A Comparative Study of Carbon Payment Policy Design for Agricultural Soil Carbon Sequestration *

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Abstract

This paper develops a theoretical framework to evaluate carbon payment policies aimed at promoting soil organic carbon (SOC) sequestration through conservation tillage. We compare four policy designs based on payments tied to carbon stocks, incremental carbon changes, and flat incentives. The results show that policies based on carbon stocks, particularly those conditional on conservation practice adoption, achieve the desired incentives at lower payment levels and avoid perverse incentives associated with incremental schemes. Required payments vary with biophysical conditions such as initial SOC and sequestration rates, but remain below the social cost of carbon, indicating welfare gains. We also show that constant payment schemes lead to long payback periods, while front-loaded payments can accelerate adoption but must be carefully designed to prevent defection. Overall, the findings highlight the importance of dynamic, incentive-compatible policy design for cost-effective and sustained carbon sequestration in agriculture.

Keywords: soil carbon sequestration, bioeconomic model, EPIC, agricultural productivity

1 Introduction

Global temperatures have risen approximately 1.1^{o}C above pre-industrial levels, approaching the critical 1.5^{o}C threshold, beyond which irreversible climate impacts become increasingly likely (Masson-Delmotte et al., 2021). To address this urgent climate challenge, policymakers increasingly prioritize investment in carbon capture and sequestration (CCS). Yet current CCS infrastructure in the United States captures less than 1% of annual carbon dioxide emissions and remains costly compared to land-based approaches Congressional Budget Office (2023). Agricultural soils therefore emerge as an economically attractive and scalable alternative carbon sink, given their extensive coverage and responsiveness to conservation practices.

Agricultural soils emerge as an economically attractive and scalable alternative carbon sink, given their extensive coverage and responsiveness to specific conservation practices. Recent research suggests land-based sequestration strategies could offset approximately 10 to 15 gigatons of carbon dioxide equivalents annually by 2050 (Griscom et al., 2017; Roe et al., 2021). Practices such as reduced or no tillage, cover cropping, diversified rotations, and organic amendments enhance soil organic carbon (SOC) levels, simultaneously improving soil health and agricultural productivity (Singh et al., 2023; Eagle et al., 2010). The agricultural carbon market remains nascent because of uncertainty surrounding achievable SOC levels, inadequate knowledge of how the management approaches affect carbon dynamics, poorly formulated payment mechanisms, and incomplete understanding of how conservation practices influence regional agricultural productivity (Capon et al., 2013; Buck and Palumbo-Compton, 2022; Pendell et al., 2006; Yao and Kong, 2018).

The Midwest United States is particularly well-suited for large-scale adoption of agricultural carbon sequestration policies. The region contributes over $152 billion annually to national agricultural production, representing more than 40% of total U.S. crop and livestock output (AgAmerica, 2023). With a cultivated area exceeding 125 million acres, the Midwest has significant potential to achieve negative emissions through soil carbon seques-

tration (Lal, 2004; Christopher et al., 2009). Realizing this potential would allow the farmers to earn supplemental income by providing carbon sequestration services, while policymakers could effectively advance the national emissions reduction targets. However, accurately quantifying sequestration potential, farmer incentives, and associated economic costs requires careful analysis that considers complex regional heterogeneity in soil characteristics, climate variability, and the yield - carbon sequestration tradeoffs associated with different agricultural practices.

The use of agricultural soils as a carbon emissions mitigation strategy remains subject to skepticism due to several challenges. First, soil carbon sequestration is reversible (Kim et al., 2008; Ruseva et al., 2020). While sequestration is a slow process that occurs over decades, a return to conventional practices can release the accumulated carbon at a faster rate (Sadatshojaei et al., 2021). Second, soils have a finite capacity to store carbon (Chen et al., 2019). As soils approach their saturation limit, the sequestration rate declines (West and Six, 2007; Paustian et al., 2016; Stewart et al., 2007). Third, sequestration occurs through complex biophysical processes that are not fully understood, and the rate of sequestration depends on soil type, weather conditions, and agricultural practices (Chen et al., 2019). In addition, measuring soil carbon stocks accurately is difficult. Many conservation practices reduce crop yields relative to conventional practices (Blevins et al., 1977; Ismail et al., 1994), creating a trade-off between short-term revenue losses and long-term gains from carbon sequestration. Finally, carbon markets are subject to uncertainty and price volatility.

Policies designed to promote soil carbon sequestration must address these constraints. Carbon payments should account for farmers' long-term profitability, discourage reversion to conventional practices that would release stored carbon, and reduce the time required to break even on adoption costs. Moreover, payment schemes should account for differences in soil type, weather conditions, and management practices.

This paper develops a theoretical economic framework to evaluate alternative carbon payment policies designed to promote soil organic carbon (SOC) sequestration through con-

servation tillage. We model a forward-looking farmer who chooses between conventional and conservation practices by weighing short-run costs, including potential yield losses, against long-run carbon payments. The analysis compares four commonly discussed policy designs: payments based on total carbon stock, payments conditional on conservation practice adoption, payments based on incremental changes in carbon stock, and flat payments for adopting conservation practices. By incorporating biophysical dynamics of carbon accumulation and release, the model captures how soil characteristics, initial carbon levels, and sequestration rates shape optimal incentives and adoption decisions over time.

