CHAPTER 3

Potential for CO_2 Removal and Storage in US Cropland Soils

SUMMARY

Increasing organic carbon stocks in cropland soils is a prime target for near-term, soil-based CO_2 removal because croplands are already heavily managed and cover a large expanse of the United States. In addition, practices that enhance organic carbon in croplands are established, low-energy, and immediately deployable with many co-benefits. Our analysis examined the coupled economic and technical potential for cropland soil-based CO_2 removal at a county-level across the contiguous United States. We analyzed spatially explicit responses of cropland organic carbon and greenhouse gas (GHG) emissions to a suite of management practices (cover crops, perennial field borders, and perennial carbon crops), from 2025 through the year 2050 using the DayCent and SALUS biogeochemical models. We used soil organic carbon (SOC) changes and GHG emissions as inputs in an economic land-use decision model across a range of incentives for climate-change mitigation to explore sensitivity to a future carbon price. We deconflicted and prioritized land use to avoid double-counting and summed additive practices to quantify local, regional, and national potential for soil-based CO_2 removal. Here, we consider key uncertainties such as durability and measurability, discuss environmental and social co-benefits of each practice, and note important equity considerations with the financial valuation of soil-based CO_2 removal.

Key Findings

- Soil-based CO_2 removal and storage is one of many benefits of cropland-management practices designed to reduce soil erosion, reduce nitrous oxide (N_2O) emissions, improve water retention, and provide bird and other wildlife habitat.
- Cropland-management practices, including cover crops (unharvested vegetation planted on otherwise fallow fields), perennial field borders (trees or native grasses planted along edges of a cropped field), and perennial carbon crops (planting native perennial grasses to harvest and sell to a carbon biomass market) (**Figure 3-1**) remove atmospheric CO_2 through increased photosynthesis and subsequent storage of a portion of newly photosynthesized carbon in roots and SOC.
- Soil-based CO_2 storage in croplands is a low-energy, immediately deployable strategy that could economically remove a cumulative 130 million tonnes of CO_2 between 2025 and 2050 if farmers were offered a moderate price of $40/tonne CO_2 equivalent (CO_2e) (**Table 3-1**).

CHAPTER SCOPE

This chapter assesses potential soil-based CO_2 removal through managing croplands to increase annual photosynthesis. We evaluated economically viable potential CO_2 removal across a range of carbon prices. Topics covered include:

- Constraints on cropland soil-based CO_2 removal
- Cover crops
- Perennial field borders
- Perennial carbon crops
- Uncertain potential under no-till management
- Effect of future climate projections on CO_2-removal potential
- Soil-based CO_2-removal practices through socioeconomic and environmental perspectives

- Hotspots of opportunity for cropland soil-based CO_2 removal are the Lower Great Lakes, Southeast, and Lower Mississippi River regions, with cover cropping composing more than 75% of cumulative profitable CO_2 removal between 2025 and 2050.
- Durability of soil-based CO_2 storage is highly uncertain, and cropland soil management should be considered a near-term component to a national strategy that eventually transitions the equivalent CO_2 storage to highly durable geologic storage.
- To avoid exacerbating existing extreme inequalities in land ownership, an equitable cropland soil-based CO_2-removal incentive program must carefully consider to whom funds will flow.

Table 3-1. *Summary of soil-based CO_2-removal and climate-benefit outcomes from three cropland-management practices across a range of carbon prices.*

Practice	Carbon Price	Bio-mass Price	Economically Viable Land Area	Mean Annual Soil-Based CO_2-Removal Rate	Soil-Based Climate Benefit *(incl. avoided emissions)*	Cumulative Soil-Based CO_2 Removal 2025–2050	Cumulative Soil-Based Climate Benefit *(incl. avoided emissions) 2025–2050*
	\$/tonne CO_2e	*\$/dry tonne*	*Million hectares (ha)*	*Million tonnes CO_2/year*	*Million tonnes CO_2/year*	*Million tonnes CO_2*	*Million tonnes CO_2e*
Cover Crop	\$0		0.6	0.5	0.6	12.8	14.3
	\$40		2.8	4.1	4.2	101.3	105.0
	\$100		20.8	33.1	34.5	827.7	862.4
Perennial Field Border	\$0		0.0	0.0	0.0	0.0	0.0
	\$40		0.3	0.4	0.9	10.4	22.3
	\$100		0.3	0.4	0.9	10.6	23.1
Carbon Crop – Zero Cropland-Area Change	\$0	\$73	1.9	3.8	1.2	16.3	50.6
	\$40	\$73	2.1	4.4	1.3	17.7	59.1
	\$100	\$183	1.8	3.8	1.1	15.3	50.7
Sum of Additive Practices	\$0		2.4	4.3	1.8	29.1	64.9
	\$40		5.2	8.9	6.4	129.5	186.4
	\$100		22.9	37.3	36.6	853.5	936.2

