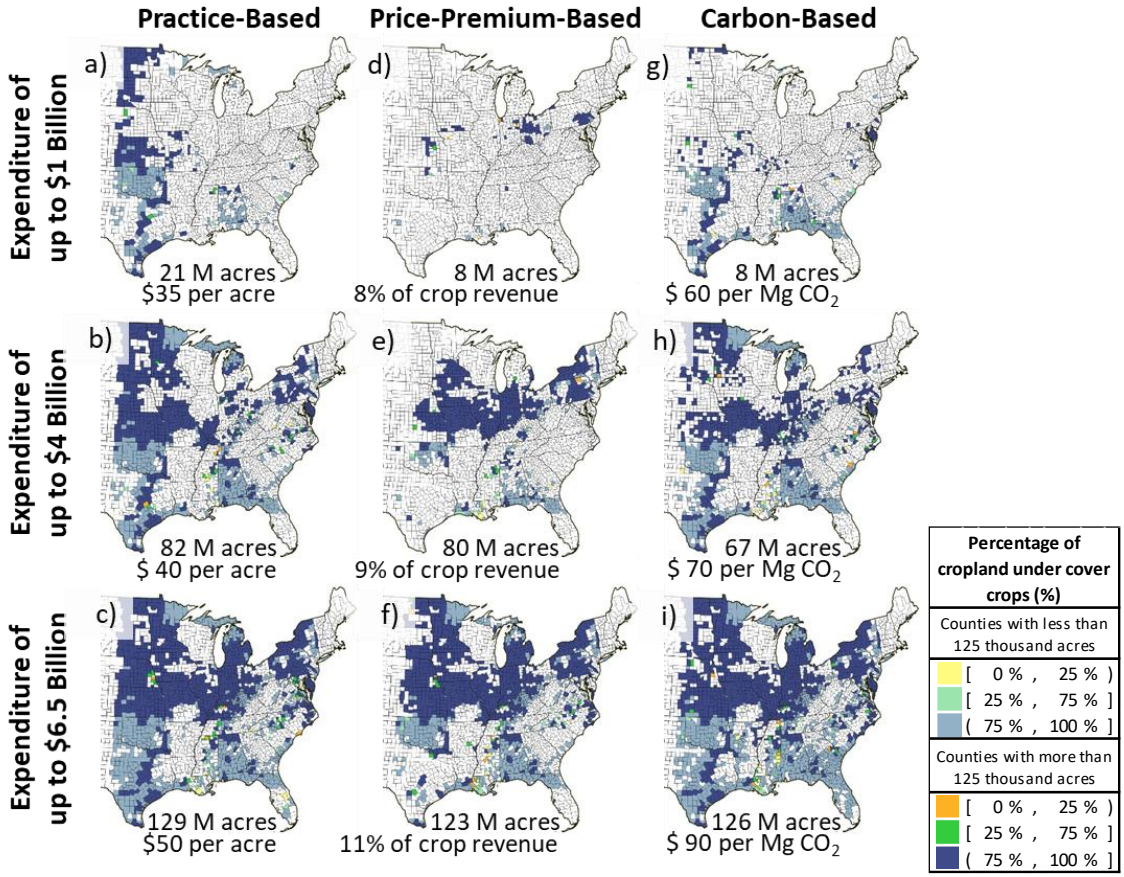
FIGURE 4. Aggregate Cost to Mitigate Carbon under Alternate Policy Instruments and Different Internalizations of Benefits and Farmer Risk and Time Preferences.



In this figure, we present the aggregate cost to mitigate carbon through cover crop adoption under alternate policy instruments and different internalizations of benefits, farmer risk, and time preferences. Figures (a-d) depict aggregate costs when farmers consider no private benefits to cover crop adoption. Carbon mitigation costs when farmers consider *Yield-Risk-Reduction* benefits only, *Cost-Saving* benefits only, *Long-Term-Yield* benefits only or *All-Private* benefits are shown in Figures (e-h), (i-l), (m-p), and (q-t) respectively. In each figure, policy instruments are depicted by colored lines such that orange represents *Practice-Based* payments, yellow for *Price-Premium-Based* payments, and green for *Carbon-Based* payments; however, in each case the difference in costs between policy instruments is small.

When farmers internalize the private benefits of cover cropping, the aggregate abatement cost changes depending on which private benefits they internalize. For example, costs do not change significantly relative to when they consider no benefits (Figures (a-d)) when *Yield-Risk-Reduction* is considered by farmers (Figures (e-h)), but is reduced under *Cost-Saving* (Figures (i-l)). When farmers consider *Long-Term-Yield* benefits (Figures (m-p)) or *All-Private* benefits (Figures (q-t)), farmer risk-aversion and time-discounting have a significant effect as well. Similarly, abatement costs are low for *High-Constraint farmer profiles when they consider All-Private* benefits, and have no cost in *Low-Constraint All-Private* benefits..

FIGURE 5. Spatial Pattern of Adoption of Cover Crops at under Different Policy Instruments.



We present in this figure the spatial pattern of adoption of cover crops at different aggregate policy instruments at similar levels of expenditures under consideration of no private benefits for *High-Risk-Aversion* and *High-Time-Discounting* farmers. The spatial adoption pattern of cover crops varies by each policy instrument and aggregate expenditure levels. Under *Practice-Based* payments (Figures (a-c)), adoption occurs in the Great Plains under for expenditures up to $1 billion annually (Figures (a)), followed by adoption in the lower Midwest and the remainder of the Midwest at annual expenditures up to $4 and $6.5 billion (Figures (b-c)). Under *Price-Premium-Based* payments (Figures (d-f)), cover crop adoption occurs in the Midwest (Figure 1 (d)) for expenditures up to $1 billion annually, and expands to the Great Plains and upper Midwest at higher expenditures (e-f). Under *Carbon-Based* payments (Figures (g-i)), adoption for expenditures up to $1 billion annually occurs in the Southern States, followed by adoption in the lower Midwest at higher expenditures.