The results show that policy design plays a critical role in determining both the effectiveness and efficiency of carbon incentives. Policies based on carbon stocks—particularly those conditional on conservation practice adoption—require lower payment levels and provide consistent incentives for sustained sequestration. In contrast, incremental carbon payment schemes can create perverse incentives and become increasingly costly as soils approach carbon saturation, while flat payments fail to account for heterogeneity in carbon dynamics and require substantially higher compensation. The analysis also highlights an important trade-off between payment levels and adoption timing: constant payments lead to long break-even periods, whereas front-loaded payment schemes can accelerate adoption but must be carefully calibrated to prevent reversal to conventional practices. Overall, the findings emphasize the importance of dynamic, incentive-compatible policy design for achieving cost-effective and durable carbon sequestration outcomes.

This study contributes to existing literature in three distinct ways. First, while prior economic analyses (e.g., Antle et al. (2003); Murray et al. (2007); Feng et al. (2002); Raj Kunwar et al. (2025)) have examined issues such as sequestration reversibility, delayed accumulation, variable sequestration rates, and potential yield losses, they have not consistently quantified their economic implications or integrated them with detailed field-level biophysical evidence. Second, this research advances existing work by combining empirical observations from rigorous long-term agricultural experiments (Blevins et al., 1983; Ismail et al., 1994; Blevins

et al., 1977) with detailed simulations from the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1984). The EPIC model expressly captures the interactions among soil properties, climatic factors, management practices, and yield outcomes, enabling precise quantification of SOC dynamics. Third, this analysis identifies economic thresholds necessary to incentivize adoption of carbon sequestration services and highlights that these thresholds reflect the interaction of economic conditions (profits and yield impacts) with geophysical factors (soil type and initial SOC).

2 Background

Previous studies have examined the economic and environmental dimensions of various soil carbon sequestration practices. Empirical evidence demonstrates substantial SOC gains from biochar amendments (De Gryze et al., 2010), grassland management (Bai and Cotrufo, 2022; Conant et al., 2001, 2017), leaving highly erodible lands fallow (Sperow, 2007), afforestation (Stavins, 1999), and no-till farming (Sperow, 2019). Additionally, practices such as cover cropping, agroforestry, and rotational grazing are shown to enhance SOC, particularly in water-limited regions.(Blanco-Canqui, 2022; Ardenti et al., 2023; Ghimire et al., 2024) However, local soil conditions, climate variability, cropping systems, microbial interactions, and mineralogical factors affect SOC potential, complicating sequestration outcomes across regions.(Pittelkow et al., 2015; Van den Putte et al., 2010; Bai et al., 2019; Sun et al., 2020; Ogle et al., 2005, 2019; Lehmann et al., 2020) Occasional disturbances such as infrequent tillage are argued to rapidly diminish accumulated carbon stocks.(Blanco-Canqui and Wortmann, 2020; Dynarski et al., 2020; Conant et al., 2007)

Given this variability, spatially differentiated payment structures to address differences in sequestration potential and adoption costs across diverse agricultural contexts have been proposed.(Antle et al., 2003; Baylis et al., 2022) Uniform per-hectare subsidies inadequately capture spatial heterogeneity, risking inefficient resource allocation and unintended incen-

tives for farmers who would adopt practices without additional payments.(Horowitz and Just, 2013) Also, narrowly targeted payments may unintentionally shift emissions elsewhere, undermining broader climate objectives. Hertel (2018); Engel and Muller (2016) argue that well-structured incentives explicitly balance environmental objectives with agricultural productivity. Effective policy frameworks require understanding factors influencing adoption decisions, including short-term costs (seed purchase, labor, termination), contractual flexibility, yield risks, and payment levels.(Gramig, 2012; Gramig and Widmar, 2018; Campbell et al., 2021; Bergtold et al., 2019; Blanco, 2023)

Recognizing limitations inherent in government-run incentives, voluntary carbon markets offer complementary mechanisms to enhance SOC sequestration. Yet these markets face operational challenges in accurately measuring, verifying, and ensuring the permanence of stored carbon.(Thamo et al., 2020; Wongpiyabovorn et al., 2023; Plastina, 2021) To further inform efficient policies, integrated assessment models clarify interactions among agricultural practices, carbon sequestration, and climate feedbacks. For instance, Antle et al. (2001) show that economically incentivized conservation agriculture mitigates climate impacts, an insight extended by Thomson et al. (2008) to global terrestrial ecosystems.

A complementary line of research has developed bioeconomic models of SOC dynamics. Antle et al. (2003) emphasized spatial heterogeneity in sequestration costs, Murray et al. (2007) incorporated permanence and leakage, Feng et al. (2002) examined delayed accumulation, and Ragot and Schubert (2008) modeled sequestration and release as asymmetric exponential functions. In reality, absorptive thresholds are shaped by factors such as soil type, climate, and nutrient availability (Wiesmeier et al., 2019), yet most frameworks abstract away from these influences. These studies provide important foundations but generally simplify biophysical processes, often omitting absorptive thresholds, reversibility, or relative sequestration and release rates, and rarely integrate detailed field-level data.

