Stock or Flow? Carbon Payment Designs for Soil Carbon Sequestration *

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Abstract

The design of carbon payments determines whether farmers store soil carbon over the long run. I derive closed-form minimum payment conditions for five designs and show which sustain sequestration. Designs that reward incremental carbon gains fail structurally: without penalties for carbon release, the payment rises without bound as soils approach saturation and farmers cycle rather than accumulate carbon. Paying for the maintained stock, conditional on continued conservation, is the design that sustains adoption and limits the additionality problem. Lifetime payments stay below the U.S. social cost of carbon, and spatial targeting cuts program costs by 22%.

Keywords: Carbon payment design, Voluntary carbon markets, Payment for ecosystem services, Soil carbon sequestration, Additionality

1 Introduction

Whether conservation practices are adopted at scale is, at its core, a payment design problem. Farmers who adopt conservation tillage can be compensated for the carbon they sequester, yet most intuitive payment designs inadvertently reward them to stop. As soils approach their storage ceiling, the carbon added each period shrinks, and any payment tied to incremental sequestration shrinks with it, until it becomes rational for the farmer to abandon the practice, let stored carbon revert, and begin collecting payments anew. The resulting equilibrium sustains little permanent sequestration, no matter how large the payment. This failure is not a matter of weak monitoring or idiosyncratic behavior; it follows from the dynamics of how carbon accumulates in soil. Yet it remains unclear which payment designs avoid it and why. This paper investigates that question.

The stakes are substantial. Land-based sequestration strategies could offset 10 to 15 gigatons of carbon dioxide equivalents per year globally through 2050 (Griscom et al., 2017; Roe et al., 2021). One approach is to incentivize landowners to commit their land to afforestation through optimal contract designs (Lubowski et al., 2006; Mason and Plantinga, 2013). Because agriculture is essential for food production and human livelihoods, an alternative is to increase carbon sequestration within agricultural systems by incentivizing conservation practices, such as no-till farming and cover cropping. Yet long-term no-till adoption covers only 38% of US cropland (Horowitz et al., 2010). Three features of soil carbon dynamics make this a problem of design rather than of setting the right carbon price. Sequestration is reversible, and reversion releases stored carbon rapidly (Kim et al., 2008; Ruseva et al., 2020; Sadatshojaei et al., 2021; Sawadgo and Plastina, 2022). Soils have finite storage capacity, so sequestration rates decline as stocks approach saturation, the cause of the incremental payment trap (Chen et al., 2019; West and Six, 2007; Paustian et al., 2016; Stewart et al., 2007; Gulati and Vercammen, 2005, 2006). Conservation practices reduce short-run crop yields, creating a wedge between immediate costs and long-run sequestration benefits (Blevins et al., 1977; Ismail et al., 1994). Two further frictions make payment design

consequential. First, inframarginal participation is pervasive: Aspelund and Russo (2026) report that a large fraction of United States Department of Agriculture's Conservation Reserve Program participants would have conserved without payment. So any design that ignores counterfactual behavior spends public resources on non-additional sequestration. Second, distrust in institutions limits the reach of standard payment for ecosystem services schemes (Jack et al., 2025; Jayachandran et al., 2017). Prior work has studied reversibility, delayed accumulation, variable sequestration rates, and yield losses (Antle et al., 2003; Murray et al., 2007; Feng et al., 2002; Kunwar et al., 2026), and has mapped the landscape of result-based, action-based, and hybrid farming contracts (Raina et al., 2024). Yet, these strands have not been reconciled into the payment conditions a designer would need.

I answer that question with a bioeconomic model of a forward-looking farmer who chooses between no-till and conventional tillage each period, trading short-run yield losses against long-run carbon payments. I compare five payment designs: payments proportional to the total carbon stock (P1); payments proportional to the carbon stock, conditional on adopting a conservation practice (P2); payments and penalties based on incremental changes in the stock (P3); incremental payments conditional on adoption but without penalties for reversal (P4); and flat adoption payments (P5). For each design I derive a closed-form minimum payment condition for sustained adoption, and I validate these conditions against a stochastic Bellman equation that incorporates uncertainty in soil organic carbon (SOC) dynamics. The model is parameterized with EPIC simulations (Williams et al., 1989; Izaurralde et al., 2006) across 70 representative fields in five Midwestern watersheds spanning four soil types defined by their drainage characteristics, which I refer to as soil hydrology groups. Bringing biophysical simulation together with dynamic optimization lets me address reversibility, saturation, and yield tradeoffs jointly at field scale, where prior analyses have typically treated these constraints in isolation. The dynamic optimization framework builds on the capital-theoretic tradition of Burt (1981) and McConnell (1983), who applied dynamic programming and optimal control to soil resource management, and on recent extensions to soil carbon

and environmental services (Berazneva et al., 2019; Lichtenberg, 2024).

The results identify a clear policy hierarchy. Incremental payment designs fail in both variants. Without penalties for carbon release (P4), a fundamental defection problem emerges: as soils approach carbon saturation, the payment rate required to sustain no-till rises without bound, and farmers rationally revert to conventional tillage regardless of prior sequestration. With penalties (P3), the defection incentive is suppressed but replaced by a lock-in problem at saturation, where farmers bear continued yield costs while receiving no additional payments and facing prohibitive reversal costs. Flat adoption payments (P5) require the same lifetime payment as P2 under certainty but are not contingent on the carbon actually stored, and so transfer sequestration risk to the payer. Stock-based payments conditional on conservation practice adoption (P2) emerge as the optimal design. This structure holds farmers accountable for maintaining a carbon stock, limits the additionality problem that arises when farmers with high legacy carbon stocks collect payments without changing practices, and maintains consistent adoption incentives throughout the sequestration horizon. Lifetime discounted payments under P2 remain below the U.S. Environmental Protection Agency's (EPA) social cost of carbon (U.S. Environmental Protection Agency, 2023), indicating net welfare gains. Required payment rates vary substantially with soil type and initial SOC. Across the five watersheds studied, spatially targeted payments calibrated to biophysical characteristics reduce total program costs by approximately 22% relative to uniform payment schemes, with direct implications for the design of conservation incentive programs and voluntary carbon markets.

2 Data

I parameterize the theoretical model using simulated data from the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1989; Izaurralde et al., 2006), which integrates soil properties, climate inputs, topography, and land management decisions to

simulate field-level physicochemical processes over long time horizons. Soil data are drawn from the Soil Survey Geographic Database (SSURGO), daily climate inputs from the World Climate Research Programme Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016), and field boundary and land-use information from the USDA Cropland Sequence Boundaries dataset (Hunt et al., 2024). Simulation inputs comprise geospatial characteristics (latitude, longitude, slope, elevation, and aspect ratio) and daily weather variables (precipitation, minimum and maximum temperature, solar radiation, humidity, and wind speed). Soil parameters include albedo, hydrologic group, layer depth and bulk density, sand and silt fractions, pH, organic carbon content, calcium carbonate concentration, rock fragment content, and hydraulic conductivity.

Soil carbon accumulation under conservation tillage operates over horizons of 60 to 90 years, making it impractical for field experiments to observe a complete sequestration cycle within a standard research timeline. Administrative data on voluntary carbon market contracts do not yet span sufficient time to identify long-run adoption dynamics. EPIC is the standard simulation tool in the agronomic literature precisely because it has been extensively validated against observed soil carbon trajectories across diverse climatic and edaphic conditions (Izaurralde et al., 2006; Causarano et al., 2008). Importantly, the model inputs used here are drawn from real observational data. The simulation methodology is accordingly best understood as a structured integration of observational inputs through a validated biophysical process model that generates the parameter estimates needed to characterize long-run sequestration dynamics at field scale.

Management practices are standardized across simulations to isolate tillage effects. Tillage operations are scheduled in late April, corn planting in early May, and harvest in mid-September, with residue shredded post-harvest. Annual fertilizer applications are fixed at 185 kg/ha, 150 kg/ha, and 116 kg/ha, and irrigation follows an automatic stress-triggered schedule. I evaluate three tillage systems: no-till (NT), reduced tillage (RT, tandem disk), and conventional moldboard plow tillage (CT). Fields are drawn from five representative

Midwestern watersheds — Sugar, Lower Maumee, Maple, Macoupin, and Upper Fox — selected to capture soil and climate heterogeneity across the region. Within each watershed, I stratify by hydrologic soil group and sample fields proportionally, yielding 70 fields in total. Simulations are first run under CT for over 200 years until SOC reaches its long-run equilibrium value, establishing realistic baseline conditions. I then conduct 60 to 90 year simulations under NT, RT, and CT to compare SOC trajectories and crop yields. The 70-field sample is stratified by soil characteristics across five watersheds to ensure systematic coverage of the dominant soil and climate conditions in Midwestern agriculture. The market price of corn is set at \$4.04 per bushel (Macrotrends, 2024), which translates to \$160 per ton of corn (U.S. Grains Council, 2024).

Table 1 reports the key EPIC-derived parameters: C^* (ton/ha), the maximum attainable carbon stock under a given practice; C_0 (ton/ha), the baseline stock under long-run CT; s (year^{-1}), the sequestration rate; and y (ton/ha), average crop yield. NT dominates RT in both SOC sequestration and yields across all fields; the analysis accordingly focuses on the NT versus CT comparison.

Table 1: Simulated mean corn yield (y, t ha^{-1}), lowest soil organic carbon (SOC) stock (C_0, t ha^{-1}), SOC threshold (C^*, t ha^{-1}), and annual carbon sequestration rate (s, yr^{-1}) under conservation tillage practices: no-till (NT) and reduced tillage (RT) for each soil hydrology group. Estimates are derived from Environmental Policy Integrated Climate (EPIC) model simulations covering 70 fields in five watersheds (Sugar Creek, Lower Maumee, Maple, Macoupin, and Upper Fox). Field-level observations appear in the Appendix (Table 4).