**** For carbon-crop assessments, costs are more than offset by the income from selling biomass, not included here.*

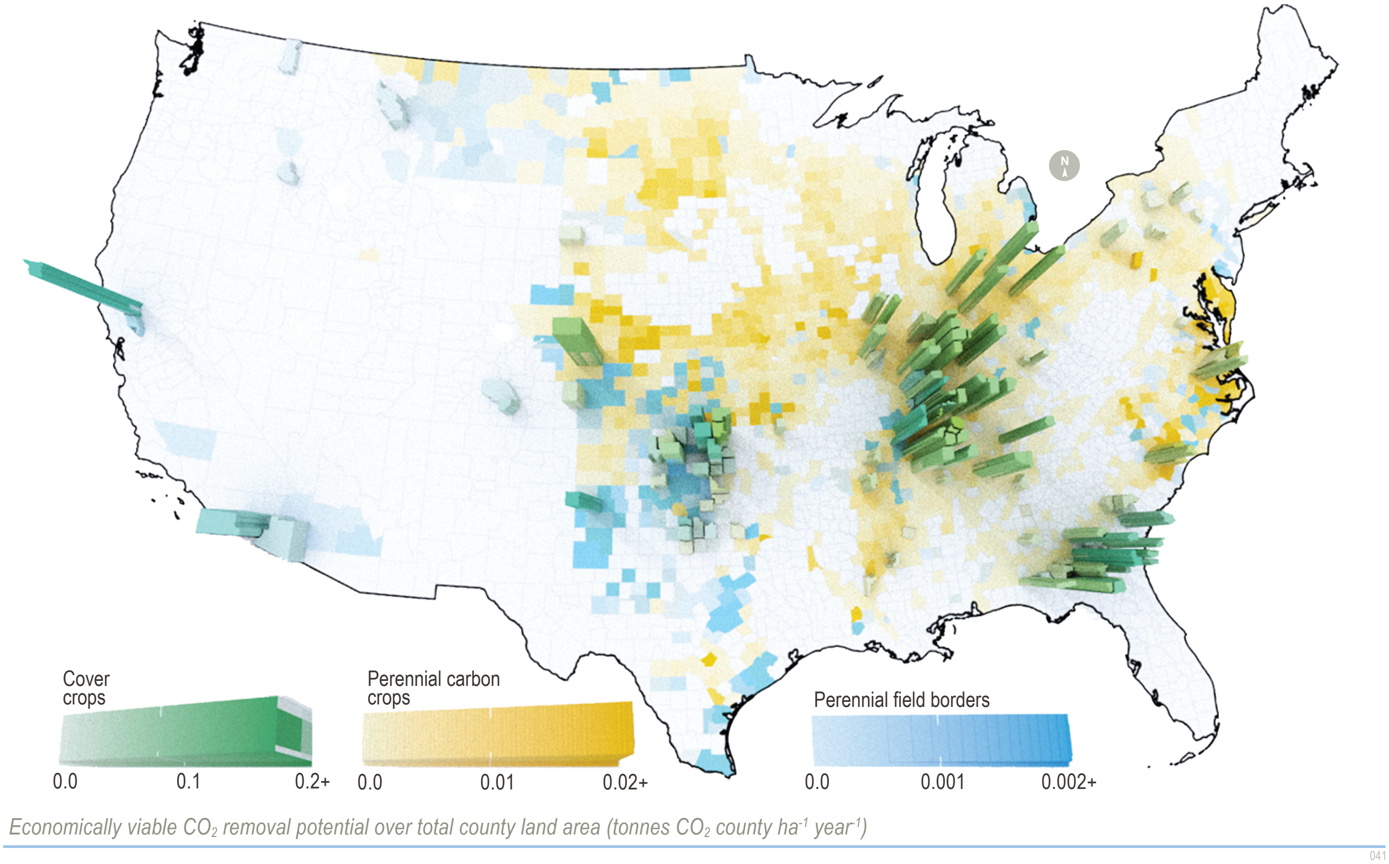


Figure 3-1. *County-level potentials for soil-based CO_2 removal from planting perennial carbon crops (yellow), cover crops (green), and perennial field borders (blue) are boldest in areas of highest potential within each practice. The height of the county is scaled to the total economically viable CO_2-removal potential within the county. Cover crops (green) are mapped on a scale one order of magnitude greater than perennial carbon crops (yellow), which in turn are mapped on a scale one order of magnitude greater than perennial field borders (blue). Land area under each practice shown here is for a $40/tonne CO_2e climate benefit price.*

Introduction

Why Agricultural Soils?