Building on these limitations, three critical gaps remain in the existing economic literature. First, prior studies inadequately quantify how temporal SOC dynamics shape op-

timal economic incentive structures.Second, use of field-level biophysical data in economic analysis is largely absent, hindering policymakers' ability to better understand how spatial differentiation of policies affects cost-effectiveness. Finally, despite extensive discussion of spatial variability (Antle et al., 2003; Ogle et al., 2019; Baylis et al., 2022) and additionality (Horowitz and Just, 2013; Mezzatesta et al., 2013), the conditions under which adoption of carbon sequestration practices becomes economically viable, considering farmer incentives, yield reductions, and sequestration reversibility, remain underexplored.

My research addresses these gaps by combining EPIC simulations and empirical data from long-term agricultural experiments. I quantify the economic effects of nonlinear SOC dynamics, including rapid accumulation, saturation, and reversibility. Additionally, I identify payment thresholds tailored to field-specific conditions, providing actionable guidance for designing carbon sequestration incentives that remain effective over time.

3 Data

I utilize simulated data from EPIC to parameterize and then solve the theoretical model. The EPIC simulations provide the key parameters for carbon dynamics, yields, and soil characteristics, while the field data serve as a robustness check.

For EPIC simulations, I obtain soil data from the Soil Survey Geographic Database (SSURGO), and daily weather data from the World Climate Research Program (WCRP) Coupled Model Intercomparison Project (CMIP)-6, the most up-to-date weather model. I source site (field-level) data from the Cropland Sequence Boundaries dataset provided by the United States Department of Agriculture. I use the following data: location of the field (latitude/longitude), field slope, field elevation, field aspect ratio, daily precipitation, maximum and minimum daily temperatures, solar radiation, humidity, and daily wind speed.

Soil characteristics considered in the simulations include soil albedo, hydrology group, layer depths and densities, sand content, silt content, soil pH, organic carbon concentration,

calcium carbonate content, rock content, and soil conductivity. In these simulations, tillage (if applicable) is performed on April 25 each year with corn planting on May 2. Fertilizers are added in the amounts 185 Kg/ha, 150 Kg/ha, and 116 Kg/ha each year. Automatic irrigation schedule is used, that is, field is irrigated when the water stress on the crops reaches a certain threshold. Corn is harvested on September 14, and then shredded. Three different tillage practices are studied: NT, reduced till (RT), and CT (moldboard plow). Within the Midwest region, I selected fields from five different watersheds: Sugar, Lower Maumee, Maple, Macoupin, and Upper Fox. I selected these watersheds because they capture soil and climate heterogeneity within the Midwest and provide suitable data for initializing EPIC simulations. For each watershed, I calculated the proportion of areas belonging to different hydrology groups and then randomly selected fields from each hydrology group based on these proportions. In total, I selected 70 fields covering all hydrology groups and the watersheds. I find that EPIC simulations are initiated at high SOC levels, ensuring realistic initial conditions representative of continuous cultivation practices. Once the SOC levels were stable, I performed 30-year simulations with NT, RT, and CT practices to compare changes in SOC and crop yield. In total, I conducted EPIC simulations for the selected 70 fields providing a comparative analysis of tillage effects on SOC and yield across different hydrology groups within the selected watersheds. I chose to study 70 fields so that I am able to capture the heterogeneity in soil and weather conditions in yield and SOC, and also keep the computational costs reasonable. The market price of corn is \$4.04 per bushel in 2025. The average corn price over the last 10 years, excluding the COVID-19 pandemic years of 2020-2022, is \$4.06 per bushel (Macrotrends (2024)). Given that 1 bushel of corn equals 0.0254 metric tons (U.S. Grains Council (2024)), the 10-year average price of corn translates to \$160 per metric ton.

The parameter values obtained from EPIC simulations, including yields, sequestration rates, and long-run SOC levels, are reported in Table 1. C^* (ton/ha) is the maximum carbon stock attainable under a given practice; C_0 (ton/ha) is the baseline carbon stock

that is attained after long-term conventional tillage; s (1/year) is the parameter defining the rate of sequestration; and y (ton/ha) refers to crop yield. For the fields considered, NT dominates RT in both yields and SOC sequestration, and we therefore focus on the comparison between NT and CT practices.

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

Table 1: Average corn yield (y) (tons/ha), soil organic carbon (SOC) sequestration amounts (C_0 and C^*) (tons/ha), and sequestration rates (s) (1/year) under conventional tillage (CT), no-till (NT), and reduced tillage (RT) across hydrology groups, based on simulations from the Environmental Policy Integrated Climate (EPIC) model. The results are based on 70 fields across five watersheds: Sugar, Lower Maumee, Maple, Macoupin, and Upper Fox.

4 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 β is the discount factor. Period profits depend on the carbon payment policy. We consider four alternative designs: (1) payments proportional to the current carbon stock; (2) payments proportional to the current carbon stock, conditional on adopting a conservation practice; (3) payments based on the incremental change in carbon stock during the period; and (4) a flat payment for adopting a conservation practice, irrespective of the carbon stock level. The conservation and conventional practices analyzed are no-till (NT) and conventional tillage (CT), respectively. Each policy is described in detail below.

4.1 Policy 1: Payments proportional to the current carbon stock

The 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, and C_0 is the baseline carbon stock corresponding to long-run conventional tillage. The parameter m denotes 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 two tillage practices: 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 may reduce crop yields ($y_{NT} < y_{CT}$), while CT does not sequester carbon and releases carbon when $C_t > C_0$.