	Yield (t ha^{-1})			Sequestration rate		Lowest SOC stock	Critical SOC threshold	
Hyd.	y_{CT}	y_{NT}	y_{RT}	s_{NT}	s_{RT}	C_0	C^*_{NT}	C^*_{RT}
A	12.04 (0.29)	11.87 (0.28)	11.79 (0.32)	0.075 (0.005)	0.078 (0.005)	32.26 (4.30)	37.51 (4.65)	36.31 (4.62)
B	11.42 (0.24)	10.49 (0.22)	10.28 (0.24)	0.058 (0.004)	0.064 (0.004)	54.31 (5.70)	65.02 (6.91)	61.85 (6.52)
C	11.15 (0.23)	10.33 (0.25)	10.14 (0.27)	0.057 (0.002)	0.067 (0.002)	53.91 (3.04)	61.91 (3.23)	59.43 (3.10)
D	11.50 (0.40)	10.79 (0.49)	10.67 (0.47)	0.060 (0.002)	0.068 (0.003)	40.46 (3.29)	46.79 (3.73)	45.25 (3.66)

Note: Standard errors in parentheses.

3 Theoretical Framework and Results

A representative farmer chooses a tillage practice θ_t in each period to maximize expected discounted profits:

$$V = \max_{\theta_1, \theta_2, .. \theta_\infty} \sum_{t=0}^{\infty} \beta^t \mathbb{E}[\pi_t] \tag{1}$$

where $\beta \in (0, 1)$ is the discount factor. Period profits depend on the carbon payment policy in place. I consider five alternative designs, differing in the basis of payment (carbon stock level, incremental carbon change, or conservation practice adoption) and in whether penalties apply for carbon release. The sub-sections 3.1 through 3.5 characterize each design in turn.

3.1 Policy 1: Payments proportional to the current carbon stock

Period profits are given by:

$$\pi_t = (\mathbb{E}[C_t] - C_0) \times m + \mathbb{E}[y_t] \times P - Cost(\theta_t). \tag{2}$$

Here C_t denotes the soil carbon stock at the end of period t, C_0 is the baseline carbon stock under long-run conventional tillage, m is the carbon payment rate (\$ per ton of carbon), P is the crop price, y_t is crop yield, and $Cost(\theta_t)$ represents the cost associated with practice θ_t.

The farmer chooses between no-till (NT, θ_{NT}) and conventional tillage (CT, θ_{CT}), where $\theta_t \in \{\theta_{NT}, \theta_{CT}\}$. NT increases SOC over time but reduces crop yields ($y_{NT} < y_{CT}$), while CT releases carbon whenever $C_t > C_0$.

When m is sufficiently high to induce NT adoption, the value function is:

$$V_{NT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{NT}] \times P + (\mathbb{E}[C_t] - C_0) \times m - Cost(\theta_{NT})] \tag{3}$$

Following Ragot and Schubert (2008); Malik (2026), SOC sequestration dynamics under conservation practice are modeled as

$$\mathbb{E}[C_t] = C^* - (C^* - \tilde{C})e^{-s(t+1)} \tag{4}$$

where s governs the sequestration rate, and depends on soil type, weather conditions, and management practices, and $\tilde{C}$ denotes the SOC at the beginning of period $t = 0$. The value function in closed-form is:

$$V_{NT} = \frac{\mathbb{E}[y_{NT}] \times P - Cost_{NT}}{1-\beta} + \frac{(C^* - C_0)m}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}m}{1-\beta e^{-s}} \tag{5}$$

When m is sufficiently low, the farmer adopts CT at all SOC levels. The initial SOC level $\tilde{C}$ decreases over time and asymptotically approaches C_0. The corresponding value function is:

$$V_{CT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{CT}] \times P + (\mathbb{E}[C_t] - C_0) \times m - Cost(\theta_{CT})] \tag{6}$$

SOC release dynamics are modeled as $\mathbb{E}[C_t] = C_0 + (\tilde{C} - C_0)e^{-s'(t+1)}$, where s' governs the release rate (Ragot and Schubert, 2008; Malik, 2026). The closed-form value function is:

$$V_{CT} = \frac{\mathbb{E}[y_{CT}] \times P - \text{Cost}_{CT}}{1-\beta} + \frac{(\tilde{C} - C_0)e^{-s'}m}{1-\beta e^{-s'}} \tag{7}$$

For the farmer to adopt NT, it must be that $V_{NT} \geq V_{CT}$, which requires:

$$m \geq \left(\frac{C^* - C_0}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}}{1-\beta e^{-s}} - \frac{(\tilde{C} - C_0)e^{-s'}}{1-\beta e^{-s'}} \right)^{-1} \left(\frac{\Delta y \times P - \Delta\text{Cost}}{1-\beta} \right) \tag{8}$$

where $\Delta y = \mathbb{E}(y_{CT} - y_{NT})$ is the expected yield loss under NT, and $\Delta Cost = Cost(\theta_{CT}) - Cost(\theta_{NT})$ is the difference in implementation costs. Equality in (8) defines the minimum carbon payment required to induce NT adoption.

The lifetime carbon payment per ton of sequestered carbon under NT is:

$$Payment_{NT} = \frac{m}{1-\beta} - \frac{C^* - \tilde{C}}{C^* - C_0} \frac{e^{-s} m}{1 - \beta e^{-s}} \tag{9}$$

Next one can ask, once a field reaches its saturation value, C^*, is the farmer better off in the future periods than not enrolling in the policy in the first place? This question can be answered by substituting $\tilde{C} = C^*$ in the expression for V_{NT} (equation (5)) and comparing it to the lifetime payoff from conventional tillage, that is, $\big(\mathbb{E}[y_{CT}] \times P - Cost(\theta_{CT})\big) \times \big(1-\beta\big)^{-1}$. V_{NT} is maximized at $\tilde{C} = C^*$. Therefore, for the minimum m that incentivizes NT, the farmer is better off to continue practicing NT rather than not enrolling in the policy. One can also determine the cost of abandoning the policy at any carbon level, $\tilde{C}$. This is determined from the expression of V_{CT} and is given by,

$$Cost_{abandon} = \frac{-(\tilde{C} - C_0) e^{-s'} m}{1 - \beta e^{-s'}} \tag{10}$$

$Cost_{abandon} < 0$ because the farmer collects carbon payments from the legacy stock they hold.

3.2 Policy 2: Payments proportional to the carbon stock, conditional on adopting a conservation practice

In this policy, farmers receive payments proportional to their carbon stock only in periods when they adopt the conservation practice. Period profits are given by:

$$\pi_t = (\mathbb{E}[C_t] - C_0) \times m \times \mathbf{1}(\theta_t = \theta_{NT}) + \mathbb{E}[y_t] \times P - Cost(\theta_t). \tag{11}$$

The key distinction from Policy 1 is that the farmer receives no carbon payment when CT is adopted, eliminating the incentive to collect payments on legacy carbon stocks without changing practices.

The value function for NT is:

$$V_{NT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{NT}] \times P + (\mathbb{E}[C_t] - C_0) \times m - Cost(\theta_{NT})] \tag{12}$$

Using the SOC dynamics for the conservation practice, the closed-form value function is:

$$V_{NT} = \frac{\mathbb{E}[y_{NT}] \times P - Cost_{NT}}{1-\beta} + \frac{(C^* - C_0)m}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}m}{1-\beta e^{-s}} \tag{13}$$

With CT, the farmer receives no carbon payment, so the value function simplifies to:

$$V_{CT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{CT}] \times P - Cost(\theta_{CT})] = \frac{\mathbb{E}[y_{CT}] \times P - \text{Cost}_{CT}}{1-\beta} \tag{14}$$

For the farmer to adopt NT, it must be that $V_{NT} \geq V_{CT}$, which requires:

$$m \geq \left(\frac{C^* - C_0}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}}{1-\beta e^{-s}} \right)^{-1} \left(\frac{\Delta y \times P - \Delta\text{Cost}}{1-\beta} \right) \tag{15}$$

Note that m does not depend on the carbon release rate s', since the farmer receives no payment under CT regardless of the SOC trajectory. The lifetime carbon payment per ton of sequestered carbon for NT is given by equation (9).

Similar to Policy 1, it is clear that after a field has reached its saturation value, C^*, a farmer is still better off in the future periods compared to not enrolling in the policy because of the carbon payments from the existing stock. However, the $Cost_{abandon} = 0$ in this policy as no carbon payments are made and no penalties are imposed when CT is adopted.

3.3 Policy 3: Payments or penalties proportional to the incremental carbon stock

Under this policy, farmers are compensated for increases in SOC within a given period and penalized for any SOC released in periods of conventional practices. Period profits are

given by:

$$\pi_t = \mathbb{E}[C_t - C_{t-1}] \times m + \mathbb{E}[y_t] \times P - Cost(\theta_t) \tag{16}$$

The value function for NT is:

$$V_{NT} = \frac{(C^* - \tilde{C})(1 - e^{-s})m}{1 - \beta e^{-s}} + \frac{\mathbb{E}[y_{NT}] \times P - Cost_{NT}}{1 - \beta} \tag{17}$$

The corresponding expression for CT is:

$$V_{CT} = \frac{(\tilde{C} - C_0)(e^{-s'} - 1)m}{1 - \beta e^{-s'}} + \frac{\mathbb{E}[y_{CT}] \times P - Cost_{CT}}{1 - \beta} \tag{18}$$

The condition $V_{NT} \geq V_{CT}$ requires:

$$m \geq \left(\frac{(C^* - \tilde{C})(1 - e^{-s})}{1 - \beta e^{-s}} + \frac{(\tilde{C} - C_0)(1 - e^{-s'})}{1 - \beta e^{-s'}} \right)^{-1} \frac{\Delta y \times P - \Delta Cost}{1 - \beta} \tag{19}$$

The lifetime carbon payment per ton of sequestered carbon is:

$$Payment_{NT} = \frac{C^* - \tilde{C}}{C^* - C_0} \frac{(1 - e^{-s})m}{1 - \beta e^{-s}} \tag{20}$$

In this policy, the farmer collects no carbon payments when the soil reaches saturation (C^*). Therefore, when $C = C^*$, a farmer enrolled in Policy 3 is worse off than one who did not in the first place. Furthermore, the cost of abandoning the policy is

$$Cost_{abandon} = \frac{(\tilde{C} - C_0)(1 - e^{-s'})m}{1 - \beta e^{-s'}} \tag{21}$$

The $Cost_{abandon} > 0$, that is a farmer will pay penalties for abandoning the policy and releasing carbon to the atmosphere. Therefore, in this policy, a farmer is "locked in" once they have signed up for it.