Soils are a large natural carbon reservoir: more carbon is stored in the top 30 cm of soil globally than in the entire atmosphere [1]. Management of soil in ecosystems, especially agricultural systems, can either enhance or degrade this natural carbon reservoir. Since the beginning of cultivation, agricultural soils have lost the equivalent of more than 450 billion tonnes of CO_2 [2], but land managers have also been employing soil-carbon-building practices for at least as long (e.g., field buffers and agroforestry [3]). The active management of agricultural land presents an opportunity for rapid deployment of climate-smart practices, and the vast extent of cropland (more than 100 million hectares (ha) in the United States [4]) amplifies the benefit of even incremental soil-carbon gains. Most agricultural practices that increase soil carbon are primarily implemented to reduce erosion [5], improve water and nitrogen retention [6], or provide habitats for native species [7], with CO_2 removal being a serendipitous co-benefit. Current public programs, such as the US Department of Agriculture's (USDA) Environmental Quality Incentives Program (EQIP), that incentivize soil-carbon-building practices evolved from the Soil Conservation Act of 1935 as a response to Dust Bowl erosion in the 1930s [8]. Expansion of these programs could improve the sustainability and resilience of US agriculture while also yielding meaningful climate benefits.

Agricultural soils gain organic carbon when inputs of carbon fixed by plants to the soil outpace carbon losses from microbial respiration and erosion (**Figure 3-2**). Cropland practices that increase the in-field annual duration of vegetation cover result in CO_2 removal that is relatively straightforward to demonstrate and does not rely on imports of exogenous biomass (e.g., manure, biochar, or compost; see **Box 3-1**). We chose practices with published field-scale measurements in climates and soil-types throughout the United States to maximize the validity of model calibration.

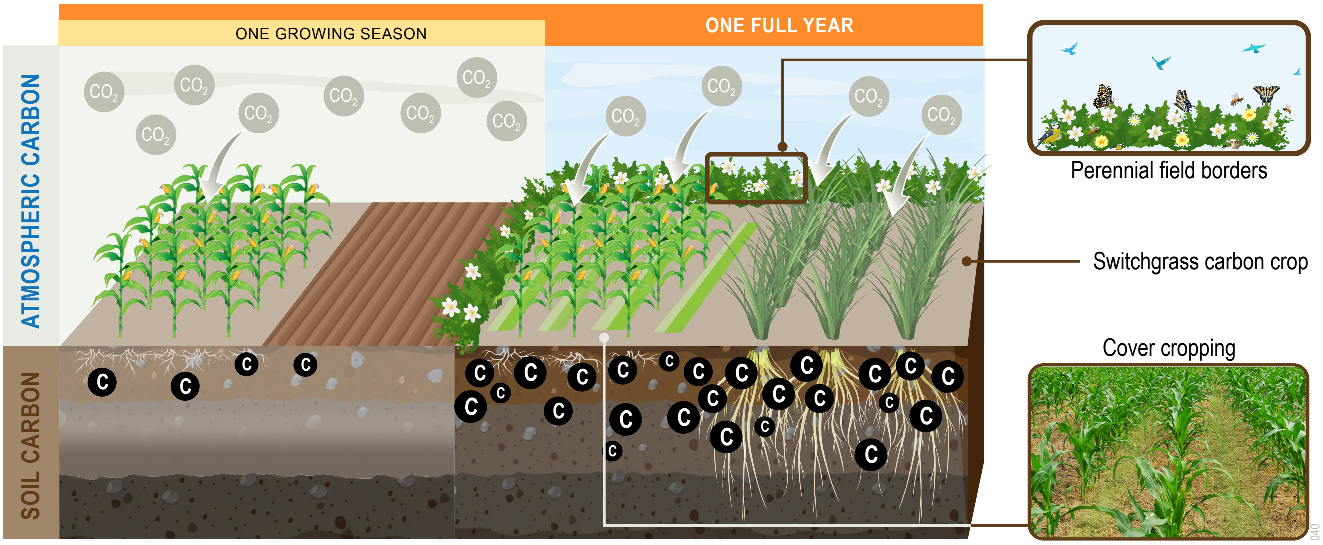


Figure 3-2. *Cropland managers can contribute to CO_2-removal efforts by switching from conventional annual commodity-crop rotations with fallow periods to adopting year-long vegetation via cover crops, perennial carbon crops (such as switchgrass), or perennial field borders. Adopting these practices increase transfer of atmospheric CO_2 to soil-carbon storage.*

In this analysis, we focus on three promising and scalable cropland-management practices that increase soil carbon via in-field enhancement of vegetation cover: cover cropping, perennial field borders, and conversion of annual bioenergy crops to perennial carbon crops.