TABLE 1. Parameters for Numerical Simulation

Parameters	**Values**		
Cover crop effects and costs	Corn	soybean	
Expected yield effect (%)[a]	-13.20	0.00	
Long-term yield effect (%)[a]	16.30	0.00	
Short-term yield risk effect (%)[a]	-0.50	0.00	
Long-term yield risk effect (%)[a]	-39.60	0.00	
Fertilizer benefit (lb./acre)[b]	15	0	
Establishment cost ($/acre)[b]	20		
Termination fuel usage (for no-till) (gallons/acre)[b]	0.3		
Termination cost (for no-till) ($/acre)[b]	5		
Weed cost reduction ($/acre)[c]	7.50		
Erosion cost reduction ($/acre)[c]	2.00		
Yields (DayCent, 2021)	County average	Average within county SD	SD of county average
Corn - Conventional Till (bu./acre)	131.4	6.51	31.73
Soybean - Conventional Till (bu./acre)	47.1	1.62	8.70
Soybean - No-Till (bu./acre)	47.5	1.62	8.79
Total Costs (State extension documents, 2016)			
Corn - Conventional Till ($/bu.)	3.35	-	0.5
Soybean - Conventional Till ($/bu.)	7.97	-	1.81
Prices (NASS, 2016)			
Corn - farm gate level ($/bu.)	3.7	0.20	0.46
Soybeans - farm gate level ($/bu.)	9.2	0.33	0.3
Acreage (CDL, 2019-2023)			
County-level acreage (thousand acres)	77.5	-	102.2
Total acres in rainfed US (million acres)	166.7		
Cover crop soil carbon effect (Poeplau and Dan, 2015)			
Soil carbon sequestration (Mg CO_2/acre)	0.53	-	0.15
Total potential of rainfed US (million Mg CO_2 /year)	92.5		
Cover crop soil carbon effect (COMET model)			
Soil carbon sequestration (Mg CO_2/acre)	0.17		0.20 -
Total potential of rainfed US (million Mg CO_2 /year)	35.5		

Notes: [a] The parameters are obtained from Ma et al. (2023); [b] The parameters are obtained from Schnitkey et al. (2016); and [c] The parameters are obtained from Myers et al. (2019). For more details, see the Data section and the Appendix.

TABLE 2. Summary of Adoption, Carbon mitigation, Per Acre and Per Mg CO_2 Costs and Regions of Adoption

	Policy Instruments	Expenditure (Bil. $ per year)	Acres Adopted (Mil. acres)	Cost per acre ($)	Carbon Mitigated (Mg CO_2 per year)	Carbon cost ($ per Mg CO_2)	Regions where Cover Crops are Adopted
up to $1 Bil. per year	Practice-Based	0.8	21.6	35.0	11.0	68.4	Great Plains
	Price-Premium-Based	0.3	8.5	41.4	4.7	73.7	Midwest
	Carbon-Mitigation-Based	0.3	7.7	36.3	4.7	60.0	Southern states
up to $4 Bil. per year	Practice-Based	3.3	82.0	40.0	44.2	74.2	Great Plains, Southern states, Northwest
	Price-Premium-Based	3.6	80.0	44.4	45.8	77.6	Midwest
	Carbon-Mitigation-Based	2.7	67.0	40.1	38.4	70.0	Southern states, Lower Midwest
up to $6.5 Bil. per year	Practice-Based	6.5	129.0	50.0	71.3	90.7	All US rainfed
	Price-Premium-Based	6.2	123.0	50.8	68.0	91.9	All US rainfed
	Carbon-Mitigation-Based	6.4	126.0	50.7	70.9	90.0	All US rainfed

Notes: We present in this table a summary of the extent of adoption of cover crops, the carbon mitigation provided, the cost per acre, the cost of mitigating carbon, and the spatial adoption pattern under three alternative policy instruments in farmers' adoption decisions when they do not consider the private benefits of cover crops at three expenditure levels when farmers have a *High-Risk-Averse* and *High-Discount* profile. At every payment level, the lowest cost per acre is through *Practice-Based* payments, and the lowest cost per Mg CO_2 is through *Carbon-Mitigation-Based* payments. *Price-Premium-Based* payments usually have the highest cost per acre and cost per Mg CO_2 at these expenditure ranges. When policy expenditure is lower than $ 1 billion per year, adoption occurs mainly in lower-yield regions in the Great Plains with *Practice-Based* payments. *Carbon-Based* payments incentivize adoption in the southern states. *Price-Premium-Based* payments incentivize adoption in some counties in the Midwest. These adoption patterns do not change at expenditures of lower than $ 4 billion per year. When policy expenditure is higher up to $6.5 billion per year, there is little difference between the policy instruments in terms of spatial adoption as all three (*Practice-Based* payments, *Carbon-Based* payments, and *Price-Premium-Based* payments) incentivize cover crop adoption throughout the rainfed .

Incentivizing Cover Crop Adoption: Effectiveness of Alternative Policy Approaches

Appendices

Appendix A.1. Crop Yield Details

Yields are presented in Table A.2 by region. As we model county-level risk, we adjust yield variance using parameters from Scott et al. (2014) and Cooper et al. (2012) to make our analysis reflect farm-level riskiness, a summary of county-level riskiness is presented in Table 1. Farmers who adopt cover crops are subject to effects when considering certain private benefits as detailed in Table A.2.

Appendix A.2. Soil Carbon Effects of Cover Crops

The carbon effects of establishing cover crops include soil carbon effects and carbon mitigated through reduced fertilizer application for conventional crops. We estimate the mean annual change in soil carbon from establishing cover crops using a method described by Poeplau et al. (2015). They find through a meta-analysis that the equation that best determines the change in the overall soil carbon stock is $\Delta SOMC_{Stock} = 0.227\ Time - 0.003\ Elevation + 0.108\ Depth$, where $Time$ is the number of years cover crop is grown, $Elevation$ is meters the location above sea level, and $Depth$ is the sampling depth in cm. We take the annual change in soil carbon sequestration as $\Delta SOMC_{Stock}/Time$ in Mg CO_2 Ha^{-1} per year. We take $Elevation$ as the mean county elevation and $Time$ as the time period in our model (fifteen years) and estimate and soil carbon $Depth$ as 30cm as it is a common depth used in the literature (e.g. Joshi et al., (2023)). In Figure A.5, we show the spatial difference in soil carbon sequestration from cover crop establishment.

Appendix A.3. Conventional Crop Costs

We construct conventional crop costs for each rotation and tillage option at the state level using crop budget quantities and prices provided by state extension services. These include chemicals, seeds, harvesting, storage, drying, and inputs. N, P, and K prices are applied using prices consistent with corn and soybean crops. We present a summary of conventional crop costs in Table A.3.

Appendix A.4. Cover Crop Costs

Costs to establish cover crops for each tillage option are based on Cereal Rye cover crop adoption costs from Schnitkey et al. (2016), who estimates a cost of approximately $20 per acre and $25 per acre on cropland under till and no-till conventional crops. Covering crops under conventional tillage includes drilling/planting and seed costs. Additionally, we assume that under no-till, farmers employ a burn-down spray to remove cover crops before planting conventional crops, increasing the cost of establishing cover crops under a no-till conventional crop setup. We do not consider vetch or legume-based cover crops, which may have higher costs and differing benefits. Further, we take cover crop costs to be uniform across the rainfed region. Costs and effects of cover crops are presented in Table A.2.