When the carbon payment rate m is sufficiently high that the farmer adopts NT, the value function is:

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

Following Ragot and Schubert (2008); Malik (2026), SOC sequestration dynamics for conservation practice are modeled as $\mathbb{E}[C_t] = C^* - (C^* - \tilde{C})e^{-s(t+1)}$, where s governs the rate of sequestration, and depends on soil type, weather conditions, and agricultural practices. $\tilde{C}$ is the SOC at the beginning of the period $t = 0$. The value function can be written in closed form as:

$$V_{NT} = \frac{\mathbb{E}[y_{NT}] \times P - Cost_{NT}}{1 - \beta} + \frac{(C^* - C_0)m}{1 - \beta} - \frac{(C^* - \tilde{C})e^{-s}m}{1 - \beta e^{-s}} \tag{4}$$

When the carbon payment rate 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_o. The

corresponding value function is:

$$V_{CT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{CT}] \times P + (\mathbb{E}[C_t] - C_o) \times m - cost(\theta_{CT})] \tag{5}$$

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

$$V_{CT} = \frac{\mathbb{E}[y_{CT}] \times P - \text{Cost}_{CT}}{1-\beta} + \frac{(\tilde{C} - C_0)e^{-s'}m}{1-\beta} \tag{6}$$

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

$$m \geq \left(\frac{C^* - C_0}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}}{1-\beta e^{-s}} - \frac{(\tilde{C} - C_0)e^{-s'}}{1-\beta e^{-s'}} \right)^{-1} \left(\frac{\Delta y \times P - \Delta\text{Cost}}{1-\beta} \right) \tag{7}$$

where $\Delta y = \mathbb{E}(y_{CT} - y_{NT})$ denotes the expected yield loss under NT, and $\Delta Cost = cost(\theta_{CT}) - cost(\theta_{NT})$ is the difference in implementation costs. Equality in (7) defines the minimum carbon payment m required to incentivize NT adoption.

Several conclusions follow from equation (7). First, the required payment m decreases with the initial SOC stock $\tilde{C}$, since higher initial carbon levels generate larger payments (Figure 1(a)). Second, m depends on both the carbon sequestration rate (s) and the carbon release rate (s'), and is decreasing in both. A higher sequestration rate accelerates SOC accumulation, reducing the payment needed to make conservation practices optimal (Figure 1(b)). Conversely, a higher release rate implies that SOC is lost more rapidly under conventional tillage, making it less attractive. Finally, m is independent of s' when $\tilde{C} = C_o$.

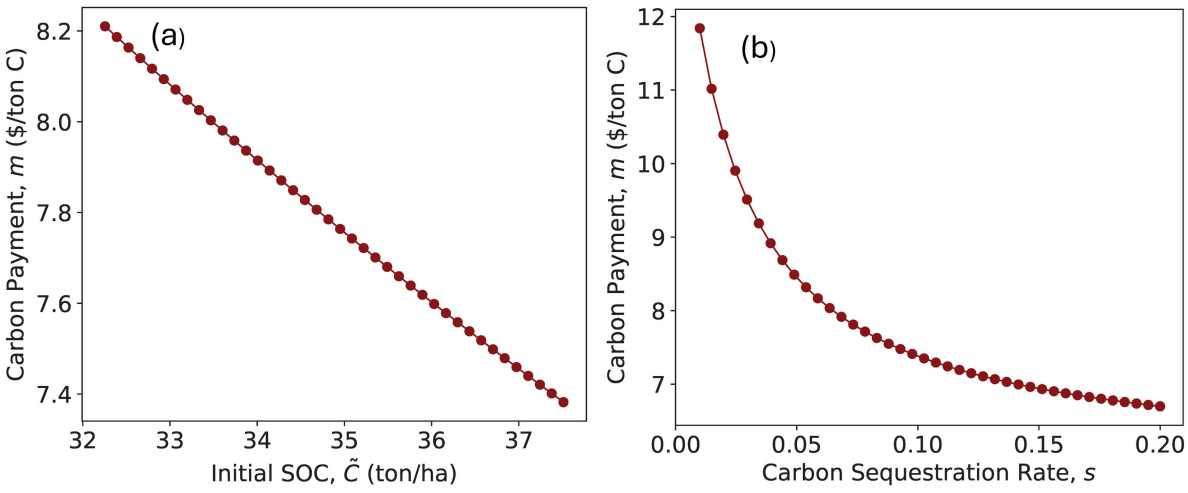


Figure 1: Optimal carbon payment m to incentivize NT as a function of (a) initial carbon stock $\tilde{C}$, and (b) carbon sequestration rate s for the representative field belonging to the hydrology group A when policy 1 is implemented. In (b), $\tilde{C}$ is set equal to the average of the saturation level (C^*) and the baseline SOC (C_0).