3.4 Policy 4: Payments proportional to the incremental carbon stock, conditional on adopting a conservation practice

This policy pays farmers proportional to the incremental increase in SOC within a given period when they adopt the conservation practice, but imposes no penalty for carbon release upon reverting to conventional tillage. Period profits are given by:

$$\pi_t = \mathbb{E}[C_t - C_{t-1}] \times m \times \mathbf{1}(\theta_t = \theta_{NT}) + \mathbb{E}[y_t] \times P - Cost(\theta_t). \tag{22}$$

The value functions for NT and CT are:

$$V_{NT} = \frac{(C^* - \tilde{C})(1 - e^{-s})m}{1 - \beta e^{-s}} + \frac{\mathbb{E}[y_{NT}] \times P - Cost_{NT}}{1 - \beta} \tag{23}$$

$$V_{CT} = \frac{\mathbb{E}[y_{CT}] \times P - Cost_{CT}}{1 - \beta} \tag{24}$$

The condition $V_{NT} \geq V_{CT}$ requires:

$$m \geq \left(\frac{(C^* - \tilde{C})(1 - e^{-s})}{1 - \beta e^{-s}} \right)^{-1} \frac{\Delta y \times P - \Delta Cost}{1 - \beta} \tag{25}$$

Equation (25) shows that m increases with $\tilde{C}$, which implies that as SOC increases over time, farmers will require higher payments to continue adopting NT. For this policy, the abandonment cost is zero.

Proposition 1. *For any finite payment rate m, there exists a threshold $\bar{C}(m) \in (C_0, C^*)$ beyond which NT adoption becomes unprofitable in infinite horizon. The threshold $\bar{C}(m)$ is strictly increasing in m, but $\bar{C}(m) < C^*$ for all finite m. Consequently, no finite payment rate sustains permanent NT adoption.*

Proof. For a given carbon payment rate, m, this threshold carbon level is determined from

(25) as the value of $\tilde{C}$ for which the equality holds. This is given by:

$$\bar{C}(m) = C^* - \frac{(\Delta y \times P - \Delta Cost)(1 - \beta e^{-s})}{m(1-\beta)(1-e^{-s})} \tag{26}$$

Differentiating (26) with respect to m yields $\partial \bar{C}(m)/\partial m > 0$, implying that the threshold increases with the payment rate. Moreover, $\bar{C}(m) < C^*$ for every finite m. For a short period, C may exceed $\bar{C}(m)$ as $\bar{C}(m)$ is the threshold value in infinite horizon, but a farmer will eventually abandon NT and switch to CT.

Proposition 2. *The long-run equilibrium under Policy 4 is characterized by repeated switching between NT and CT when the carbon payment rate m is above a threshold, m_{low}, given by*

$$m_{low} = \frac{\Delta y \times P - \Delta Cost}{(C^* - C_0)(1 - e^{-s})} \tag{27}$$

Proof. Single-period profit under NT is given by equation (22). The threshold payment rate, m_{low}, is the one that favors sequestration for at least one period. Thus, substituting the carbon sequestration dynamics equation (4) and $t = 0$, one obtains equation (27). In equation (27), $\tilde{C}$ is replaced by C_0 to obtain the lowest value of m_{low}. For $m < m_{low}$, a farmer will never adopt NT. For $m \geq m_{low}$, a farmer will adopt NT for some periods and then abandon it as dictated by Proposition 1.

The optimum cyclic equilibrium is determined in the following way. Suppose a farmer abandons NT in favor of CT when the carbon stock is at C_U and switches back to NT when the carbon stock reaches C_L. Suppose it takes t_1 periods of NT to increase the carbon level from C_L to C_U and t_2 periods to release carbon from C_U to C_L through CT. Then the following relations hold:

$$C_U = C^* - (C^* - C_L)e^{-st_1} \tag{28}$$

$$C_L = C_0 + (C_U - C_0)e^{-st_2} \tag{29}$$

Net profit in the $t_1 + t_2$ period, $\pi_{t_1+t_2}$ is given by

$$\pi_{t_1+t_2} = \sum_{t=1}^{t_1} \beta^{t-1} \Big[(C_t - C_{t-1})m + y_{NT} \times P \Big] + \beta^{t_1} \sum_{t=1}^{t_2} \beta^{t-1} y_{CT} \times P \tag{30}$$

After substituting the carbon sequestration dynamics, one gets

$$\begin{aligned} \pi(t_1, t_2) = & \frac{(C^* - C_L)(1 - e^{-s})(1 - e^{-st_1}\beta^{t_1})m}{1 - \beta e^{-s}} \\ & + y_{NT} \times P \frac{1 - \beta^{t_1}}{1 - \beta} + \beta^{t_1} y_{CT} \times P \frac{1 - \beta^{t_2}}{1 - \beta} \end{aligned} \tag{31}$$

The farmer maximizes lifetime discounted profits:

$$\max_{t_1, t_2} \frac{\pi(t_1, t_2)}{1 - \beta^{t_1+t_2}} \tag{32}$$

From equations (28) and (29), C_U and C_L can be determined as functions of t_1 and t_2. The maximization problem in (32) can be numerically solved for fixed m under the constraints that $t_1, t_2 > 0$. To illustrate, for the representative field of the best-draining soil type (hydrology group A) with m = \$300 per ton C, the optimum values are (t_1, t_2) = (16.7, 33.2) years with (C_L, C_U) = (32.39, 36.05) tons C/ha (Figures 1 and 2). In the entire (NT, CT) cycle, the average carbon sequestered is 1.52 tons C/ha at lifetime discounted payments of \$891.4/ha or \$586/ton C. The sequestration achieved is only 29% of the maximum possible amount of 5.26 tons C/ha (Table 3).

3.5 Policy 5: Payments for adopting a conservation practice

This policy pays the farmer a constant payment m in each period of conservation practice adoption, irrespective of the carbon stock level or the quantity of carbon sequestered. For the farmer to adopt NT, the payment must cover the expected yield loss and any additional adoption costs:

$$m \geq \Delta y \times P - \Delta Cost \tag{33}$$

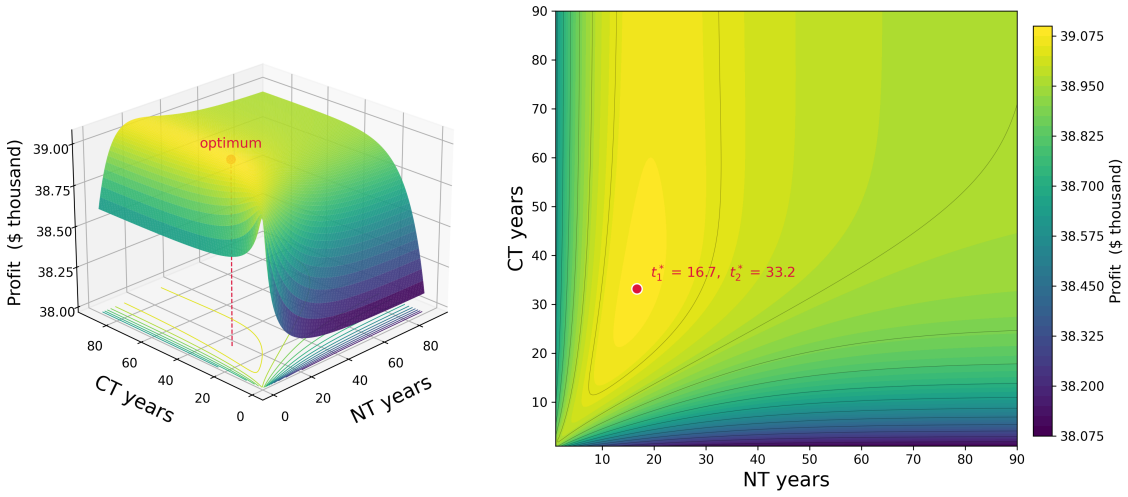


Figure 1: Lifetime profit as a function of NT and CT years with $m = \$300$ per ton C when Policy 4 is implemented for the representative field in the best-draining soil type (hydrology group A) (Left). Contour plot of the profit as a function of NT and CT years with the optimum point shown (Right).

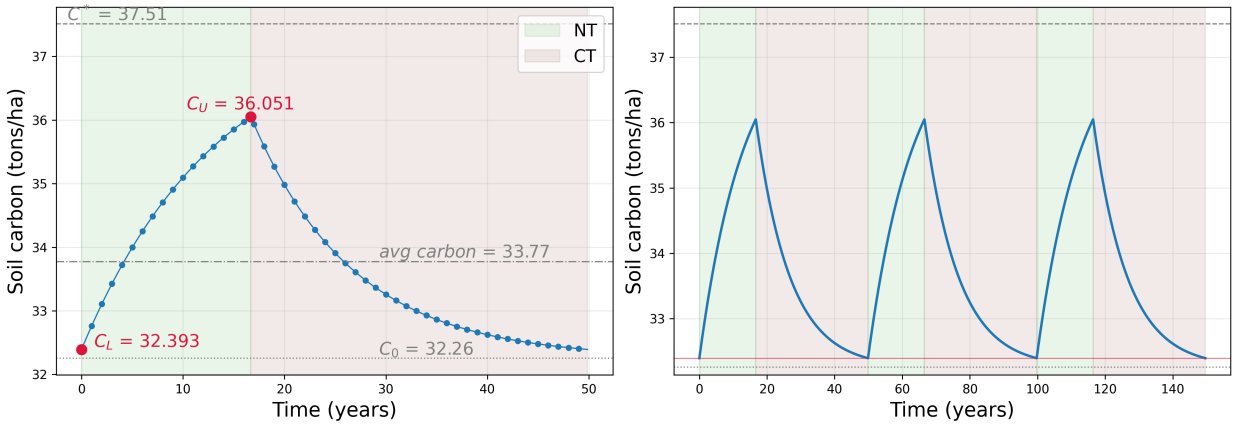


Figure 2: The carbon sequestration (NT) and release (CT) cycle when $m = \$300$ per ton C under Policy 4 for the representative field in the best-draining soil type (hydrology group A) (Left). Three cycles shown to illustrate the cyclic equilibrium (Right).