Appendix A.5. Conventional Crop Prices

The prices for conventional crops (corn and soybean) are estimated first at the national level using 52-year national-level harvest prices (NASS) and futures prices (Chicago Board of Trade) to reflect the riskiness of conventional crop prices corresponding to the years 1972-2024, National-level prices are averaged for the 2016 harvest period of available states, Sept, Oct, and Nov, with the marketing year used for States where monthly data is unavailable. Futures prices are from 1986 to 2015 and averaged for Sept, Oct, and Nov, taken from

https://www.macrotrends.net/. We convert historical prices to 2016 dollars using the Gross Domestic Product: Implicit Price Deflator obtained from the St Louis Federal Reserve, with third-quarter values used to adjust historical prices. We use the difference in historical harvest and futures prices for each year from to calculate a distribution of national-level projected crop prices following RMA (RMA, 2011) rules. We then scale the stochastic national prices to state-level prices using the national and state-level harvest prices for 2016 (USDA, 2016). We present a summary of conventional crop prices in Table A.5.

Appendix A.6. Generation of Joint Yield-Price Distribution

We assume a joint yield-price distribution where the farmer knows the distribution of prices and yields estimated for their county to reflect the stochastic nature of crop yields and prices. We model stochastic crop yields for corn grain, corn stover, and soybean grain on cropland for all rotation and tillage options and corn and soybean prices. We model the joint distributions using the copula approach following Miao and Khanna (2017), Yan (2007), and Du & Hennessy (2012). The copula approach is a modeling process that describes and then replicates the dependence structure between multiple stochastic variables. Like Du & Hennessy (2012), we assume yields have beta and price lognormal distributions. Once we estimate joint distributions, we conduct a Monte Carlo simulation from which we obtain discrete draws. We present a Table of average correlation coefficients in Table A.6.

Appendix Tables and Figures

TABLE A.6. Cover crop acreage and carbon mitigation at selected payment levels under each payment policy and internalizations of cover crop benefits.

	Practice-Based ($ per acre)					Price-Premium-Based (% of revenue)					Cost-Share-Based (% of cost)					Carbon-Mitigation-Based ($ per Mg CO_2)				
Adopted Acres (million acres)																				
High-Constraint	0	20	40	60	80	0	4	8	12	16	0	25	50	75	100	0	35	70	105	140
No-Private-Benefit	0.0	0.0	82.1	140.2	166.4	0.0	0.0	8.5	139.9	166.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	118.2	159.8	166.4
Yield-Risk-Reduction	0.0	0.0	88.5	142.5	166.7	0.0	0.0	19.2	145.2	167.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	118.2	159.8	166.4
Cost-Saving	0.0	9.8	134.7	166.7	167.7	0.0	0.0	128.5	167.7	167.7	0.0	0.0	0.0	0.0	1.2	0.0	33.9	158.8	167.1	167.6
Long-Term-Yield	3.0	129.6	162.1	166.3	167.5	3.0	115.8	158.1	166.4	167.7	3.0	7.7	13.0	39.9	95.9	3.0	135.3	162.8	167.4	167.7
All-Benefits	66.3	160.1	165.7	167.5	167.7	66.3	157.1	165.0	167.7	167.7	66.3	112.7	139.0	151.5	157.6	66.3	161.8	167.3	167.7	167.7
Low-Constraint																				
No-Private-Benefit	0.0	0.0	74.1	135.9	164.1	0.0	0.0	10.4	139.5	167.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	114.1	155.1	166.0
Yield-Risk-Reduction	0.0	0.0	74.8	137.0	164.3	0.0	0.0	13.5	140.5	167.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	114.1	155.1	166.0
Cost-Saving	0.0	5.7	130.6	164.7	167.7	0.0	0.0	126.3	167.7	167.7	0.0	0.0	0.0	0.0	0.3	0.0	24.8	152.5	166.4	167.3
Long-Term-Yield	46.7	167.4	167.7	167.7	167.7	46.7	165.3	167.7	167.7	167.7	46.7	63.3	132.4	160.7	167.1	46.7	167.4	167.7	167.7	167.7
All-Benefits	164.9	167.7	167.7	167.7	167.7	164.9	167.7	167.7	167.7	167.7	164.9	167.2	167.5	167.6	167.6	164.9	167.7	167.7	167.7	167.7
Carbon Mitigation (Million Mg CO_2 per year)																				
High-Constraint	0	20	40	60	80	0	4	8	12	16	0	25	50	75	100	0	35	70	105	140
No-Private-Benefit	0.0	0.0	44.2	77.4	92.6	0.0	0.0	4.8	77.5	92.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.8	89.7	93.0
Yield-Risk-Reduction	0.0	0.0	47.9	78.7	92.8	0.0	0.0	11.0	80.6	93.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.8	89.7	93.0
Cost-Saving	0.0	5.3	79.3	100.1	100.7	0.0	0.0	75.5	100.8	100.8	0.0	0.0	0.0	0.0	0.6	0.0	20.3	95.7	100.6	100.8
Long-Term-Yield	1.7	72.7	90.1	92.5	93.3	1.7	65.7	88.1	92.7	93.4	1.7	4.4	7.4	22.9	54.3	1.7	76.8	90.8	93.3	93.4
All-Benefits	41.1	96.1	99.6	100.9	101.0	41.1	94.6	99.3	101.1	101.2	41.1	68.7	84.0	91.1	94.5	41.1	97.4	100.8	101.1	101.1
Low-Constraint																				
No-Private-Benefit	0.0	0.0	39.8	75.0	91.2	0.0	0.0	5.9	77.4	93.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	64.4	87.0	92.8
Yield-Risk-Reduction	0.0	0.0	40.1	75.6	91.3	0.0	0.0	7.7	78.0	93.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	64.4	87.0	92.8
Cost-Saving	0.0	3.1	76.8	98.7	100.8	0.0	0.0	74.2	100.9	100.9	0.0	0.0	0.0	0.0	0.2	0.0	15.0	91.9	100.4	100.7
Long-Term-Yield	26.7	93.2	93.4	93.4	93.4	26.7	92.2	93.4	93.4	93.4	26.7	36.3	75.1	89.8	93.1	26.7	93.3	93.4	93.4	93.4
All-Benefits	100.0	101.6	101.6	101.6	101.6	100.0	101.8	102.0	102.2	102.4	100.0	101.3	101.5	101.6	101.6	100.0	101.7	101.8	101.8	101.9

Model output showing acres adopted under cover crops and carbon mitigation through cover crop adoption at selected payment levels under each payment policy and internalization of cover crop benefits.