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

Under this policy, farmers receive payments proportional to their carbon stock only in periods when they adopt a conservation practice. Thus, period profits are given by,

$$\pi_t = (\mathbb{E}[C_t] - C_0) \times m \times \mathbf{1}(\theta_t = \theta_{NT}) + \mathbb{E}[y_t] \times P - cost(\theta_t). \tag{8}$$

The value function for NT becomes:

$$V_{NT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{NT}] \times P + (\mathbb{E}[C_t] - C_o) \times m - cost(\theta_{NT})] \tag{9}$$

Using the SOC dynamics for conservation practice, the closed form expression of the value function becomes:

$$V_{NT} = \frac{\mathbb{E}[y_{NT}] \times P - \text{Cost}_{NT}}{1-\beta} + \frac{(C^* - C_0)m}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}m}{1-\beta e^{-s}} \tag{10}$$

The value function of the conventional practice is:

$$V_{CT} = \sum_{t=0}^{\infty} \beta^t [\mathbb{E}[y_{CT}] \times P - cost(\theta_{CT})] = \frac{\mathbb{E}[y_{CT}] \times P - \text{Cost}_{CT}}{1-\beta} \tag{11}$$

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

$$m \geq \left(\frac{C^* - C_o}{1-\beta} - \frac{(C^* - \tilde{C})e^{-s}}{1-\beta e^{-s}} \right)^{-1} \left(\frac{\Delta y \times P - \Delta\text{Cost}}{1-\beta} \right) \tag{12}$$

The m does not depend on the carbon release rate s'.

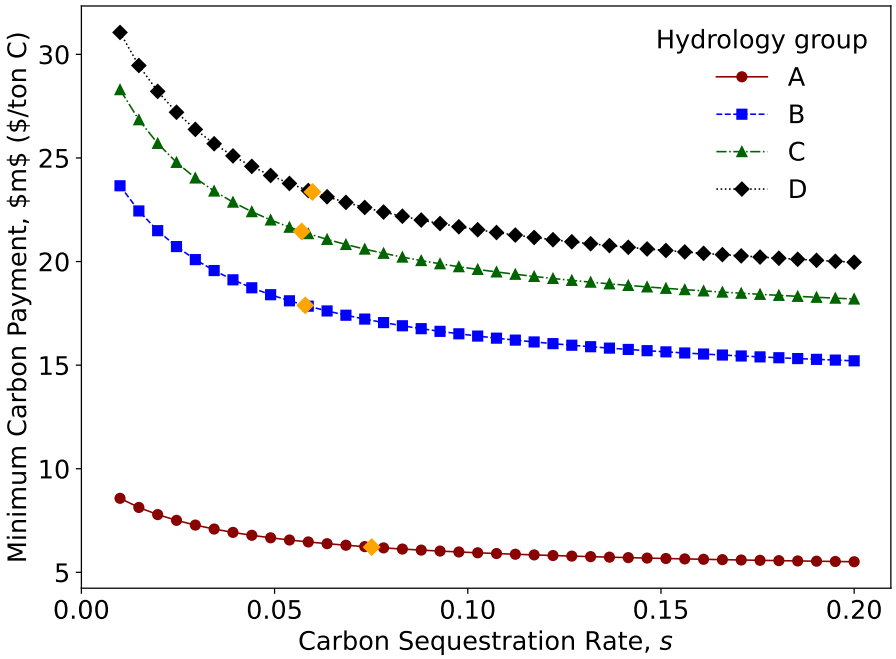


Figure 2: Minimum carbon payment, m as a function of the carbon sequestration rate parameter, s of NT for different hydrology groups. The highlighted markers in orange are associated with the values of s determined from EPIC simulations. The $\tilde{C}$ is set equal to the average of the saturation level (C^*) and the baseline SOC (C_0).

As shown in Figure 2, m is high when s is small because SOC accrues slowly, but declines sharply as s increases. This finding suggests that technologies that accelerate carbon sequestration can substantially reduce the payments required to induce adoption of conservation practices. The highlighted markers in orange correspond to m for values of s obtained for

different soil types (hydrology groups) through EPIC simulations.

4.3 Policy 3: Payments 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 under conventional practices. We do not consider a policy that rewards incremental SOC gains without penalizing subsequent carbon release, as such a design would create perverse incentives. Specifically, farmers could sequester carbon for a few years, then revert to conventional practices to release it, and subsequently repeat the cycle. In this case, net carbon sequestration would not increase over time.

The period profit equation is defined by:

$$\pi_t = (\mathbb{E}[C_t - C_{t-1}] \times m + \mathbb{E}(y_t) \times P - cost(\theta_t). \tag{13}$$

When a farmer practices NT, the value function becomes,

$$V_{NT} = \frac{(C^* - \tilde{C})(1 - e^{-s})m}{1 - \beta e^{-s}} + \frac{\mathbb{E}[y_{NT}] - Cost_{NT}}{1 - \beta} \tag{14}$$

When a farmer practices CT, the value function becomes,

$$V_{CT} = \frac{(\tilde{C} - C_o)(e^{-s'} - 1)m}{1 - \beta e^{-s'}} + \frac{\mathbb{E}[y_{CT}]P - Cost_{CT}}{1 - \beta} \tag{15}$$

The condition $V_{NT} \geq V_{CT}$ gives,

$$m \geq \left(\frac{(C^* - \tilde{C})e^{-s}}{1 - \beta e^{-s}} + \frac{(\tilde{C} - C_0)(1 - e^{-s'})}{1 - \beta e^{-s'}} \right)^{-1} \frac{\Delta y \times P - \Delta Cost}{1 - \beta} \tag{16}$$

The required payment m increases substantially with the initial carbon stock $\tilde{C}$ (Figure 3(a)). This indicates that as a field's stored carbon rises, farmers demand higher payments