The lifetime carbon payment per ton of sequestered carbon is:

$$Payment_{NT} = \frac{m}{(C^* - C_0)(1-\beta)} \tag{34}$$

In this policy, a farmer is worse off abandoning the policy at any carbon level if m satisfies (33). Also, there is no cost of abandoning the policy at any time. Comparing (34) with (9) reveals an equivalence between Policies 2 and 5. Substituting the minimum payment from (15) into (9), and from (33) into (34), yields the same expression in both cases. This equality of lifetime payments between Policies 2 and 5 can also be understood by noting that both have the same V_{CT}. The two designs therefore require identical lifetime payments per ton of sequestered carbon at their minimum incentive-compatible rates, for every field. They differ only in what the payment is contingent upon. Policy 2 requires that the carbon stock be maintained, while no such requirement applies under Policy 5.

3.6 Incorporating SOC Stochasticity Through Bellman Equation

The analytical expressions derived above abstract from stochasticity in the carbon sequestration process. I now validate these results against numerical solutions obtained by formulating the infinite-horizon optimization problem recursively through the Bellman equation. Equation (1) can be written as:

$$V(C) = \max_{\theta} \left\{ \mathbb{E}\big[\pi(C,\theta)\big] + \beta \sum_{C'} P(C' \mid C, \theta)\, V(C') \right\} \tag{35}$$

where $V(C)$ is the value function representing the maximum expected discounted profits attainable when the present state's SOC level is C, θ is the management practice chosen in a given period, $\mathbb{E}[\pi(C,\theta)]$ is expected current-period profit, and $P(C' \mid C, \theta)$ is the transition probability from state C to state C' for practice θ. Transition probabilities are constructed assuming that stochastic variation in SOC is normally distributed, subject to $C \in [C_0, C^*]$.

The Bellman equation is solved using value function iteration.

4 Results

4.1 Results from Analytical Expressions and Bellman Equation

Table 2 reports optimal carbon payments calculated from both the analytical expressions and the Bellman equation solutions with $\tilde{C}$ chosen to be the average of C_0 and C^*. For Policies 1 and 2, Bellman-derived m values are slightly higher than their analytical counterparts, reflecting the additional compensation required to offset uncertainty in carbon sequestration outcomes. For Policy 3, the numerical and analytical solutions converge closely. Across all policies, m varies substantially with soil type, confirming that cost-effective program design calls for spatially targeted payments calibrated to biophysical characteristics.

Table 2: Minimum carbon payments m (\$/ton C) from analytical expressions and from the Bellman equation.

	Analytical				Bellman equation		
Hydrology	Policy 1	Policy 2	Policy 3	Policy 5	Policy 1	Policy 2	Policy 3
A	7.77	6.22	155.49	26.31	8	7	151
B	22.60	17.89	452.05	147.78	25	20	450
C	27.13	21.45	542.55	132.19	30	24	540
D	29.48	23.36	589.59	114.74	32	26	580

Notes: Initial soil carbon $\tilde{C}$ is set to the average of C_0 and C^*. The Bellman solution searches over m in increments of \$1, so those values are integers. Policy 4 is omitted.

Figure 3 illustrates optimal farmer decisions as a function of SOC for the representative field in the best draining soil type (hydrology group A). With Policy 2, farmers adopt CT at all SOC levels when $m \leq \$5/ton\ C$. For payment rates between \$6 and \$11 per ton C, farmers adopt CT for small $\tilde{C}$ and switch to NT for higher $\tilde{C}$. For $m \geq \$12/ton\ C$, NT is optimal at all SOC levels. Farmer behavior with Policy 1 is qualitatively similar.

In Policy 3, farmer behavior exhibits a richer pattern consistent with the lock-in problem identified in Section 3.3. For $m < \$162/ton\ C$, farmers adopt NT for small $\tilde{C}$ where

sequestration rates are high and incremental payments are large. At intermediate $\tilde{C}$, as the sequestration rate slows, farmers revert to CT. At high $\tilde{C}$, the penalty for carbon release is sufficiently large to make NT optimal again. This generates two equilibrium points, indicated by the red circles in Figure 3: a lower equilibrium at $\tilde{C}_1 = 32.44$ tons C, where the farmer switches from NT-to-CT, and an upper equilibrium at $\tilde{C}_2 = C^*$. The reverse switch from CT-to-NT occurs at $\tilde{C} = 33.81$ tons C. Farmers with $\tilde{C} < 33.81$ tons C sequester carbon up to $\tilde{C}_1$; those with higher initial stocks sequester to saturation at $\tilde{C}_2$.

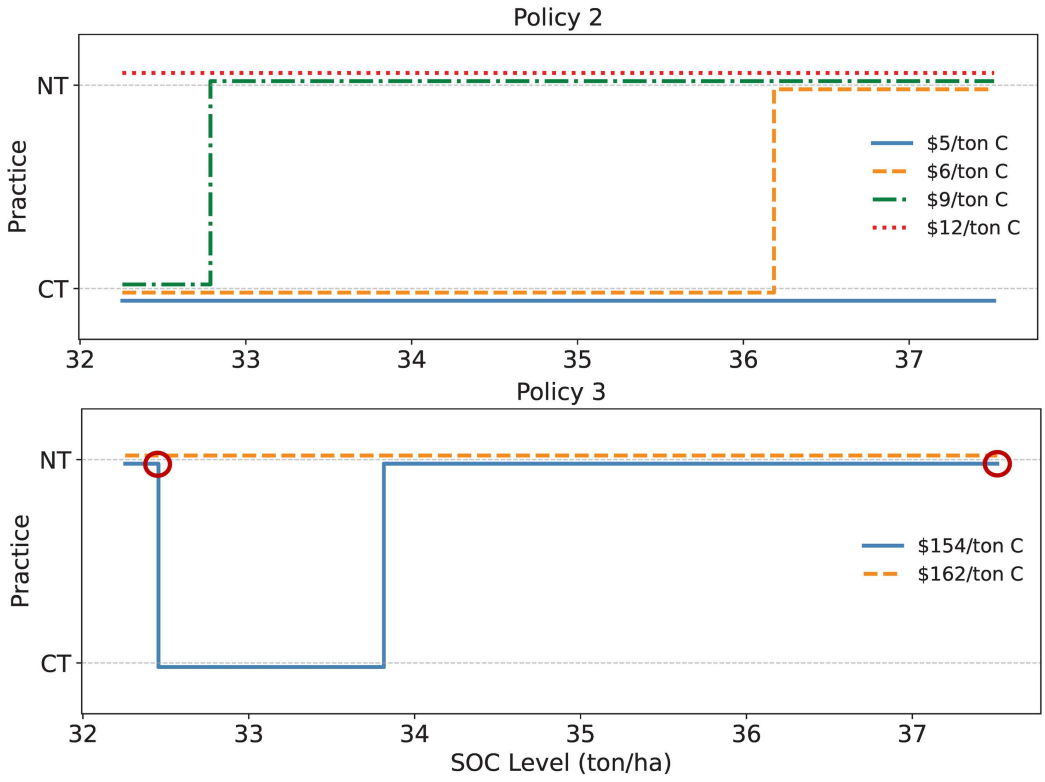


Figure 3: Optimal farmer decisions for the representative field in the best draining soil type (hydrology group A) under Policies 2 and 3 for different values of m. Red circles indicate the two equilibrium points under Policy 3.

4.2 Comparative Analysis of Payment Policies

Figure 4 shows how the minimum carbon payment m varies with the initial carbon stock $\tilde{C}$ under Policies 1 through 4. Under Policies 1, 2, and 3, m is decreasing in $\tilde{C}$: farmers with

higher initial carbon stocks require lower payments to adopt NT because they generate larger carbon revenues from the outset. Under Policy 4, the relationship reverses: m is strictly increasing in $\tilde{C}$, and as $\tilde{C} \to C^*$, equation (25) implies $m \to \infty$. This is the structural defection problem established in Propositions 1 and 2: for any fixed payment rate, farmers facing declining incremental sequestration gains rationally revert to conventional tillage to release stored carbon and restart the payment cycle. Policy 4 is therefore excluded from the welfare comparison that follows.