We consider the effect of the four alternative policy instruments on farmers' adoption decisions under various assumptions about the extent to which farmers internalize the private benefits. We show the land on which cover crops will be adopted and the carbon mitigation achieved at various payment levels under each policy instrument.

Farmers who consider no private benefits only adopt cover crops under *Practice-Based* payments at payments higher than $30 per acre. The perceived conventional crop yield penalty of adopting cover crops also implicitly reduces the conventional crop yield riskiness, leading to lower adoption in the *Low-Constraint* farmer profiles when compared to *High-Constraint* profiles. Under *Price-Premium-Based* payments, farmers who consider no private benefits adopt cover crops when payments exceed 8% of crop revenue, with 165 million acres adopted at 14%. Under *Cost-Share-Based* payments, farmers who do not consider private benefits (red curves in Figure 2 (i-l)) do not adopt cover crops even at 100% *Cost-Share-Based* payments. Under *Carbon-Based* payments, farmers adopt cover crops at payments exceeding $50 per Mg CO_2, with approximately 116 to 167 million acres adopted (red curves in Figure 2 (m-p)) at carbon payments between $80 and $140 per Mg CO_2.

When farmers consider only *Yield-Risk-Reduction* benefits, there is little difference in adoption relative to farmers who internalize no benefits. The *Yield-Risk-Reduction* benefits of cover cropping are more appealing to *High-Risk-Averse* farmers than *Low-Risk-Averse* farmers. For example, in the *Low-Constraint* farmer profile, additional adoption is lower than with *High-Constraint* profiles relative to not considering any private benefits. When farmers consider *Cost-Saving* benefits only, *Practice-Based* payments needed to induce cover crop adoption are reduced by approximately $10-$15 per acre relative to when they consider no benefits. Farmers start to adopt cover crops at payments above $15 per acre and can adopt up to 167 million acres at $60 per acre. In the *High-Constraint* farmer profile, adoption increases from 0 to 9.8 million acres at payment levels of $20 per acre and from 0.8 to 120.3 million acres at a payment of $30 per acre relative to no internalization. When farmers consider *Long-Term-Yield* benefits, some may adopt cover crops without policy payments. Farmers adopt cover crops on 167 million acres at a payment of $60 per acre per year in the *High-Constraint* farmer profile and $15 per acre per year in the *Low-Constraint* profile. When farmers consider *All-Private* benefits, adoption without payments under all farmer risk and time profiles extends to large parts of the rainfed region.

TABLE A.2. Effects of cover crop adoption on conventional crop yield, risk, fertilizer use, and private benefits.

Short-term duration	ends at year 3		Ma et al. (2023)
Long-term duration	ends at year 15		
	corn	soybean	
Expected yield effect	-13.20%	0.00%	Ma et al. (2023)
Long-term yield effect	16.30%	0.00%	
Short-term yield risk effect	-0.50%	0.00%	
Long-term yield risk effect	-39.60%	0.00%	
Expected yield effect in sensitivity analysis	-3.90%	0.00%	Qin et al. (2023)
Long-term yield effect in sensitivity analysis	0.00%	0.00%	
Fertilizer benefit	15 lb/acre	0 lb/acre	Schnitkey et al. (2016)
Establishment cost	$20/acre		
Termination fuel usage (for no-till)	0.3 gallons/acre		
Termination cost (for no-till)	$5/acre		
Weed cost reduction	$7.50 /acre		Myers et al. (2019)
Erosion cost reduction	$2.00 /acre		

We provide here a set of descriptive statistics for the costs and effects of adopting cover crops.

TABLE A.3. Generated yield distributions (average for regions)

Crop	Rot.	Tillage	Unit	Northern Great Plains	Southern Great Plains	Upper Midwest	Central Midwest	South Central	Delta Region	Northeast	Central East	Southeastern states	All Counties	All Counties SD
Corn	Corn or CS.	Conv. Till	bu ac^{-1}	121.3	84.9	138.3	166.4	131.9	143.0	114.0	141.8	122.8	131.4	31.73
Soybean	CS rot	Conv. Till	bu ac^{-1}	42.8	40.6	47.8	55.9	45.3	50.3	47.2	54.0	42.0	47.1	8.70
		No-Till		43.4	40.8	48.5	56.4	45.5	50.4	47.7	54.3	42.1	47.5	8.79

TABLE A.4. Conventional crop costs

$ per Mg	Total Operating Cost	Upper Great Plains	Lower Great Plains	Upper Midwest	Lower Midwest	Upper Delta	Lower Delta	North East	Central East	South East	Overall	SD Over Counties
	Corn											
CL	CC_CT	2.91	3.39	3.13	3.47	3.60	2.72	3.50	3.20	3.71	3.35	0.50
	Soybean											
CL	CT	6.63	9.21	6.16	6.68	10.52	9.66	8.34	7.40	8.86	7.97	1.81

Price per bushel of corn and soybean - Computed using crop budgets from state extension services and expected model yields. Costs per bushel are based on county-level expected yields.

TABLE A.5. Conventional crop prices

Conventional Crop Prices	Unit	Mean	Std Dev	Min	Max
Corn - farm gate price over states [b]	$/bushel	3.7	0.46	3.45	5.19
Soybeans - farm gate over states [b]	$/bushel	9.20	0.30	8.77	10.12