- **Cover cropping** is planting a non-cash crop, often cereal rye [9] or a mixture of grasses and forbs, during a time of year when a field would otherwise be left fallow. Planting cover crops increases SOC by extending the period of vegetative production and below-ground root inputs to the soil [10, 11]. Cover crops are designed to enhance yields by improving soil fertility but can also reduce early-season soil moisture; planting a cover crop can increase or decrease cash-crop yields, depending on resource competition and timing of implementation and termination, but does not directly compete for land with cash-crop production. Since cover cropping is not yet widely adopted across the United States [12] (**Appendix 3, Figure A3-1**), the opportunity for expanding this practice is high.
- **Perennial field borders** involve planting perennial trees, grass, or forb species along the edges of a cash-crop field. Perennial field borders can serve as windbreaks for erosion control [6], wildlife habitat [7], and a filter for water runoff [13]. They also provide biodiversity benefits such as biocontrol and pollination [14]. Perennial field borders increase soil carbon by increasing year-round plant cover. These practices apply only to a small fraction of agricultural land area but are likely to have high local potential.
- **Perennial carbon crops** include biomass crops, such as switchgrass, poplar, and willow, planted instead of annual cash crops (e.g., corn, wheat, cotton, soybean, oats, barley, sorghum grain, and hay). Perennial carbon crops increase soil carbon by growing denser and deeper root systems and eliminating fallow periods. We assessed the land constraints for this practice using two approaches. First, we constrained carbon-crop planting to achieve zero competition for food-producing cropland (subsequently termed "zero-cropland-change"). Specifically, the zero-cropland-change approach outlines a potential future in which electric vehicles (EVs) increase substantially by 2050, which could reduce ethanol consumption and demand. The resulting reduction in corn-planted cropland could then be compensated by planting the native perennial carbon crop switchgrass with low-nitrogen fertilizer inputs. Second, we considered an unconstrained land-use approach, including all non-arid cropland (termed "maximum-biomass-potential"), in which land use is based purely on market competition and biomass price. Both assessment approaches are described in detail in **Section 2** of **Chapter 6 – BiCRS** (Biomass Carbon Removal and Storage)." Notably, both approaches consider marginal and abandoned cropland, rangeland, and pasture as viable for carbon crops, but we do not include a soil-carbon assessment for perennial carbon crops planted on these lands as they likely already host perennial vegetation [15-18].

Cropland-conservation practices are beneficial for reasons beyond increasing carbon and may in some cases have a greater climate benefit beyond net CO_2 removal. Attributing CO_2 removal to a management practice requires the net movement of atmospheric carbon into soil as a result of that practice. We account for soil-based CO_2 removal as

BOX 3-1

Roads not Taken

Several types of cropland soil management that we did not include in our analyses may be promising soil-based CO_2-removal strategies, but they require nuanced accounting. For instance, shifting cropland management from full or reduced tillage to no tillage has the potential to contribute to soil-based CO_2 removal; we discuss the potential for this practice in the subsection **Uncertain Potential for No-Till** below.

Organic amendments, such as **compost, manure**, and **biochar**, increase soil carbon content on agricultural land [15, 16]. We did not consider these practices due to as-yet unresolved uncertainties for monitoring, reporting, and verification (MRV). In the case of organic amendments, CO_2-removal accounting must include an assessment of the full life-cycle and alternative fates of the organic waste product [17], and must partition the SOC due to increased on-farm productivity from the lateral movement of carbon from the waste stream to the farm [22].

Enhanced rock weathering is a CO_2-removal technology that accelerates the natural process of mineral weathering by adding crushed rock (typically basalt) to soils. The chemical dissolution of rock dust releases base cations (such as Mg_2+, Ca_2+, and Na_2+) that make soil water more alkaline. This increase in alkalinity ultimately increases the amount of dissolved inorganic carbon stored in groundwater and the oceans, removing CO_2 from the atmosphere [23]. Depending on soil conditions, some inorganic carbon may remain stored in soil or subsurface geologic deposits as solid carbonates. Enhanced weathering on croplands has high theoretical capacity for CO_2 removal, scalability, and potential agronomic co-benefits [18, 24]. However, to date, few published field studies have verified modeled estimates in the field. A long-term field trial in the Corn Belt of the Midwestern United States (released as a preprint at the time this report was written) recently estimated the CO_2 removal potential of enhanced rock weathering to be approximately 3.9 tonnes CO_2/ha per year over four years and also found that rock dust decreased soil acidification, lowered emissions of soil N_2O, and increased soybean and corn yields by 12%–16% [25].