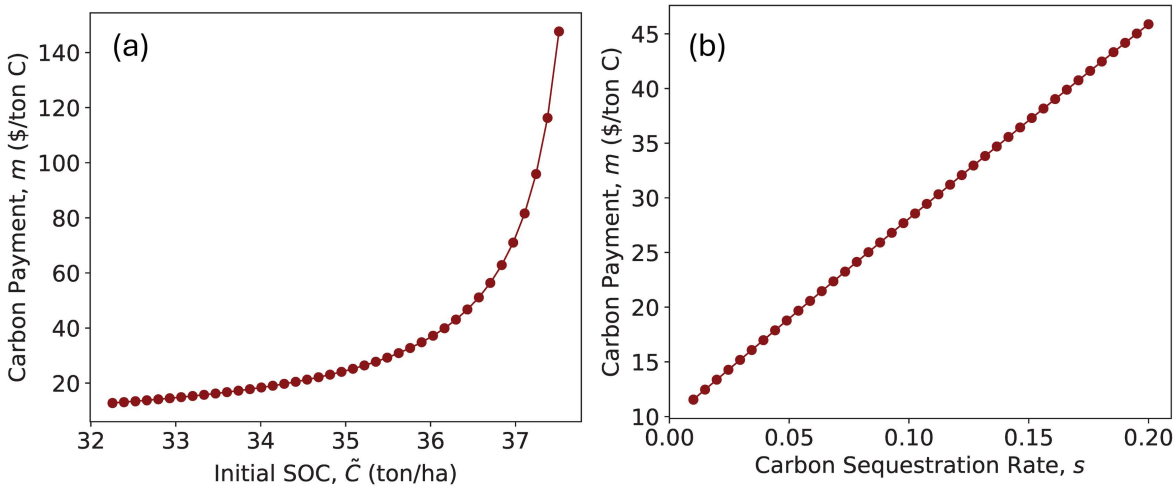


Figure 3: Optimal carbon payment m to incentivize NT as a function of (a) initial carbon stock, and (b) carbon sequestration rate for the representative field of hydrology group A, when policy 3 is implemented. In (b), $\tilde{C}$ is set equal to the average of the saturation level (C^*) and the baseline SOC (C_0).

to continue sequestering additional carbon, because the marginal carbon gain diminishes as SOC approaches the saturation level (C^*). Similarly, m increases with the carbon sequestration rate s (Figure 3(b)), since faster sequestration brings the field closer to saturation more quickly. Once the field reaches carbon saturation, farmers no longer receive payments for stored carbon and may be penalized if SOC declines. These characteristics make this incremental payment policy less practical for implementation.

4.4 Policy 4: Payments for adopting a conservation practice

The farmers are paid a constant amount for adopting a conservation practice. The carbon payment becomes:

$$m \geq \Delta y \times P - \Delta Cost \tag{17}$$

So, in each period, the farmers need to be compensated for the expected loss in revenue from crop yields and the additional cost of adoption, if any.

The analysis indicates that policies 1 and 2 are preferable, as the required payment m decreases with SOC stock, unlike policy 3, where m increases with SOC. Table 2 reports

m values for each policy when the initial SOC $\tilde{C}$ is set to the average of the saturation level (C^*) and the baseline SOC (C_0). Policy 2 consistently requires lower payments than policy 1, making it more efficient. Although policy 3 shows low m values at some SOC levels, m rises substantially as $\tilde{C}$ increases. Policy 4 requires comparatively high payments and is therefore less optimal. Across all policies, m varies considerably with soil type. The social cost of carbon (SCC) of the United States is estimated to be \$190/ton CO_2, which translates to \$697/ton C (Farah and Clark, 2022). The lifetime discounted carbon payments ($= m/(1-\beta)$) associated with policies 1 and 2 are lower than the SCC, indicating that the payment levels are welfare-improving and do not exceed the marginal social benefit of carbon sequestration.

Table 2: Carbon payments m (\$/ton C) for each policy for the representative fields belonging to different hydrology groups. The initial carbon stock is set equal to the average of the saturation level (C^*) and the baseline SOC (C_0) in each case.

Hydrology	Policy 1	Policy 2	Policy 3	Policy 4
A	7.77	6.22	23.58	26.31
B	45.83	17.89	11.31	147.78
C	77.89	21.45	11.21	132.19
D	41.08	23.36	22.30	114.74

4.5 Policy 2: Break-even times and front-loaded carbon payment schemes

The above analysis established policy 2 as superior to all the other carbon payment policies considered. Therefore, we focus our further analysis on policy 2 only.

For a farmer with the initial SOC, C_0, adoption of NT leads to losses in early periods due to lower crop yields, which are offset by future carbon payments. For any payment level

m, there exists a break-even time T that is determined by:

$$\sum_{t=0}^{T} \beta^t \left[(\Delta y \times P - (C^* - C_0)(1 - e^{-s(t+1)})m - \Delta Cost \right] = 0 \tag{18}$$

The corresponding closed-form expression is:

$$\frac{(\Delta y \times P - \Delta \text{Cost})(1 - \beta^{T+1})}{1 - \beta} - \left[\frac{1 - \beta^{T+1}}{1 - \beta} - \frac{[1 - (\beta e^{-s})^{T+1}]e^{-s}}{1 - \beta e^{-s}} \right] (C^* - C_o)m = 0 \tag{19}$$

At the minimum payment level, the break-even time is infinite. Figure 4 shows the relationship between T and m for the representative field belonging to hydrology group A. A marginal increase above the minimum m yields a break-even time of 35 years. Reducing the break-even time to fewer than 5 years requires payments approximately four times larger than the minimum.