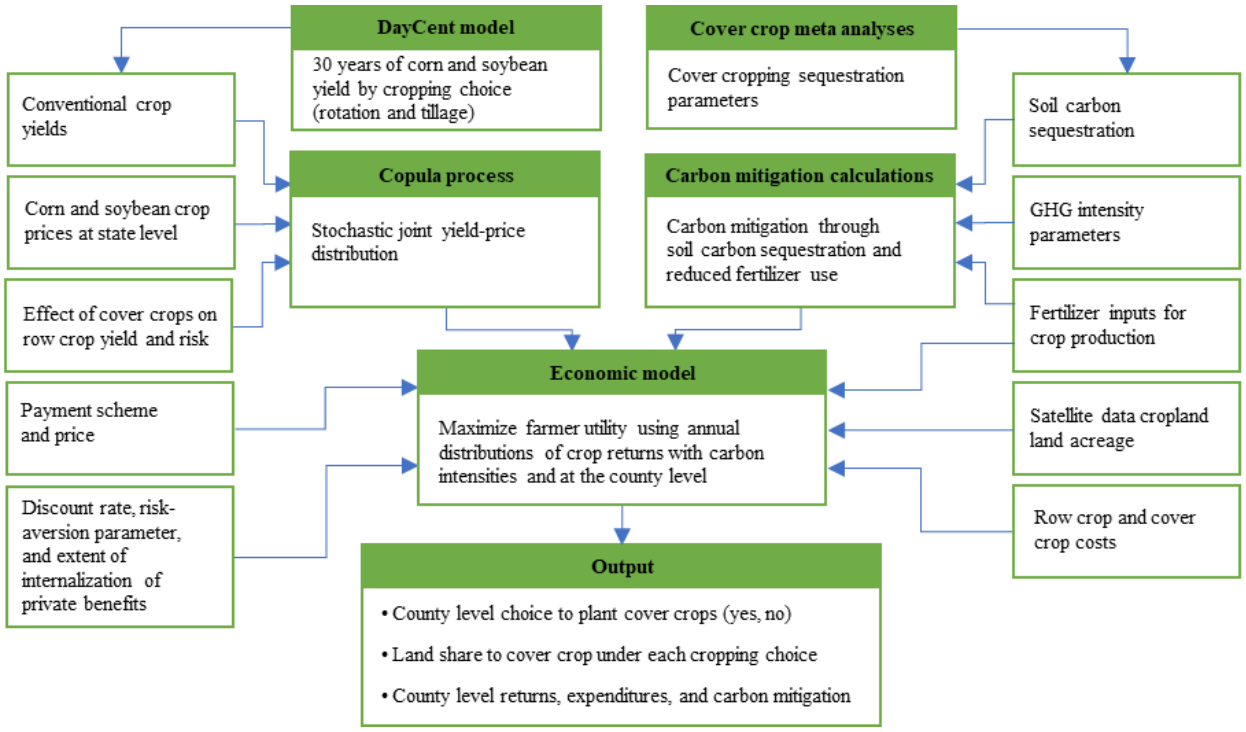
[a] Computed by authors

TABLE A.6. Average correlation coefficients matrix for model yields and prices

		Corn	Soybean	Corn	Sb
Corn		1.00			
Soybean		0.39	1.00		
Row Prices	Corn	-0.01	0.01	1.00	
	Soybean	-0.02	-0.02	0.65	1.00

Computed by authors.

FIGURE A.1. Flow Diagram of Numerical Simulation Model.

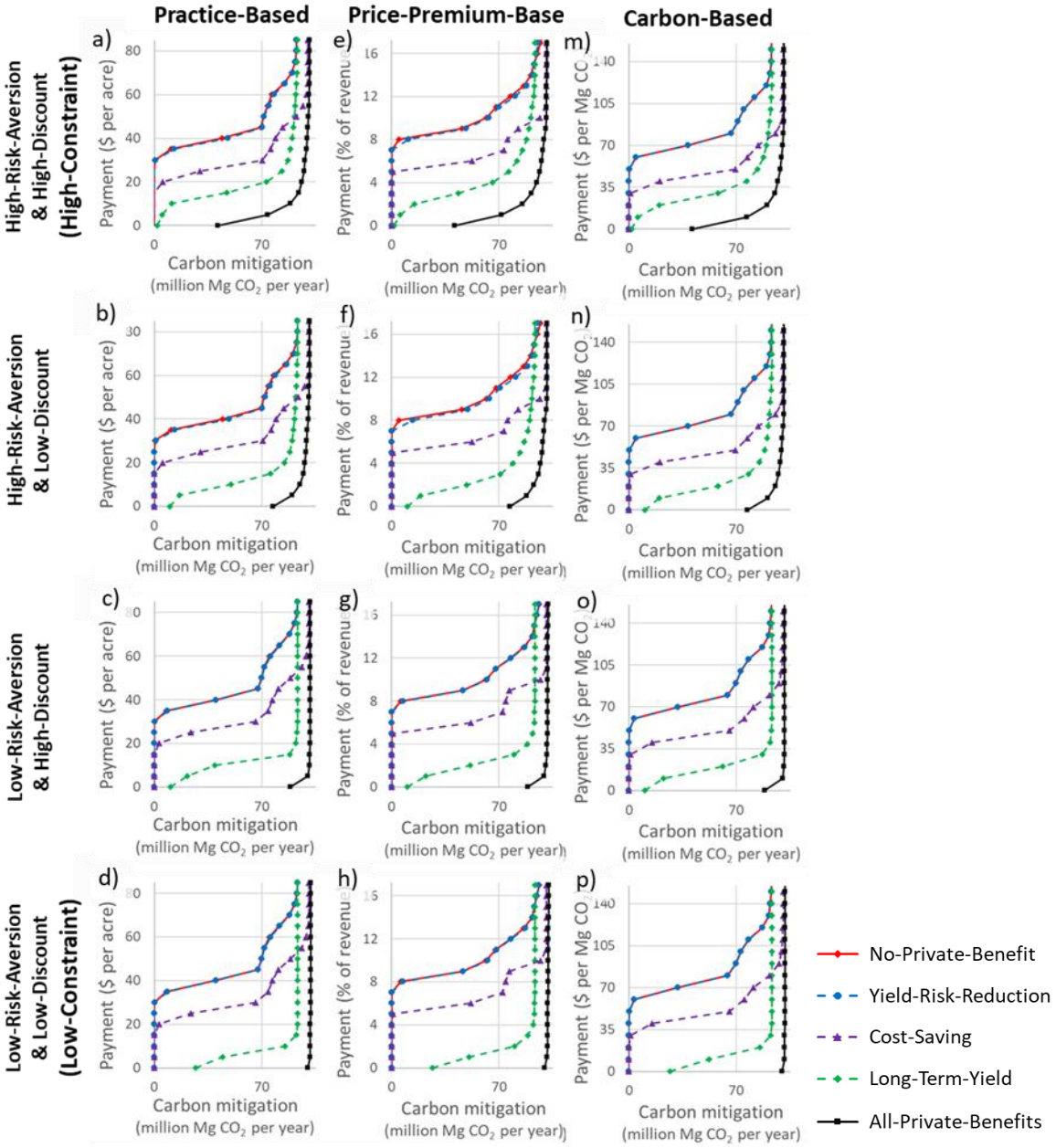


Flow Diagram of Numerical Simulation Model. This flow diagram illustrates the numerical simulation and shows how a representative farmer decides to adopt cover crops and the land share of cover cropping at the county level. See Conceptual Framework (Section 3) and Data and Model Calibration (Section 4) sections for more details.

Our stylized framework examines the economic incentives for an expected utility-maximizing farmer to adopt cover cropping with varying risk and time preferences and perceptions about the private benefits of cover crop adoption, with and without any policy or carbon credit market incentives. We analyze the implications of internalizing the various private benefits of cover crop adoption one at a time to isolate the key factor that could change their incentives to adopt cover crops and how this varies with the farmer's risk and time preferences. We then apply this framework to examine the cost-effectiveness of four policy instruments in inducing cover crop adoption and their carbon mitigation outcomes under various assumptions about the extent to which farmers internalize the private benefits of cover cropping and farmer risk and time preferences.