Enhanced rock weathering was not considered in this report due to the paucity of field studies published at the time this report was written. Due to the spatial and temporal lags between the site of rock dust application (i.e., surface soil) and the ultimate sites of sequestration (i.e., soil subsurface or the ocean), substantial uncertainty remains in how to accurately measure and model CO_2 removal from enhanced weathering [26]. The lack of adequate field measurements in different crop types, soil types, and climates across the United States meant that it was not yet possible to model and validate the CO_2 removal potential of enhanced rock weathering at a county-level as required for this report. However, the potential for CO_2 removal via enhanced rock weathering may be significant and should be evaluated in future analyses as more published data become available.

any increase in the stock of soil carbon since the time of practice implementation, less any increase that occurs under baseline counterfactual management and penalized for any increases in soil-N_2O emissions (**Figure 3-3**). If soil carbon is declining under the baseline counterfactual, avoided soil-carbon loss is not included in the accounting for CO_2 removal [19, 20]. We also account for the comprehensive climate benefit as including both CO_2 removal and avoided GHG emissions, including both N_2O avoided due to reduced fertilizer usage and avoided soil-carbon loss as CO_2. Therefore, the climate benefit is any increase in soil carbon under a given management practice relative to the soil carbon under a baseline counterfactual management, regardless of whether the baseline is increasing or decreasing, plus any N_2O emissions avoided from adopting the practice. We report both the net CO_2 removal and climate benefit of each practice. To avoid perverse outcomes of ignoring N_2O emissions or partial mitigation of SOC losses [20, 21], we assume that the carbon price reflects the total climate benefit.

Guiding Principles

In this analysis we prioritized cropland soil-based CO_2 removal practices that 1) Remove CO_2 from the atmosphere directly on-field (i.e. via increased photosynthesis and allocation of root biomass), and 2) have been demonstrated at the field level in climates and soil types across the United States. Practices that were excluded from the analysis may also contribute significantly to soil-based CO_2 removal, some of which are discussed in Box 3-1. We prioritized

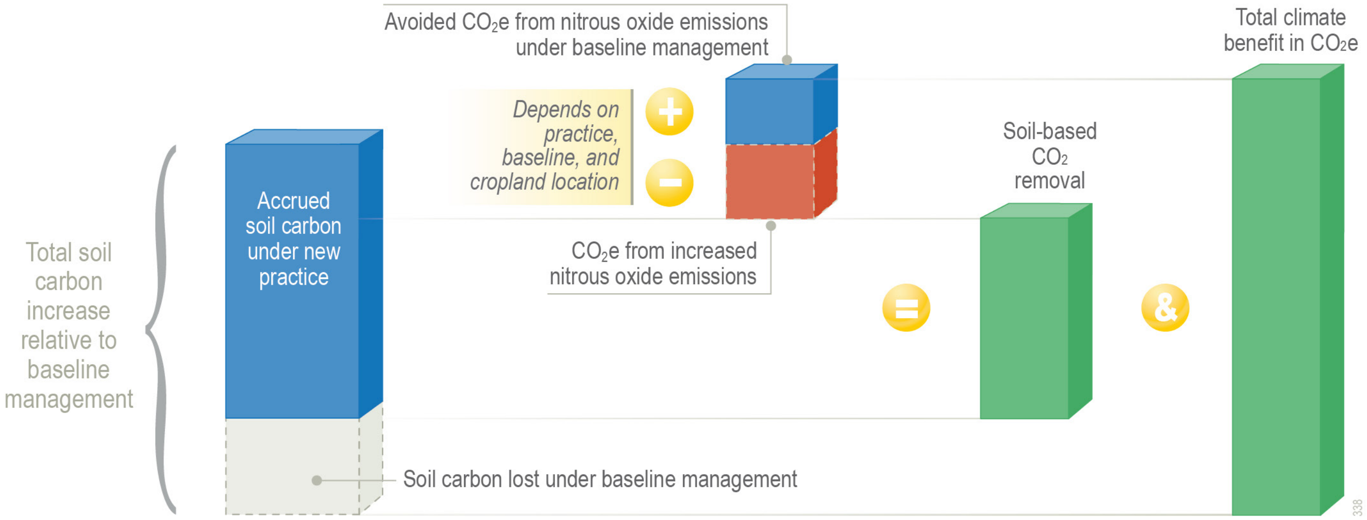


Figure 3-3. *For each cropland-location sampling site, we calculate soil-based CO_2 removal as the absolute amount of soil CO_2 accrued under a new practice, subtracting the CO_2 equivalent (CO_2e) of any increased nitrous oxide (N_2O) emissions due to the new practice. We calculate "total climate benefit" as the total soil-carbon increase relative to baseline management (including avoided soil-carbon loss), plus any avoided N_2O emissions.*

implementation of practices to avoid double-counting of soil carbon accrual, in the order of perennial carbon crops, cover crops, and field borders. We excluded potential CO_2 removal for any cropland already implementing each practice (to adhere to the principle of additionality for each CO_2 price simulated.)