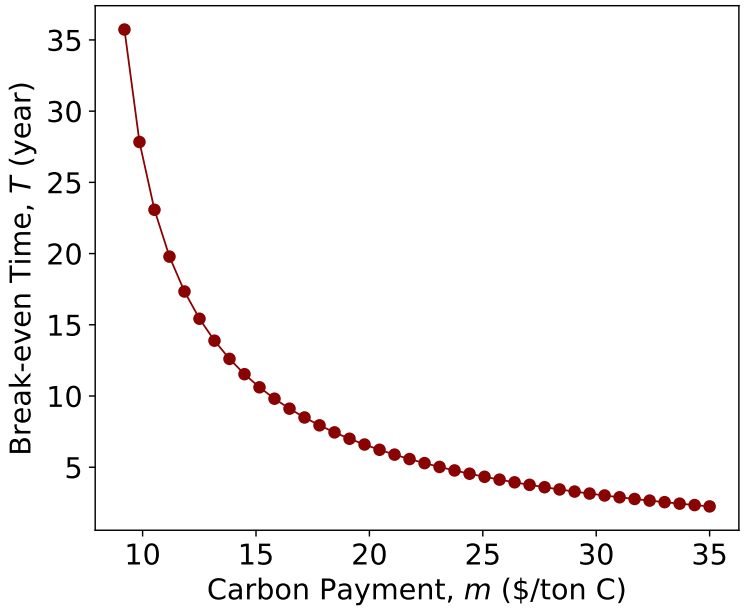


Figure 4: Break-even time, T as a function of the carbon payment, m for the hydrology group A.

The above analysis assumes a constant carbon payment rate. This leads to long payback periods, reducing the attractiveness of adoption. A natural alternative is a time-varying

payment scheme that front-loads payments. Let $m(t)$ denote the payment at time t, with $\lim_{t\to\infty} m(t) = m_\infty$. For adoption to remain optimal at the saturation SOC level C^*, m_∞ must satisfy:

$$m_\infty \geq \frac{\Delta y \times P - \Delta\text{Cost}}{C^* - C_0} \tag{20}$$

Table 2 lists the m_∞ values. The minimum payment schedule satisfies:

$$\sum_{t=0}^{\infty} \beta^t \left[\mathbb{E}(y_{NT}) \times P + (C^* - C_0)(1 - e^{-s(t+1)})m(t) - \text{Cost}_{NT}\right] = \sum_{t=0}^{\infty} \beta^t \left[\mathbb{E}(y_{CT}) \times P - \text{Cost}_{CT}\right] \tag{21}$$

As an example of a front-loaded carbon payment scheme, one can consider the form of $m(t) = ae^{-bt} + m_\infty$. Substituting into (21) yields:

$$\frac{a}{1 - \beta e^{-b}} - \frac{ae^{-s}}{1 - \beta e^{-(s+b)}} = \frac{\Delta y \times P - \Delta\text{Cost}}{(1-\beta)(C^* - C_0)} - \frac{m_\infty}{1-\beta} + \frac{m_\infty e^{-s}}{1 - \beta e^{-s}} \tag{22}$$

The break-even time T under this time-varying payment scheme is obtained by solving:

$$\begin{aligned} &\frac{(\Delta\text{y} \times P - \Delta\text{Cost})(1 - \beta^{T+1})}{1-\beta} \\ &\quad -(C^* - C_0)\left[a\frac{1 - (\beta e^{-b})^{T+1}}{1 - \beta e^{-b}} - ae^{-s}\frac{1 - (\beta e^{-(s+b)})^{T+1}}{1 - \beta e^{-(s+b)}}\right. \\ &\quad \left. + m_\infty \frac{1 - \beta^{T+1}}{1-\beta} - m_\infty e^{-s}\frac{1 - (\beta e^{-s})^{T+1}}{1 - \beta e^{-s}}\right] = 0 \end{aligned} \tag{23}$$

The parameter b governs the front-loading of payments, with higher b implying larger initial payments and faster decline over time. Figure 5 illustrates payment paths for different values of b, with a determined from (22). Break-even times (orange markers) decrease with b.

Front-loaded payments, however, introduce a defection incentive: farmers may revert to conventional tillage once payments decline. To prevent this, payments must remain above the level that makes a one-period deviation unprofitable. Define this threshold as $m_{single-period}(t) = \Delta y \times P/[(C^* - C_o)(1 - e^{-st})]$. A payment schedule is incentive-compatible