Since the yield and soil carbon sequestration impacts of cover cropping are expected to vary spatially and over time, we link the economic model with a biogeochemical model, DayCent, to analyze the spatial heterogeneity in the share of acres on which a utility-maximizing representative farmer in each county will decide to plant cover crops. We consider varying levels of internalization of the private benefits of cover cropping and farmer risk and time preferences. This analysis also considers the stochasticity in conventional crop yields and prices at the county level. It thus incorporates the underlying risks associated with conventional crop production that can also vary spatially. We aggregate the carbon mitigated through cover cropping and compare the effectiveness of alternative policies in mitigating carbon by incentivizing cover crops.

FIGURE A.2. Carbon Mitigation through Cover Crop Adoption at Various Payment Levels under Alternate Policy Instruments and Different Internalizations of Benefits and Farmer Risk and Time Preferences.



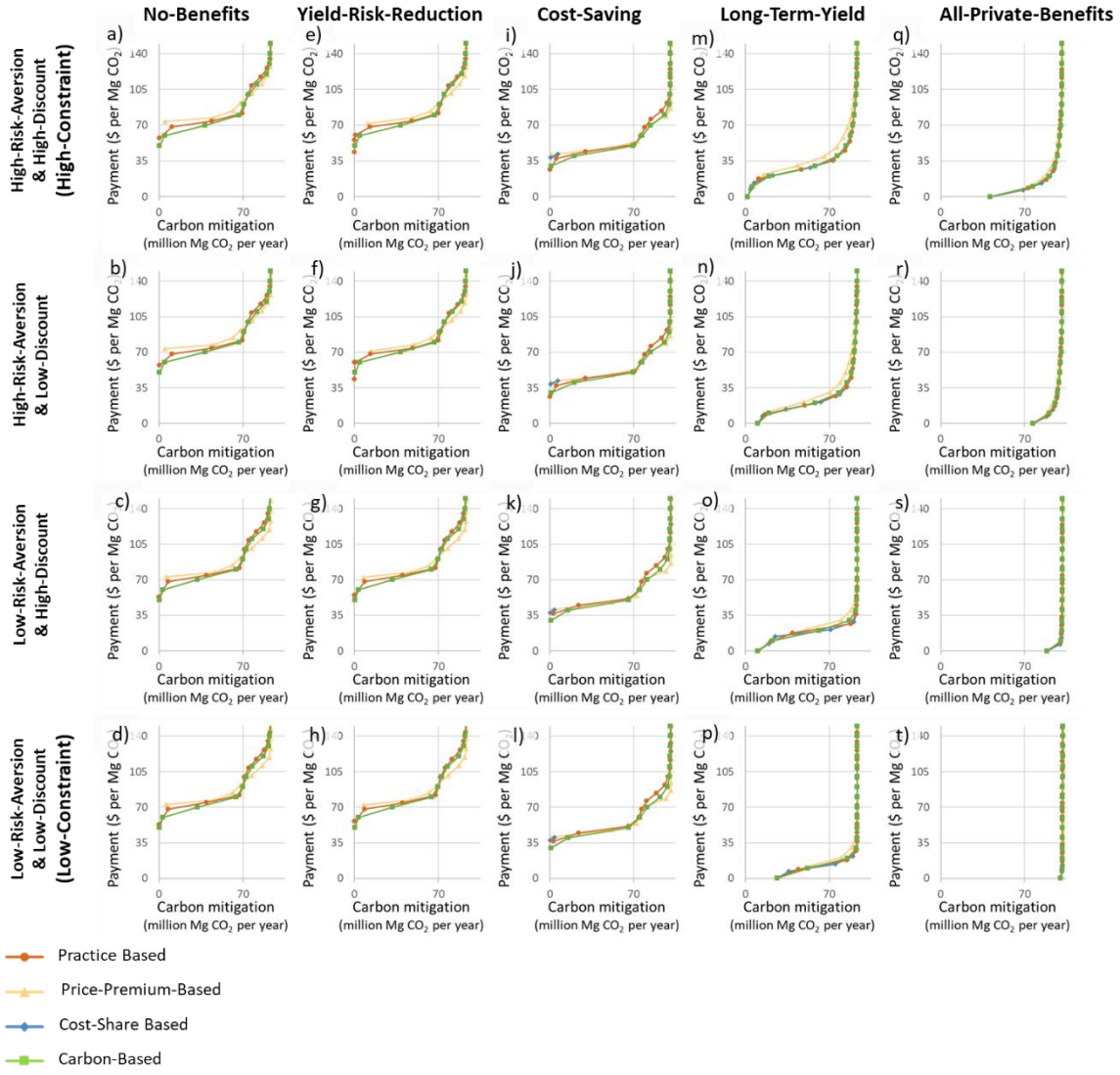
Carbon mitigation through cover crop adoption at various payment levels under alternate policy instruments and different internalizations of benefits and farmer risk and time preferences.

When farmers consider no benefits (red lines) or only *Yield-Risk-Reduction* benefits (blue dashed lines), incentive payments that can mitigate up to 75 Mg CO_2 per year at $45 per acre under *Practice-Based* payments (a-d), 11% of revenue under *Price-Premium-Based* payments (e-h), and $80 per Mg CO_2 under *Carbon-Based* payments (m-p). Costs to mitigate carbon are lower under *Cost-Saving* benefits (purple dashed lines), followed by *Long-Term-Yield* benefits (green dashed lines) and *All-Private* benefits (black lines).

When farmers consider *Cost-Saving* (purple dashed lines) or *All-Private* (black lines) benefits, they mitigate more carbon than other internalizations of private benefits due to reduced fertilizer use.

When farmers consider *Long-Term-Yield* benefits (green dashed lines) or *All-Private* benefits (black lines), they mitigate more carbon through higher adoption of cover crops under *Low-Constraint* farmer profiles than under *High-Constraint* farmer profiles.

FIGURE A.3. Carbon Mitigation through Cover Crops at Various Payment Levels under Alternate Policy Instruments and Different Internalizations of Benefits and Farmer Risk and Time Preferences.