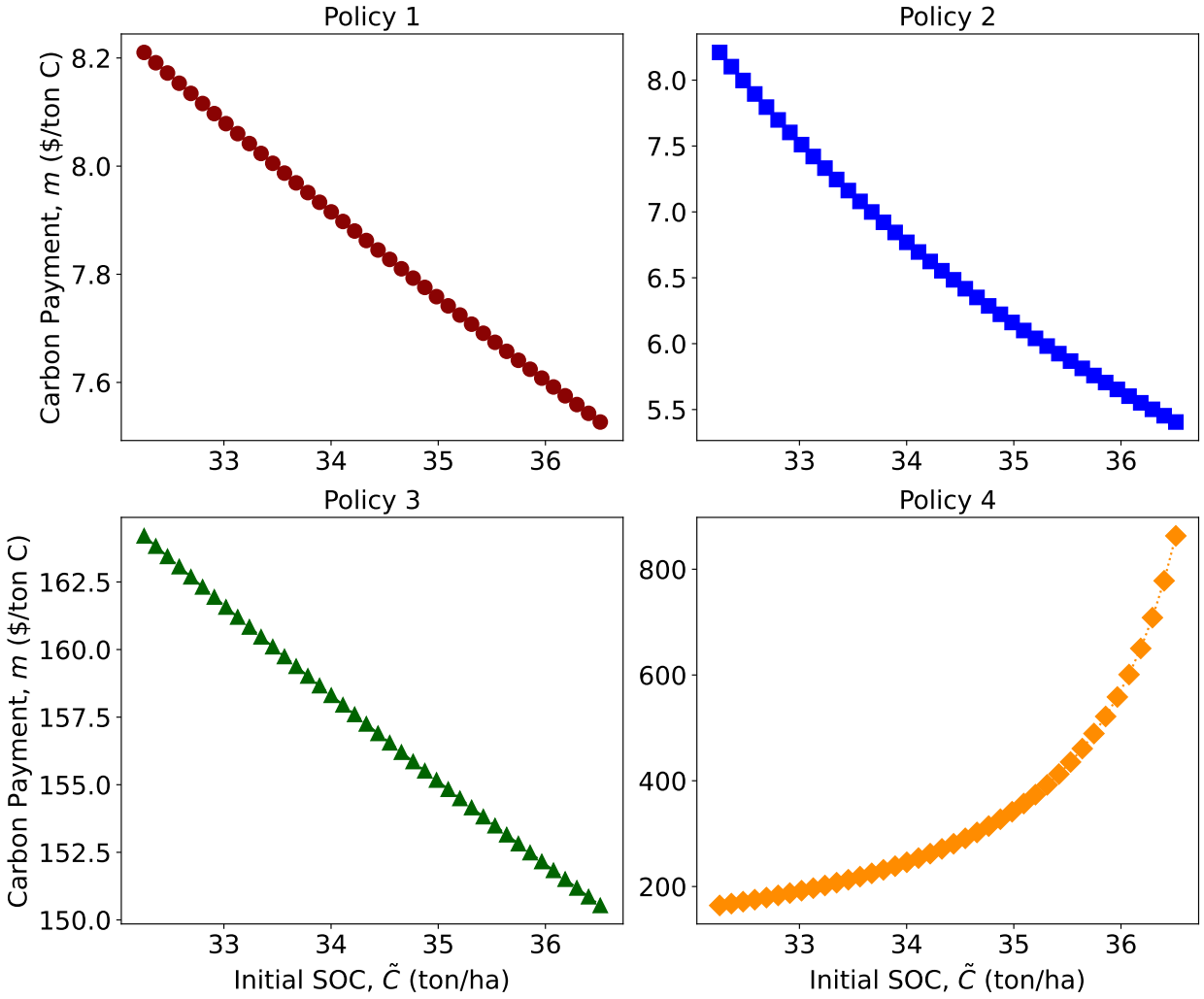


Figure 4: Minimum carbon payment m required to incentivize NT as a function of initial carbon stock $\tilde{C}$ under Policies 1 through 4, for the representative field in the best-draining soil type (hydrology group A).

The welfare comparison across the remaining designs uses the discounted lifetime carbon payment as the relevant cost measure, evaluated at $\tilde{C}$ equal to the average of C_0 and C^*. Figure 5 reports these lifetime payments. Policy 2 requires smaller lifetime payments than Policy 1. Although Policy 3 requires the highest per-period m, it generates the lowest lifetime payments because payments are made only on incremental SOC gains each period, and cease entirely once the carbon stock reaches its saturation level C^*.

I compare lifetime payments with the U.S. social cost of carbon (SCC). The EPA's SCC for 2020 is \$190 per ton of CO_2, equivalent to \$697 per ton of carbon (U.S. Environmental Protection Agency, 2023).[1] Discounted lifetime payments of all policies remain below this threshold for all soil types studied, confirming that these designs are welfare-improving.[2]

Figure 6 shows the cost of abandoning the policies per ton of carbon evaluated at the saturation stock (C^*). This cost is zero for Policies 2, 4, and 5. Abandonment cost per ton of carbon is determined by dividing the total abandonment cost calculated from Equations (10) and (21) by $(C^* - C_0)$ so that they can be directly compared to the lifetime payments. The abandonment cost is negative for Policy 1 implying that the farmers get paid for their legacy carbon, which constitutes non-additional payments characteristic of Policy 1. Policy 3 has significant abandonment costs that exceed the lifetime payments, which means that farmers are "locked in" when they have high soil carbon because of the prohibitive penalties for its release.

4.3 Policy Ranking and Additionality

The analysis yields a clear policy ranking. Policy 4 is eliminated by Proposition 1: the cycling equilibrium ensures that participating farmers rationally defect to conventional tillage

[1] I compare lifetime payments with EPA's year 2020 value. However, soil carbon accumulates over horizons of 60 to 90 years, so the appropriate benchmark is the SCC over the period during which sequestration is actually delivered rather than at the date the program begins. The EPA's estimates rise over this horizon (U.S. Environmental Protection Agency, 2023), so the 2020 value understates the average SCC across the delivery period and the comparison is conservative in that respect.

[2] The lifetime payments in Figure 5 are calculated for the initial carbon $\tilde{C}$ as the average of C_0 and C^*. The lifetime payments for hydrology group D exceed the 2020 SCC value when $\tilde{C}$ is set to C_0 (see Table 3).

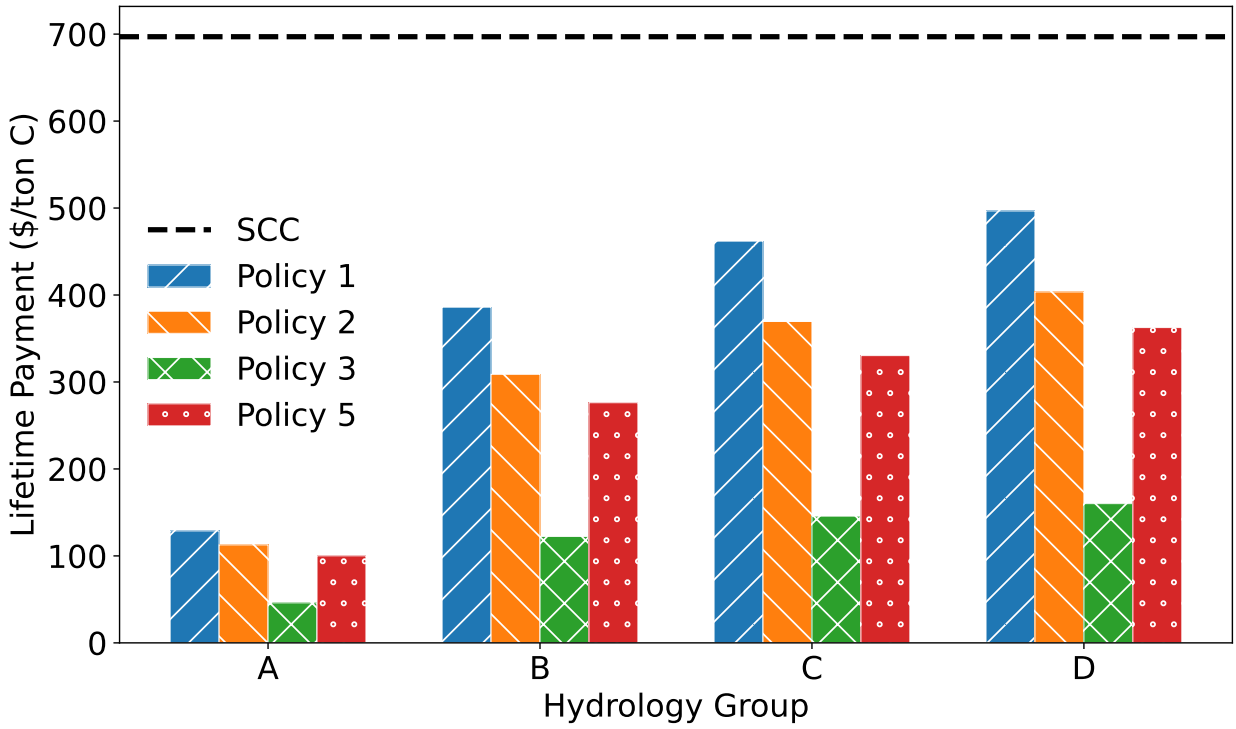


Figure 5: Discounted lifetime carbon payments for Policies 1, 2, 3, and 5 when NT is adopted and $\tilde{C} = 0.5 \times (C_0 + C^*)$, computed using m values obtained from the Bellman equation solution (except for Policy 5). The dashed line indicates the U.S. social cost of carbon for 2020 as per the EPA. Policy 5 appears lower than Policy 2 in the figure because the m for Policy 5 is taken from the analytical solution while the other policies use the Bellman solution; at a common basis the two coincide, as shown in Section 3.5.

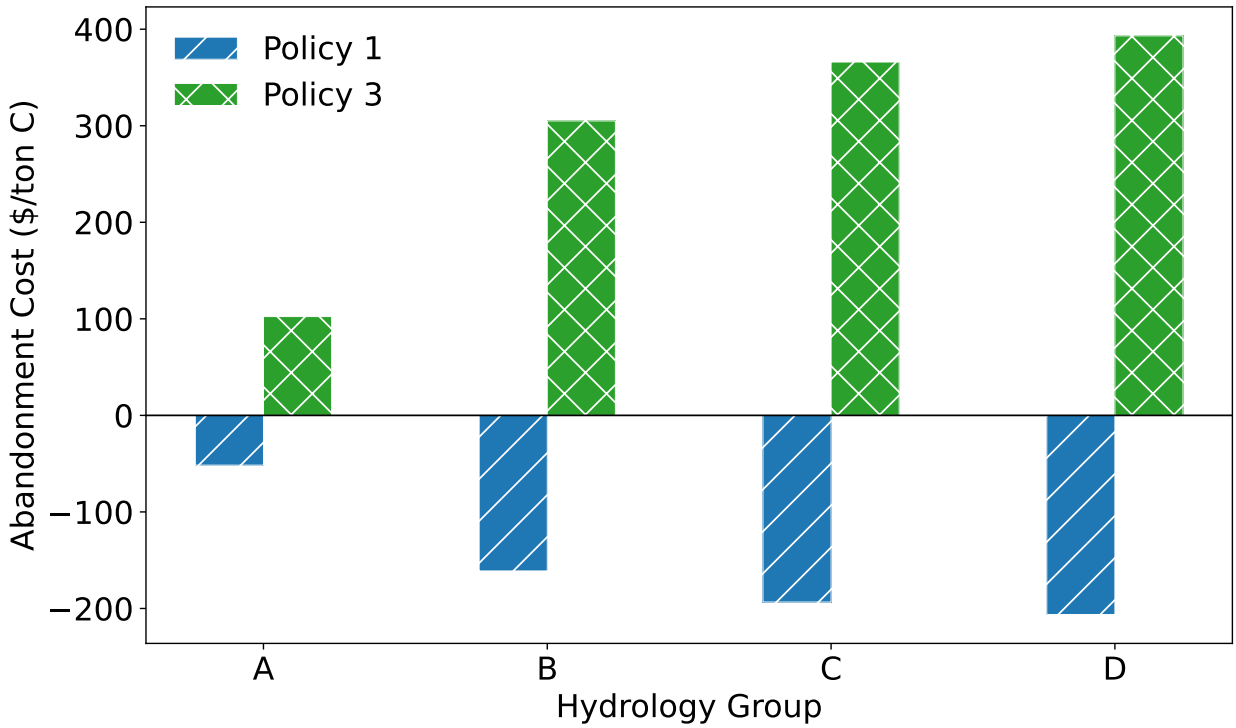


Figure 6: Discounted lifetime abandonment costs of Policies 1 and 3 evaluated at the saturation stock C^* using the m values from the Bellman solution. For Policy 3, positive values are penalties for releasing stored carbon. For Policy 1, negative values are payments the farmer continues to receive on legacy carbon after abandoning conservation tillage.

as their carbon stock rises, producing little sequestration for any finite payment rate. Policy 3 has the lowest discounted lifetime payments, however, this policy's abandonment costs exceed the lifetime payments. Furthermore, when the saturation SOC level, C^* is reached, the farmer does not get any carbon payments, and so is worse off than a farmer who never enrolled in this policy. Therefore, Policy 3 is unlikely to achieve sustained adoption because the lock-in problem makes it unattractive to farmers regardless of payment levels.