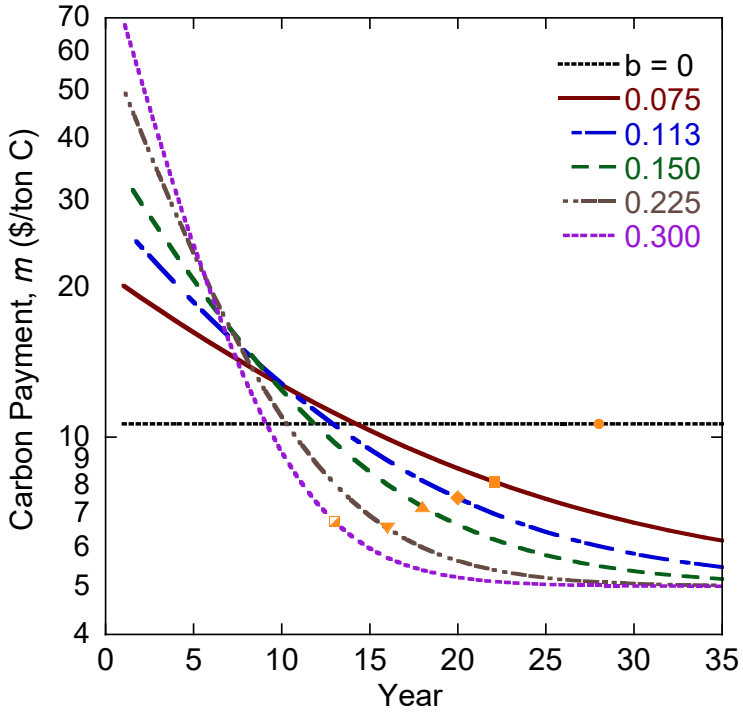


Figure 5: Carbon payment of the form $m(t) = ae^{-bt} + m_\infty$ for different values of b for the representative field of hydrology group A. The orange markers represent the break-even time for each $m(t)$.

if $m(t)$ intersects $m_{single-period}(t)$ at most once. Figure 6 compares these profiles. For sufficiently large b (e.g. $b \geq 0.113$), the two curves intersect twice, implying potential defection in later periods.

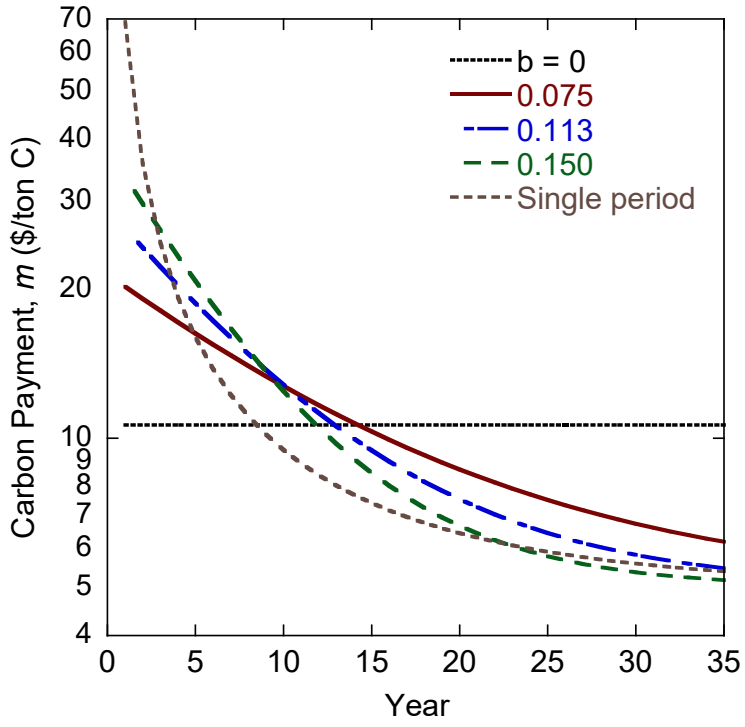


Figure 6: Comparison of the payment schedule $m(t)$ and the single-period deviation threshold, $m_{single-period}(t)$ for different values of b. Multiple intersections indicate potential defection.

5 Conclusion

This paper develops a theoretical framework to evaluate alternative carbon payment policies for incentivizing soil organic carbon (SOC) sequestration through conservation tillage. By explicitly modeling the intertemporal trade-offs faced by farmers, the analysis highlights how policy design influences both adoption decisions and the efficiency of carbon payments.

The results show that policies based on total carbon stock (Policies 1 and 2) are more effective and economically consistent than those based on incremental changes (Policy 3) or flat payments (Policy 4). In particular, Policy 2, where carbon payments are conditional on

the adoption of conservation practices, emerges as the most attractive design. It delivers lower required payment levels, and avoids rewarding for released carbon. In contrast, Policy 3 generates perverse incentives and increasingly high payment requirements as SOC approaches saturation, making it impractical despite seemingly low initial payment rates. Policy 4, while simple, requires substantially higher payments because it does not account for carbon dynamics.

Across all policies, the required carbon payment rate varies significantly with biophysical conditions such as initial SOC levels and sequestration rates. Faster sequestration and higher initial carbon stocks reduce the payments needed to induce adoption under stock-based policies. Importantly, the lifetime discounted carbon payments under the preferred policies remain below prevailing estimates of the social cost of carbon, suggesting that these policies are welfare-improving.

A key limitation of constant payment schemes is the long break-even period faced by farmers, which may discourage adoption despite long-run profitability. The analysis shows that front-loaded payment schemes can substantially shorten payback periods and improve adoption incentives. However, such schemes must be carefully designed to remain incentive-compatible over time. Excessive front-loading can induce defection, as farmers may revert to conventional practices once payments decline. Ensuring that payment paths do not fall below the threshold required to prevent one-period deviations is therefore critical.

Overall, the findings underscore the importance of aligning carbon payment structures with the dynamic nature of soil carbon accumulation. Policies that reward carbon stocks conditional on conservation practices, combined with appropriately calibrated front-loaded payments, can achieve cost-effective and sustained carbon sequestration. Future work could extend this framework to heterogeneous farmers, uncertainty in carbon measurement, and market-based policy instruments to further refine the design of agricultural carbon programs.

6 Declaration of competing interest

The author declares no potential conflict of interest

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