Our economic evaluation awarded a carbon price to the full climate benefit: additional soil-based carbon dioxide removal as well as avoided soil carbon losses and avoided N_2O emissions. We valued decarbonization of the agricultural system as well as CO_2 removal, as both are simultaneously required to reach targets for climate-change mitigation. We evaluated the full climate benefit for a range of equivalent CO_2 prices from $0 to $100 per tonne and separately report the achievable CO_2 removal (the absolute increase in SOC storage after subtracting any increase in N_2O emissions) in alignment with the main scope of this report.

All CO_2-removal strategies, especially soil-based CO_2 removal, must carefully consider additionality, leakage, and durability. Strategies identified in this report are intended to avoid violating additionality assumptions, which means that the CO_2 removal would not occur in the future without a financial or policy incentive [27, 28]. For example, in abandoned croplands where volunteer vegetation already grows year-round, replanting with a different perennial species (i.e., a carbon crop) would not necessarily provide additional photosynthetic inputs beyond what would have occurred if left abandoned. Additionality also depends on the direction of change compared to what was occurring prior to the practice—if the baseline case is losing carbon, then the reduction of that loss due to management is avoided emissions rather than additional CO_2 removal. On the other hand, if the baseline case is gaining carbon, then the additional CO_2 removal is the positive change from the case prior to the start of management minus the positive change in the baseline case. Finally, additionality depends on human decision making: "baseline" management is a function of decisions by landowners and is not necessarily static. Whenever possible, we limited our analysis to include only additional CO_2 removal by accounting for present-day land use when modeling baseline management and determining land availability for improved management (e.g., land currently cover-cropped was not available for future expansion of cover cropping).

Practices in this report are also intended to avoid leakage, whereby indirect land-use change occurs due to the lost supply of a commodity crop within the United States. Increases in commodity prices may lead to conversion of land to cropland and consequent carbon loss elsewhere in the world [29]. While our reported top-line potential for carbon crops from the zero-cropland-change assessment minimizes leakage, we also explored an alternative carbon-crop approach—the maximum-biomass-production assessment (see **Box 3-2**)—that does result in commodity-price increases.

Finally, the efficacy of CO_2-removal strategies for mitigating climate-change increases with greater durability, the time over which atmospheric CO_2 can continue to be removed due to a practice, and the time over which that carbon will remain stored. Agricultural soil-based CO_2-removal strategies are not constant over time and generally remove less and

BOX 3-2

Biodiversity in carbon crops

A planter's choice of which perennial carbon crop to plant will depend on their preferred balance of tradeoffs. Switchgrass (*Panicum virgatum*) is native to North America, and has high yield and soil organic carbon benefits when planted as a monoculture carbon crop. Planting switchgrass within a polyculture of other native prairie species, especially forbs, may slightly decrease yield and soil-based CO_2 removal in some places relative to a switchgrass monoculture (see **Table 3-2**), but will increase the both the diversity and abundance of both flowers and pollinators [59]. Both monoculture and polyculture perennial native carbon crops will have improved soil organic carbon and multifunctional ecosystem outcomes relative to annual crop rotations [60]. Taking into account both climate change mitigation goals and biodiversity and resilience goals, native prairie perennial polycultures may improve overall ecosystem outcomes [61] even more than a native switchgrass monoculture.

Figure 3-5. *Annual per-area CO_2 removal rates for planting carbon crops instead of corn-soy rotation for each county (thin lines), and national mean (bold lines)*

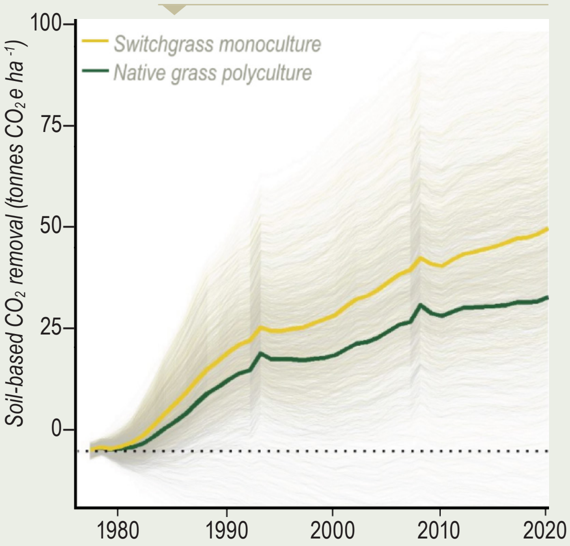


Table 3-2. *Comparison of polyculture and monoculture carbon crops.*

Carbon Crop	Mean Soil-Based CO_2 Removal 2025—2050	Mean Soil-Based Climate Benefit (incl. Avoided Emissions) 2025—2050	Biodiversity Benefit Relative to Annual Cropping System
	Tonnes CO_2 ha^{1}	Tonnes CO_2 ha^{1}	
Switchgrass monoculture	39.7	46.3	Medium
Prairie grass polyculture	34.6	34.6	High