Policy 2 dominates Policy 1 on both cost and additionality grounds. In Policy 1, a farmer with a high legacy carbon stock who adopts conventional tillage continues to collect carbon payments proportional to that stock, generating inframarginal transfers with no associated sequestration. These non-additional payments are associated with the negative abandonment cost of Policy 1. With Policy 2, payments are conditional on conservation practice adoption, which eliminates this incentive entirely. Flat adoption payments (Policy 5) cost the same as Policy 2 under certainty but make no payment contingent on the carbon actually stored, shifting sequestration risk onto the payer. Policy 2 is therefore the optimal design as it maintains consistent adoption incentives throughout the sequestration horizon, and limits the additionality problem.

A farmer is inframarginal, that is, adopts NT in the absence of any carbon payment, if and only if $\Delta y \leq \Delta Cost$. With the maintained assumption that implementation cost differences are negligible, this condition reduces to $\Delta y \leq 0$: the farmer's yield does not decline under NT relative to CT. Of the 70 fields in the EPIC sample, two satisfy $\Delta y \leq 0$, indicating that non-additional participation is limited in the present sample but non-negligible in practice. Field-level results are reported in the Appendix (Table 4). Under Policy 2, such farmers receive payments only when they adopt NT, which limits but does not eliminate the welfare cost of non-additional transfers relative to the social optimum. In Policy 1, inframarginal farmers collect payments regardless of practice, making the additionality problem strictly worse.

Table 3: Cost analysis of spatially targeted payments under Policy 2 across the agricultural land of the five watersheds is shown. $\tilde{C}$ is taken as C_0 for most conservative estimates of lifetime payments. m is obtained from Bellman equation.

Hydrology	Area (ha)	m ($/ton C)	Lifetime payment ($/ton C)	ΔSOC/Area (ton ha^{-1})	ΔSOC (million tons)	Cost (million $)
A	96,609	12	193.13	5.26	0.508	98.11
B	382,155	34	524.97	10.70	4.089	2146.62
C	510,008	43	662.14	8.00	4.080	2701.54
D	52,307	48	744.99	6.33	0.331	246.59
Total	1,041,079			9.008	5192.86	

Notes: The m and lifetime payment values in this table differ from those in Table 2 and Figure 5 because the values here are calculated at $\tilde{C} = C_0$. In Table 2 and Figure 5, they are calculated for $\tilde{C} = 0.5 \times (C_0 + C^*)$, so that the additionality differences between Policies 1 and 2 are highlighted.

4.4 Welfare Gains from Spatially Targeted Carbon Payments

The variation in required payment rates across soil types documented above implies that a uniform national carbon price is costlier than a spatially targeted scheme calibrated to soil characteristics. I quantify the cost structure of Policy 2, the optimal design identified in Section 4.3, evaluated across the agricultural land of the five watersheds studied. Table 3 reports the total agricultural area, carbon payment rate m, lifetime payment per ton of carbon, SOC gain per hectare, total SOC gain, and total program cost for each hydrology group. Spatially targeted payments calibrated to each soil type imply a cumulative lifetime program cost of $5.19 billion for a total carbon sequestration of 9.008 million tons, or $576.4 per ton C. This is substantially below the U.S. SCC of $697 per ton C (U.S. Environmental Protection Agency, 2023), confirming that the targeted policy is welfare-improving. A uniform payment scheme set at $48 per ton C, the rate required to induce adoption on the most costly soil type, implies a sequestration cost of $745 per ton of carbon. While the lifetime payment for hydrology group D exceeds the 2020 SCC, it is below the projected U.S. SCC for the year 2030 ($843 per ton C). Spatially targeted payments therefore reduce total program costs by approximately 22% relative to the uniform scheme while achieving the same sequestration outcome.

5 Conclusion

This paper develops an analytically tractable framework to evaluate five carbon payment designs for incentivizing soil organic carbon sequestration through conservation tillage, deriving closed-form minimum payment conditions under each design and parameterizing the model using EPIC simulations across 70 representative Midwestern fields. The findings establish a clear ranking across payment designs. Flat adoption payments (Policy 5) cost the same as Policy 2 under certainty but make no payment contingent on the carbon actually stored, shifting sequestration risk onto the payer. Incremental payment designs fail outright. Without penalties for carbon release (Policy 4), the minimum payment required to sustain no-till adoption is strictly increasing in the current SOC stock, generating a structural cycling equilibrium in which farmers rationally alternate between no-till and conventional tillage, with little sequestration for any finite payment rate. With penalties (Policy 3), the cycling incentive is suppressed but replaced by a lock-in problem at saturation where farmers bear continued yield costs while receiving no additional payments. Stock-based payments conditional on conservation practice adoption (Policy 2) emerge as the robust design since the additionality problem is reduced by conditioning on practice adoption, and consistent sequestration incentives are maintained throughout the carbon accumulation horizon. Lifetime discounted payments under Policy 2 remain below the U.S. social cost of carbon, confirming that the policy is welfare-improving. The required payment rate varies substantially with biophysical conditions. Spatially targeted payments calibrated to soil hydrology group characteristics reduce total program costs by approximately 22% relative to a uniform national carbon price while achieving equivalent sequestration, with welfare gains concentrated on well-drained soils where required payments are low.

Although the model is calibrated to Midwestern field conditions, the analytical results are not specific to that context. The structural cycling equilibrium under Policy 4, the additionality problem under Policy 1, and the dominance of Policy 2 follow from the carbon stock dynamics under forward-looking farmer optimization. The same properties hold for

any setting in which sequestration is reversible, soils have finite storage capacity, and conservation practices impose short-run yield costs. Voluntary carbon markets are expanding rapidly across sub-Saharan Africa and South Asia, where additionality concerns, monitoring constraints, and farmer distrust of payment institutions pose greater implementation challenges than in the United States. In such contexts, the policy hierarchy identified here carries direct practical relevance, and the closed-form minimum payment conditions derived under Policy 2 provide a tractable basis for calibrating carbon payment programs to local biophysical and economic conditions in data-scarce environments. The results carry important implications for the design of conservation incentive programs and voluntary carbon markets where payment structures remain actively debated.

More broadly, the findings recast the design problem in conservation payments. A large literature treats the risk that farmers collect payments without changing behavior as an information problem: farmers know their counterfactual and regulators do not, so verification is costly and imperfect, and the standard remedy is a contract that screens on agent type (Mason and Plantinga, 2013). The analysis here shows it is also, and more fundamentally, a design problem. Conditioning payment on the maintained carbon stock and on continued practice adoption makes collecting payment without changing behavior structurally irrational rather than merely detectable. The relevant question shifts from how to monitor compliance with a given contract to which contract makes compliance rational from the outset. That reorientation, from enforcement to contract architecture, is where the closed-form conditions derived here are most useful, because they identify the design that forecloses defection before any payment is made.

Declaration of competing interest

The author declares no potential conflict of interest.

Declaration of AI use

The author used Claude AI for improving formatting of Figures 1 and 2. The author also used Claude AI for language refinement of the final draft of the manuscript prior to submission, and thoroughly reviewed and edited all content.

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A Appendix

A.1 Derivation of carbon sequestration and release dynamics

A.1.1 Carbon sequestration

Carbon sequestration dynamics should satisfy the following boundary conditions:

$$\lim_{t\to\infty} C(t) = C^* \tag{A1}$$

$$\lim_{t \to 0} C(t) = \tilde{C} \tag{A2}$$

Carbon content asymptotically approaches the saturation value as $t \to \infty$. Hence,

$$\lim_{t \to \infty} \frac{dC(t)}{dt} = 0 \tag{A3}$$

Carbon sequestration rate, $\frac{dC(t)}{dt} \geq 0$ and its derivative, $\frac{d^2C(t)}{dt^2} \leq 0$. Also, the carbon sequestration rate is proportional to the extent to which the soil is depleted of the carbon content. Therefore,

$$\frac{dC(t)}{dt} \propto (C^* - C(t)) \tag{A4}$$

Equation (A4) is solved assuming the proportionality constant to be s, giving us:

$$C^* - C(t) = ke^{-st} \tag{A5}$$

Using the condition (A2), one gets:

$$C(t) = C^* - (C^* - \tilde{C})e^{-st} \tag{A6}$$

A.1.2 Carbon release

The analogous conditions for carbon release dynamics are the following:

$$\lim_{t \to \infty} C(t) = C_o \tag{A7}$$

$$\lim_{t \to 0} C(t) = \tilde{C} \tag{A8}$$

Carbon content asymptotically approaches C_o as $t \to \infty$. Hence,

$$\lim_{t \to \infty} \frac{dC(t)}{dt} = 0 \tag{A9}$$

Carbon release rate, $\frac{dC(t)}{dt} \leq 0$ and its derivative, $\frac{d^2C(t)}{dt^2} \geq 0$. The carbon release rate is proportional to the carbon content of the soil. Therefore,

$$\frac{dC(t)}{dt} \propto -(C(t) - C_o) \tag{A10}$$

Assuming the proportionality constant equal to *s'*, one gets:

$$C(t) = C_o + (\tilde{C} - C_o)e^{-s't} \tag{A11}$$

Alternately, the carbon release dynamics can be thought of as an inverse process of carbon sequestration with C^* replaced by C_o and s replaced by *s'* in the equation (A6).