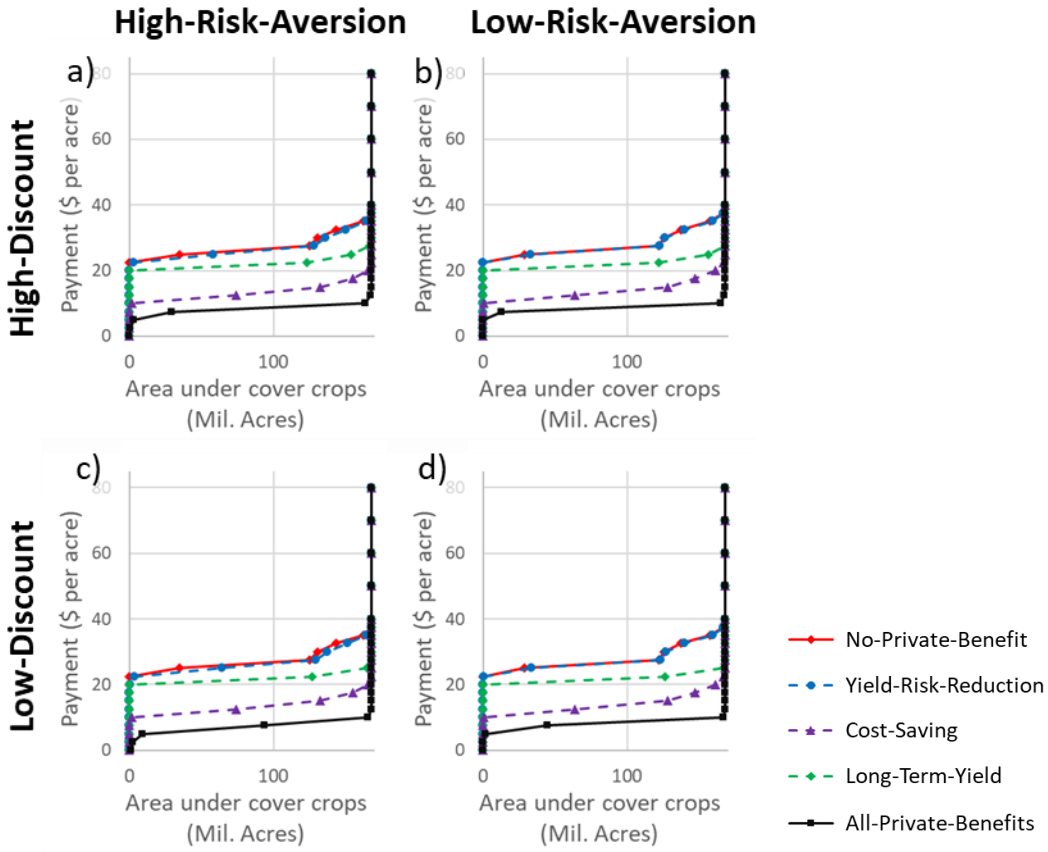
Carbon mitigation through cover crops at various payment levels under alternate policy instruments and different internalizations of benefits and farmer risk and time preferences.

When farmers consider no private benefits to cover crop adoption (a-d), the average cost to mitigate one unit of carbon ranges between $60 and $80 per Mg CO_2 across policy instruments. The lowest cost to mitigate carbon in this range is through *Carbon-Based* payments (green lines), followed by *Practice-Based* payments (orange lines), and *Price-Premium-Based* payments (yellow lines) with *Cost-Share-Based* up to 100% payment not incentivizing adoption. Costs to mitigate more than 70 million Mg CO_2 per year increase sharply, rising to $140 per Mg CO_2, and can mitigate up to 107 million Mg CO_2 per year. There is little difference in costs across the policy instruments in this range.

When farmers consider the *Yield-Risk-Reduction* benefits of cover crops, there is only a slight difference in costs (e-h) relative to when no benefits are considered. When farmers consider the *Cost-Saving* benefits of cover crop adoption, the average cost to mitigate one unit of

carbon up to 70 million Mg CO_2 per year ranges from \$40 to \$50 per Mg CO_2 across policy instruments. There is little difference in costs between these policy instruments; however, the order in which policy instruments have the lowest cost is similar to farmers considering no benefits costs. To incentivize cover crop adoption beyond 70 million Mg CO_2 per year, the average cost to mitigate one unit of carbon ranges from \$60 to \$100 per Mg CO_2, with *Carbon-Based* and *Price-Premium-Based* payments having the lowest cost to mitigate. There is no significant cost difference across policy instruments when farmers consider *Long-Term-Yield* or *All-Private* benefits of cover crop adoption (m-t) due to lowered costs and non-zero adoption without incentive policy instruments.

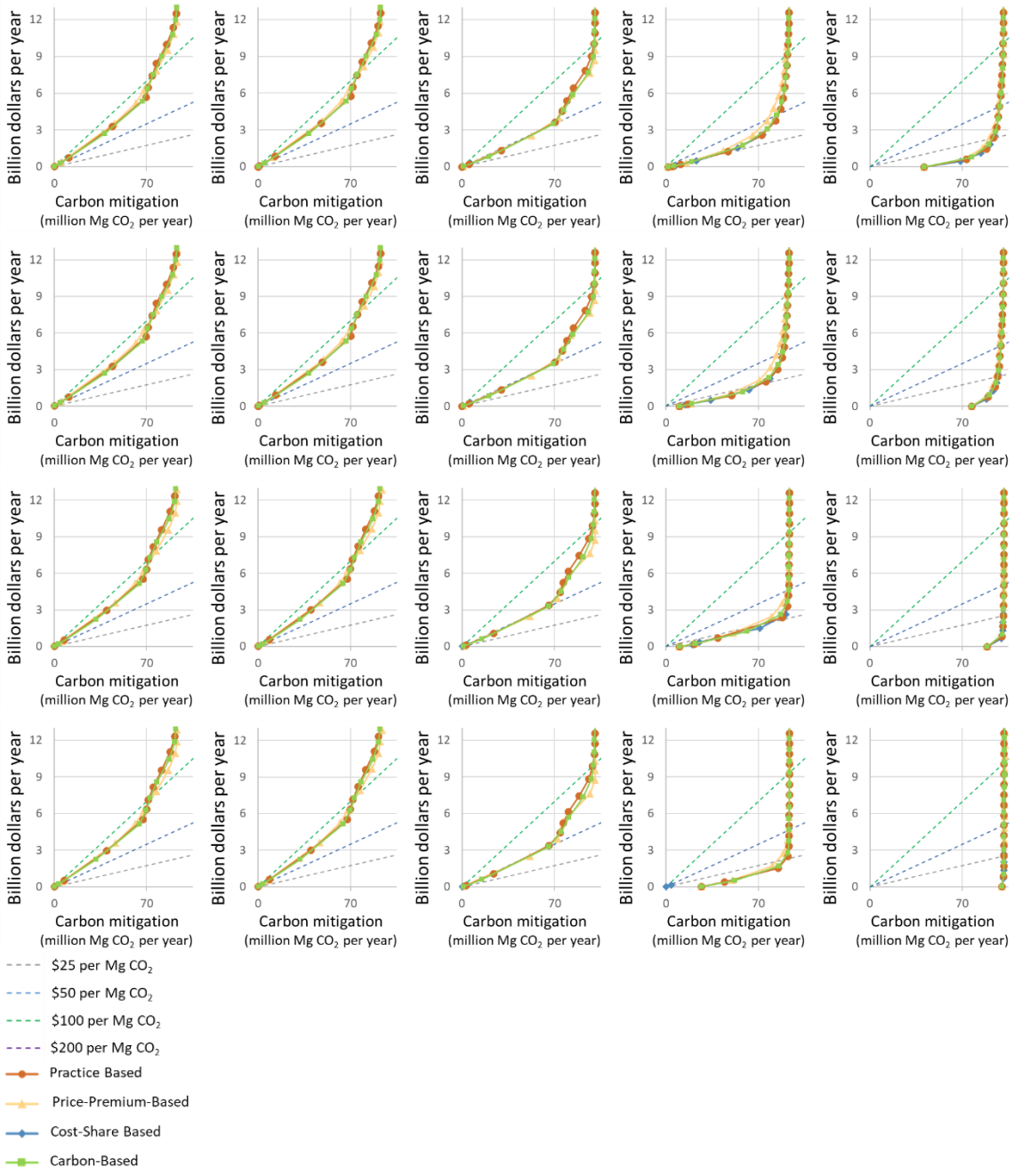
FIGURE A.4. Cover Crop Adoption through *Practice-Based* Payments under under Conservative Perceived Yield Loss and Long-Term Gain Effects.