less CO_2 over time as soils equilibrate to the new practice (see **Figure 3-4**). Beyond the durability of the CO_2-removal rate, the maintenance of carbon that is already stored in soil depends in part on maintenance of the new practice, which in turn depends on management and land-use decisions in both the near- and long-term. The Dust Bowl in the South-Central United States in the 1930s is a prime illustration of the sensitivity of soils to management, where a few decades of unsustainable land-use practices led to an enormous loss of soil carbon and productive cropland [30]. While a portion of soil carbon has been shown to remain in soils for millennia [31], the dependence of soil-carbon stability on land-use decisions means that there is no plausible way to guarantee the durability of soil carbon except for policy or financial incentives for maintaining a practice. Even in the worst-case and unlikely scenario where soil-based CO_2 removal is completely reversed to the atmosphere once a management practice ends, near-term scaling of fully temporary CO_2 removal can still reduce peak climate warming [32, 33]. Soil-carbon storage could thus contribute to the urgent near-term need for CO_2 removal by acting as a bridge solution (with continued investment for maintaining stored soil carbon) until facilities are developed to widely implement highly durable geologic storage.

Economic incentives for farmers are one lever to increase implementation of soil-based CO_2-removal practices. The decision to implement or maintain a management practice falls upon each of the >2 million private agricultural producers in the United States [12], whose decisions could be influenced by policy; social factors including values, perceptions, and community culture; and economic incentives. Economic incentives to reduce erosion and waterway pollution already exist in local, state, and national agencies, including the USDA EQIP and Conservation Reserve Program (CRP) [34, 35]. These public incentives effectively pay farmers to implement a soil-