Table 4: Dataset summary by hydrology group.

MUKEY	CSB	HUC	Hyd.	Y_{CT}	Y_{NT}	Y_{RT}	ΔY_{NT}	ΔY_{RT}	s_{NT}	s_{RT}	C^*_{RT}	C^*_{NT}	C_0
168992	618	LowerMaumee	A	10.85	10.78	10.33	0.07	0.52	0.087	0.081	31.92	33.33	24.30
186359	801	Maple	A	12.59	12.22	12.27	0.36	0.32	0.061	0.072	36.30	37.40	23.40
187044	268	Maple	A	12.11	12.01	11.98	0.10	0.13	0.041	0.047	51.20	53.70	41.40
199256	145	Macoupin	A	12.40	12.14	11.95	0.25	0.45	0.076	0.066	61.41	62.22	51.70
423949	478	UpperFox	A	13.18	12.96	12.98	0.22	0.20	0.080	0.089	40.20	41.50	29.70
426074	479	UpperFox	A	12.61	12.53	12.54	0.08	0.08	0.091	0.091	29.49	30.40	22.60
426400	350	Sugar	A	12.56	12.49	12.49	0.06	0.06	0.078	0.080	39.40	40.50	29.70
2399566	118	LowerMaumee	A	10.67	10.55	10.34	0.12	0.33	0.089	0.089	15.35	16.06	12.60
2861390	509	UpperFox	A	11.38	11.18	11.22	0.20	0.16	0.074	0.089	21.50	22.50	17.00
162995	676	Sugar	B	11.37	10.42	10.16	0.95	1.21	0.024	0.033	139.60	148.20	103.30
163013	344	Sugar	B	11.20	10.18	9.90	1.02	1.31	0.070	0.081	34.50	36.80	22.20
163021	492	Sugar	B	9.36	8.75	8.32	0.61	1.04	0.068	0.063	75.35	77.57	62.30
163067	914	Sugar	B	13.10	11.25	11.35	1.85	1.74	0.026	0.030	125.40	132.80	78.50
168216	291	LowerMaumee	B	11.92	11.75	11.45	0.17	0.47	0.063	0.067	61.00	62.60	46.70
169019	715	LowerMaumee	B	10.14	9.61	9.09	0.53	1.05	0.036	0.045	90.10	95.40	74.50
182564	811	UpperFox	B	12.02	11.43	11.08	0.59	0.94	0.068	0.074	49.90	52.20	34.50
182578	620	UpperFox	B	10.06	10.20	9.70	-0.14	0.37	0.074	0.075	30.81	32.50	22.30
182692	281	UpperFox	B	12.21	11.06	10.90	1.14	1.31	0.046	0.060	70.60	74.90	56.10
186396	387	Maple	B	11.23	9.55	9.54	1.68	1.69	0.051	0.067	45.40	47.80	30.60
186396	898	Maple	B	11.23	9.57	9.55	1.67	1.68	0.051	0.067	45.40	47.80	30.60
199218	979	Macoupin	B	11.13	10.91	10.31	0.22	0.81	0.069	0.069	71.00	73.90	55.50
211741	537	Macoupin	B	11.57	11.12	10.82	0.44	0.74	0.032	0.039	91.30	95.50	63.20
211786	76	Macoupin	B	11.11	10.83	10.45	0.28	0.65	0.086	0.084	29.90	31.00	20.50
422801	667	UpperFox	B	13.17	11.39	11.60	1.78	1.57	0.048	0.056	62.50	66.50	34.10

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Table 4 – *continued*

MUKEY	CSB	HUC	Hyd.	Y_{CT}	Y_{NT}	Y_{RT}	ΔY_{NT}	ΔY_{RT}	s_{NT}	s_{RT}	C^*_{RT}	C^*_{NT}	C_0
423956	972	UpperFox	B	11.78	11.69	11.68	0.09	0.11	0.080	0.089	29.70	30.60	23.90
425297	111	Sugar	B	10.09	8.46	8.20	1.63	1.89	0.078	0.085	45.15	47.90	32.40
425303	630	Sugar	B	12.80	11.51	11.54	1.29	1.25	0.057	0.066	45.90	48.40	25.70
425493	598	UpperFox	B	13.17	11.41	11.60	1.76	1.57	0.048	0.053	62.90	66.50	34.10
426340	800	Sugar	B	9.85	9.04	8.75	0.80	1.10	0.071	0.053	57.97	59.69	47.20
678770	647	Sugar	B	11.20	10.18	9.90	1.02	1.31	0.070	0.081	34.50	36.80	22.20
169097	421	LowerMaumee	C	10.14	9.90	9.59	0.24	0.56	0.052	0.060	58.48	60.10	43.60
169107	433	LowerMaumee	C	13.04	12.63	12.51	0.41	0.53	0.070	0.066	56.16	57.30	40.00
169108	870	LowerMaumee	C	10.87	10.76	10.56	0.11	0.31	0.074	0.067	21.92	22.52	16.60
186399	122	Maple	C	10.61	8.50	8.59	2.11	2.02	0.049	0.071	63.00	66.90	40.30
186399	541	Maple	C	10.61	8.50	8.59	2.11	2.02	0.049	0.071	63.00	66.90	40.30
187290	374	Maple	C	12.98	12.65	12.61	0.33	0.37	0.053	0.062	59.50	61.10	37.30
187302	99	Maple	C	12.84	12.48	12.47	0.36	0.36	0.065	0.078	41.70	42.90	27.80
187833	643	Maple	C	11.30	9.95	9.98	1.35	1.32	0.052	0.070	63.93	66.10	45.50
187859	468	Maple	C	12.00	11.63	11.67	0.37	0.33	0.074	0.087	28.50	29.50	19.00
199167	545	Macoupin	C	9.28	8.93	8.37	0.35	0.91	0.077	0.077	46.46	48.90	35.40
199212	25	Macoupin	C	9.52	8.77	8.33	0.74	1.18	0.060	0.080	77.27	81.40	61.00
199219	678	Macoupin	C	11.99	11.47	11.20	0.52	0.79	0.059	0.069	67.40	69.80	45.30
199224	73	Macoupin	C	10.21	9.82	9.37	0.39	0.85	0.056	0.081	41.71	44.80	28.90
199238	243	Macoupin	C	11.93	11.59	11.28	0.34	0.65	0.059	0.068	61.50	63.80	41.70
199239	55	Macoupin	C	9.66	8.74	8.37	0.92	1.29	0.058	0.078	62.20	66.10	55.80
425271	338	Sugar	C	12.33	11.25	11.11	1.08	1.23	0.048	0.050	63.40	66.20	39.10
425321	888	Sugar	C	12.83	11.81	11.82	1.02	1.01	0.047	0.054	65.80	68.10	39.20
425384	561	Sugar	C	13.04	11.87	11.93	1.17	1.10	0.057	0.063	52.00	54.30	30.30
425391	372	Sugar	C	13.02	12.07	12.04	0.95	0.98	0.059	0.064	49.10	51.00	29.90
425901	508	UpperFox	C	11.31	10.07	10.05	1.24	1.26	0.055	0.064	45.20	47.20	29.90

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Table 4 – *continued*

MUKEY	CSB	HUC	Hyd.	Y_{CT}	Y_{NT}	Y_{RT}	ΔY_{NT}	ΔY_{RT}	s_{NT}	s_{RT}	C^*_{RT}	C^*_{NT}	C_0
426067	779	UpperFox	C	13.10	12.43	12.41	0.67	0.69	0.058	0.064	50.90	52.70	31.50
728449	314	Macoupin	C	11.31	10.50	10.22	0.81	1.09	0.052	0.072	58.80	62.00	38.00
1536637	145	LowerMaumee	C	9.71	9.31	8.88	0.40	0.84	0.058	0.056	76.15	78.40	62.90
1536637	800	LowerMaumee	C	9.71	9.31	8.87	0.40	0.84	0.058	0.056	76.15	78.40	62.90
1536637	848	LowerMaumee	C	9.71	9.30	8.87	0.41	0.84	0.056	0.056	76.15	78.50	62.90
1536661	690	LowerMaumee	C	9.88	9.15	8.78	0.73	1.11	0.041	0.051	98.20	102.40	78.00
1539735	155	LowerMaumee	C	9.88	9.15	8.78	0.73	1.11	0.041	0.051	98.20	102.40	78.00
1721557	436	Macoupin	C	9.66	8.74	8.37	0.92	1.29	0.058	0.078	62.20	66.10	55.80
2998376	559	Maple	C	10.51	9.53	9.24	0.99	1.27	0.060	0.062	75.25	77.30	58.90
3117240	503	Maple	C	10.93	9.27	9.23	1.66	1.71	0.055	0.072	33.20	35.30	21.60
3117289	658	Maple	C	11.85	10.09	10.12	1.76	1.73	0.055	0.067	48.90	50.90	30.90
169002	77	LowerMaumee	D	12.02	11.96	11.65	0.05	0.36	0.060	0.065	39.59	40.80	27.20
169123	738	LowerMaumee	D	10.17	10.36	9.78	-0.18	0.40	0.067	0.066	43.13	44.24	33.50
186999	698	Maple	D	13.12	12.71	12.69	0.41	0.43	0.051	0.058	65.30	66.80	43.40
187314	767	Maple	D	10.80	8.84	9.15	1.96	1.65	0.065	0.082	35.30	36.10	22.30
199209	574	Macoupin	D	11.79	11.36	11.09	0.43	0.70	0.065	0.071	47.80	49.90	29.30
425850	736	UpperFox	D	12.92	11.76	11.83	1.15	1.09	0.056	0.063	48.10	50.20	29.20
753459	871	Sugar	D	10.98	10.04	10.03	0.94	0.95	0.050	0.063	50.40	52.40	34.70
1591203	15	Sugar	D	10.21	9.24	9.16	0.98	1.05	0.065	0.074	32.40	33.90	21.30