Cover crop adoption through *Practice-Based* payments under different internalizations of benefits, farmer risk, and time preferences, as well as conservative perceived yield loss and long-term gain effects.

We consider a sensitivity analysis of comparing cover crop adoption using more conservative effects from Qin et al. (2021) as a sensitivity analysis. Payments needed to incentivize cover crop adoption are lower than in the primary model (Compare to Figure 2 (a-d)). However, similar to the primary model, *Yield-Risk-Reduction* benefits have little effect relative to farmers when considering no private benefits. However, the impact of *Yield-Risk-Reduction* is more prominent in this case. The purple dashed line representing *Cost-Saving* benefits has adoption at lower payments than the green dashed line representing *Long-Term-Yield* effects cost. In this sensitivity analysis, the effects of *Yield-Risk-Reduction* are more prominent due to smaller short-term and long-term yield reductions and benefits that implicitly decrease and increase return riskiness (through other sources of risk in the model, for example, price riskiness). To illustrate this, when farmers consider *All-Private-Benefits* and *Yield-Risk-Reduction* benefits only (dashed blue line), they adopt more cover crops when they are less risk-averse (a, b) than when they are more risk-averse (c, d).

FIGURE A.5. Aggregate Cost to Mitigate Carbon Under Alternate Policy Instruments and Different Internalizations of Benefits and Farmer Risk and Time Preferences.



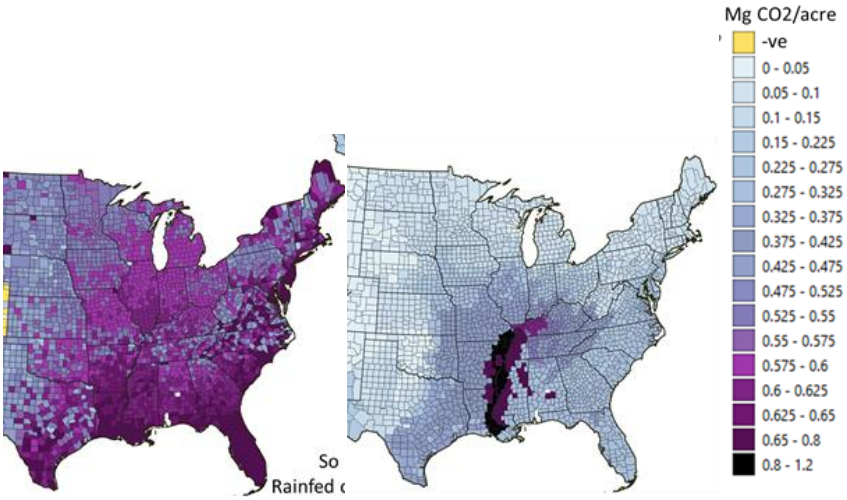
This figure shows the aggregate cost to mitigate carbon under alternate policy instruments and different internalizations of benefits and farmer risk and time preferences.

When farmers consider no benefits (a-d), costs under all farmer risk and time preferences are similar. The cost to mitigate carbon up to 70 million Mg per year is between 50 and 100 per Mg CO_2 and is lowest under *Carbon-Based* payments; however, the aggregate costs are not significantly lower than in other policy instruments. Mitigating 70 million Mg CO_2 per year costs around $5.5-6.5 billion annually across different policy instruments.

There is no significant change in aggregate costs when farmers consider risk reduction benefits (e-h). Under consideration of *Cost-Saving* benefits (i-l), the cost of carbon mitigation is approximately $50 per Mg CO_2. The aggregate cost of mitigating 70 million Mg CO_2 per year is around 4 billion annually across different policy instruments.

When farmers consider *Long-Term-Yield* benefits (m-p), they are sensitive to risk and time aversion, such that the cost of mitigating 70 million Mg per year is around $1 (*Low-Constraint* (i.e., *Low-Risk-Aversion* and *Low-Time-Aversion*) farmer profile) to $ 2 billion (*High-Constraint* (i.e., *High-Risk-Aversion* and *High-Time-Aversion*) farmer profile) per year across different policy instruments and farmer preferences. When farmers consider *All-Private* benefits (q-t), they may mitigate over 70 million Mg per year without additional incentives.

FIGURE A.6. Spatial Heterogeneity in Carbon Sequestration Rate with Cover Crop Adoption using Poeplau and Dan and COMET sequestration models.



Computed by authors for model counties based on Popleau et al. (2015) and COMET. In Poeplau and Dan, the highest soil carbon sequestration potential at the county level is in the southern and eastern states (between 0.55 and 0.66 Mg CO_2 per acre per year), followed by the Midwest (between 0.50 and 0.60 Mg CO_2 per acre per year), with the upper Midwest and Great Plains having significantly lower sequestration potential (between 0.25 and 0.50 Mg CO_2 per acre per year).In COMET the high sequestration regions are concentrated along the Mississipi river region and are significantly lower in the rest of the rainfed region.