Khyati Malik

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ACADEMIC POSITIONS

National Bureau of Economic Research (NBER)
Postdoctoral Fellow, New Perspectives on Agricultural Economics 2025-Present

EDUCATION

The Ohio State University (OSU), Columbus, Ohio USA
PhD, Agricultural, Environmental, & Development Economics 2019-2025

Ohio University, Athens, Ohio USA
MA, Economics 2015-2018

London School of Economics and Sciences Po, London UK / Paris France (Dual Degree)
Master of Public Affairs 2010-2012

ICFAI Business School, Mumbai, India
Master of Business Administration 2004-2006

Guru Gobind Singh Indraprastha University, New Delhi, India
Bachelor of Business Administration 2001-2004

RESEARCH

PEER-REVIEWED PUBLICATIONS

1. **Malik, Khyati**, Kim, Sowon, and Cultice, Brian, 2023, The Impact of Remote Work on Green Space Values in Regional Housing Markets, ***Journal of Housing Economics***, doi: 10.1016/j.jhe.2023.101967 [First authorship shared with Kim]
2. Karney, Daniel, and **Malik, Khyati**, 2026, New Compensating and Equivalent Variation Closed-Form Solutions for Non-Separable Public Goods, ***Applied Economics Letters***, doi: 10.1080/13504851.2026.2613072

BOOK CHAPTERS

1. **Malik, Khyati, 2026,** *'Farmer Adoption and Payment Design Under Risk: Variability in Soil Carbon Sequestration Across Conservation Practices'*, in T. Deryugina and B. K. Goodwin (eds.), **Risk and Risk Management in the Agricultural Economy**, University of Chicago Press (forthcoming). (NBER Working Paper 34902)
2. Gopalakrishnan, Sathya, **Malik, Khyati**, and Zhu, Kunxin, 2024, '*Climate Change and Coupled Human and Natural Systems*', **Routledge Handbook of Climate Change and Society**, 2nd Edition.

PAPERS IN REVIEW

1. Cai, Yongyang, **Malik, Khyati**, and Shin, Hyeseon, Dynamics of Global Emission Permit Prices and Regional Social Cost of Carbon Under Noncooperation ***(Revise and Resubmit: Quantitative Economics)***
2. **Malik, Khyati**, Optimal Carbon Payments and Adoption Under Soil Carbon Sequestration: An Analytical Characterization *(Under review: Resource and Energy Economics; Submitted May 27, 2026)*

WORKING PAPERS

1. **Malik, Khyati**, *Stock or Flow? Carbon Payment Designs for Soil Carbon Sequestration*

I derive closed-form minimum payment conditions for five carbon payment designs for incentivizing soil carbon sequestration through conservation tillage. Payment schemes based on incremental carbon sequestered fail structurally: without penalties for carbon release, the payment rises without bound as soils approach saturation, generating a cycling equilibrium with little sequestration. Carbon stock-based payments conditional on conservation adoption emerge as optimal, limiting the additionality problem and maintaining consistent incentives. Lifetime discounted payments remain below the US social cost of carbon, and spatially targeted payments reduce program costs by 22% relative to a uniform price.

2. **Malik, Khyati**, *Soil to Savings: Optimal Farmer Compensation for Carbon Sequestration Services in the Midwest United States*

I develop a dynamic optimization model to determine cost-effective farmer payments for adopting no-till practices aimed at soil carbon sequestration. Using experimental data and Environmental Policy Integrated Climate (EPIC) simulations, I derive field-specific payment schemes by explicitly modeling yield losses and sequestration impermanence as dynamic processes, while also incorporating soil heterogeneity. Spatially targeted payments significantly lower policy implementation costs and increase farmer adoption, sustainably sequestering approximately 9 million tons of carbon across 2.57 million acres of the studied agricultural land.

3. **Malik, Khyati**, *Ramping Up Emissions? The Implications of Intermittent Renewables for Thermal Power Plant Pollution*

I investigate how rising solar generation reshapes operational and emissions dynamics in thermal power plants. Using twelve years of hourly electric generating unit (EGU)-level data from the Environmental Protection Agency's (EPA's) Continuous Emissions Monitoring Systems, I quantify the emission rates of CO_2, SO_2, and NO_x per-megawatt of power output when EGUs start up or shutdown to balance the hourly demand fluctuations. Ramping up of the EGUs increases NO_x emission rates. NO_x emission rates are specifically higher for the EGUs that use solid fuels. These findings highlight a key externality of renewable integration and support targeted investments in energy storage, fast ramping capacity, and real-time pricing.

WORK IN PROGRESS

1. *Crop Insurance and the Adoption of Carbon-Sequestering Conservation Practices* (with Christopher Knittel and Jiyoung Lee)

This project examines whether subsidized crop insurance reduces incentives to adopt carbon-sequestering conservation practices such as no-till. Carbon-rich soils improve yield resilience to weather shocks, but conservation practices can reduce yields under normal conditions, creating a temperature–precipitation threshold beyond which conservation outyields conventional management. Fields cross this threshold with a frequency determined by local weather, so farmers facing greater weather risk have incentives to adopt both conservation and insurance, which may act as substitutes. The analysis combines EPIC crop simulations to identify the yield threshold, historical weather to measure how often it is crossed, and county-level insurance data to test for substitution in observed take-up. It then estimates the carbon price needed to induce conservation adoption with and without insurance.

TEACHING EXPERIENCE

Environmental and Resource Economics (AEDE 4310), **Instructor**, OSU (***Score: 4.42/5.00***) Spring 2024
Environmental and Resource Economics (AEDE 4310), Teaching Assistant, OSU Fall 2023
Economics of Public Policy Analysis (AEDE 4003), Teaching Assistant, OSU Fall 2020-Spring 2021

PROFESSIONAL EXPERIENCE

Research

Research Assistant, **USDA NIFA Project**, OSU — Fall 2021- Spring 2025

Research Intern, Data Integration in Food and Agriculture, OSU — Summer 2021

Industry

Analyst, UBS Investment Bank (UK) — 2009-2010

Analyst, Standard Chartered Bank (India) — 2006-2009

Executive Trainee, HDFC Bank (India) — Spring 2006-Fall 2006

FELLOWSHIPS, HONORS, AND AWARDS

Anthony Grano Fellowship Award — 2025

Bernie Erven Graduate Teaching Award — 2024-2025

Oskar Morgenstern Fellow, Mercatus Center, George Mason University — 2022-2024

EPA EmPOWER Air Data Challenge Winner — 2022-2023

Sadie Collective Annual Research Scholar — 2022-2023

University Fellowship, The Ohio State University — 2019-2020

Runner-up Award, Financial Inclusion Insights (FII) Open Data Analysis Challenge — 2014-2015

Best Paper Award, European Public Policy Conference — 2012-2013

GRANTS AND SCHOLARSHIPS

URM Travel Grant, American Economic Association — Spring 2026

Sustainability Institute Student Grant — 2023-2024

Agricultural & Applied Economics Association (AAEA) Travel Grant — Summer 2023

AAEA Pre- Conference Workshop Grant — Summer 2023

Scholarship & Travel Grant, Berkeley Summer School in Environ. and Energy Economics — 2022

Tuition Scholarship, Sciences Po — 2011-2012

Scholarship and Travel Grant, Centro Studi Luca D'Agliano — 2011

Scholarship Mountbatten Institute, UK — 2009-2010

INVITED TALKS, CONFERENCES, AND WORKSHOPS

2026 — Allied Social Science Associations (ASSA) (AERE Session), Harvard Environmental Economics Workshop (Invited Talk), AERE OSWEET, Annual Conference of the Midwest Economics Association (AERE Session), Indian Institute of Technology Gandhinagar (Invited Talk), NBER Summer Institute Workshop on Methods and Applications for Dynamic Equilibrium Models, NBER Summer Institute Macro Public Finance, NBER Summer Institute Environment and Energy Economics, Camp Resources Workshop, NBER Climate Finance Workshop (scheduled)

2025 — Annual Conference of the Midwest Economics Association (AERE Session), NBER Summer Institute, NBER Economics of Decarbonizing Industrial Production Workshop, NBER Climate Finance Workshop, Southeastern Workshop on Energy & Environmental Economics & Policy, Heartland Environmental and Resource Economics Workshop, Invited Seminar: North Carolina State University, NBER Risk & Risk Management in the Agricultural Economy Workshop, Massachusetts Institute of Technology (MIT) Center for Energy and Environmental Policy Research (CEEPR) Energy & Environmental Economics Workshop.

Camp Resources Workshop, Agricultural & Applied Economics Association Annual Meeting (AERE Session), AERE Summer Conference, Economics Seminar (Ohio University), Lal Carbon Center (The Ohio State University), RUSH (Regional/Urban/Spatial/Housing) Brownbag. 2024

Heartland Environmental and Resource Economics Workshop, RUSH (Regional/Urban/Spatial/Housing) Brownbag, Agricultural & Applied Economics Association Annual Meeting, Urban Economics Association Summer School, Housing Research Discussion: Institute for Humane Studies (Online), Annual Conference of the Midwestern Economics Association. 2023

ZTRAX Special Issue Workshop (Online), Berkeley/Sloan Summer School in Environmental and Energy Economics, Annual Conference of the Midwestern Economics Association. 2022

North American Regional Science Council (NARSC) Conference (Online). 2021

PROFESSIONAL SERVICE

Academic Journal Peer Review: *Journal of Housing Economics, Regional Studies, AAEA Annual Meeting 2026* abstracts, *Journal of Agriculture and Resource Economics*

RUSH (Regional/Urban/Spatial/Housing) **Graduate Brownbag Organizing Committee** 2023-2024

LIWOC (Leadership Initiatives for Women of Color), OSU 2021-2022

AEA, AERE and AAEA Membership 2021- Present

TECHNICAL SKILLS

R, Stata, Python, LaTeX, ArcGIS, SAS, MATLAB, Microsoft Excel, Machine Learning

Data Science and Machine Learning Boot Camp, The ErdÖs Institute Summer 2021

LANGUAGES

English (Native), Hindi (Native), French (Conversational)

PERSONAL

Citizenship: United States