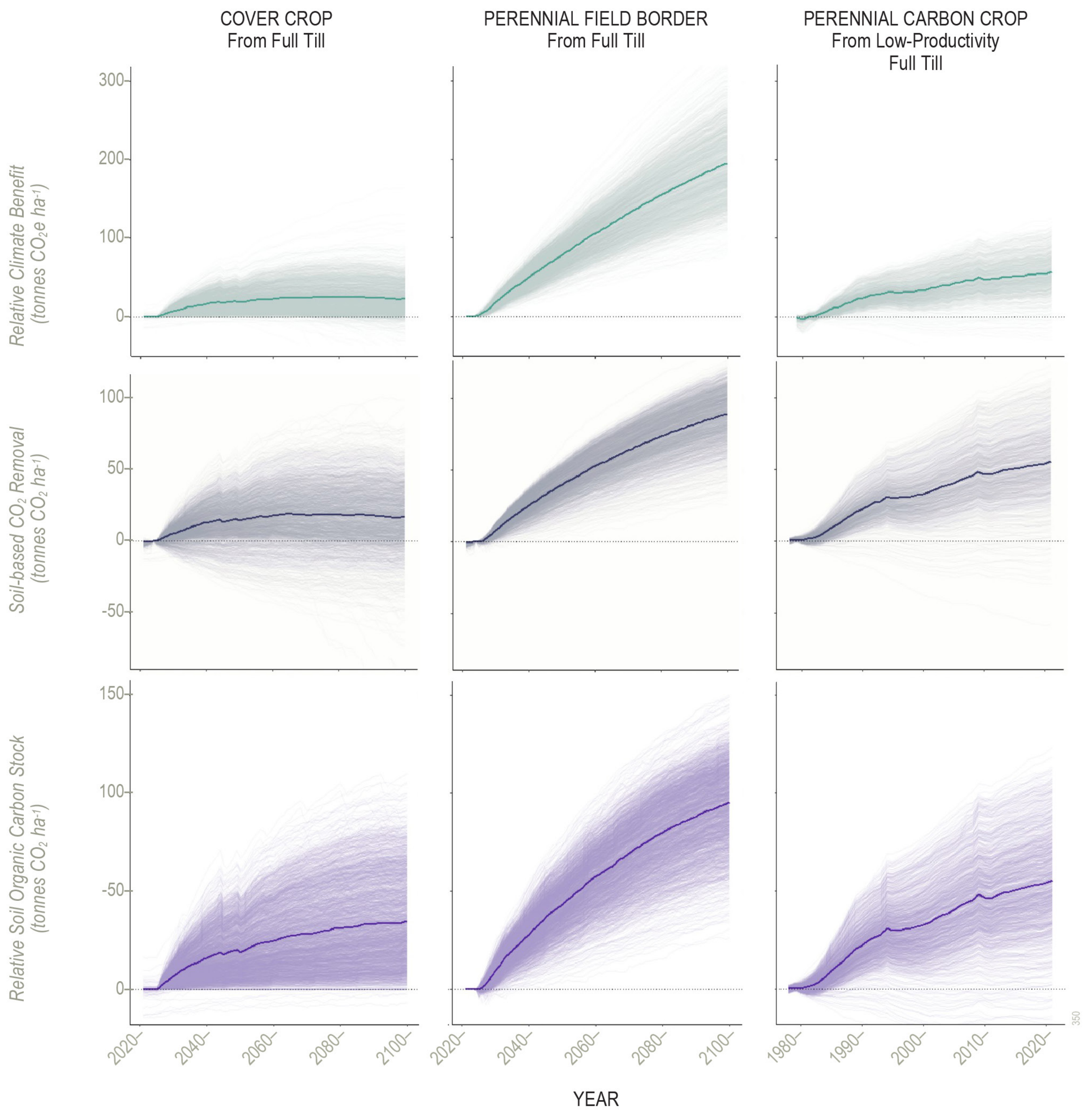


Figure 3-4. *Biogeochemical trajectories of total climate benefit (top), soil-based CO_2 removal (middle), and SOC stocks (bottom) over time relative to a full-till commodity-crop baseline for the top 0–30 cm of soil for implementing cover crops and field borders and for the top 0–40 cm of soil for perennial carbon crops. SOC stocks do not account for differences in N_2O emissions or changing baseline SOC; climate benefit accounts for SOC stocks and differences in N_2O; while CO_2 removal accounts for changes in soil-carbon baseline, as well as a penalty for any increased N_2O. Cover crops and perennial field borders were simulated across county-representative commodity cropland using the DayCent biogeochemical model [35, 36] with future climate inputs from the MIROC-ES2L Earth-system model. Perennial carbon crops were simulated on low-productivity stable cropland, forced by historical climate using SALUS [37, 38]. Trajectories for each county containing cropland in the United States are represented with individual lines. The overall mean trajectory across all counties is represented in bold.*

conservation practice for a contracted number of years (e.g., <10 years for the USDA EQIP [35]) without requiring precise measurement of improved soil-outcomes, such as increased soil-carbon stocks. This type of incentive is termed "payments for practice" [36]. More recently, private carbon markets have begun to incentivize soil-based CO_2-removal practices to sell as carbon offsets. In these contracts, farmers are paid the market-rate price per tonne of soil carbon (in CO_2e) increased relative to a baseline, as a proxy for the magnitude of CO_2 removed from the atmosphere and stored in soil. This type of incentive, termed "payment per tonne," requires precise measurement of the change in soil carbon over time [37] and, even with precise accounting, does not fully biophysically compensate for a CO_2e emission of the same magnitude [38].

Our analysis in this report goes beyond previous analyses of the technical potential of CO_2 removal and integrates spatially explicit soil-carbon and crop-yield responses together with management history and economic constraints on farmer behavior to provide a full supply model. To this end, we synthesized sub-county-level CO_2-removal potential using data on existing crop rotations, soil characteristics, climate, cost of management practices, and foregone or increased income from improved yield (**Figure 3-6**). The biogeochemical-process model DayCent simulated site-specific responses to planting perennial field borders, including cover crops in rotation, and conversion to continuous no-till, while the SALUS biogeochemical model simulated responses to planting biomass-harvested perennial carbon crops on low-productivity cropland (see detailed methods in **Appendix 3**). We assumed that farmers would only adopt a practice if it provided a net profit relative to business-as-usual management within the first ten years of adoption [39], and we constrained our analysis to the 114 million ha of United States cropland not under tree-crop or perennial specialty crops [12]. Although our modeling did not include orchards or specialty crops, these croplands also have positive potential for soil-based CO_2 removal and storage. We then analyzed the sensitivity of soil-based CO_2-removal potential to a range of carbon prices and to future climate-change projections. We report both average annual rates in the year 2050 and cumulative soil-based CO_2 removal between 2025 and 2050 because cropland soil-based CO_2-removal strategies are technically deployable immediately. We discuss regional potentials using regions defined in detail in **Chapter 10 – Regional Stories** [40-43].

Constraining Soil-Based CO_2 Removal

Soil-based CO_2-removal potential in croplands in the United States depends on both the local biogeochemical response to a new practice and the extent of land area over which the practice is implemented. In our analysis, the extent of cropland available for each practice ranged from all annual cropland not already cover-cropped for cover cropping, to annual cropland that could become available with future reduced demand for ethanol (in the case of perennial carbon crops), to the edges of annual cropland on an average of 1% of annual cropland (in the case of perennial field borders). We designed these land-use constraints to have minimal impact on food-crop production. We analyzed representative soil-carbon and GHG responses to implementation of cover cropping, field borders, and carbon crops in each county for each of the three existing baseline management regimes: full-till, reduced-till, and no-till management.

We considered the technical and economic potential for each of these three categories separately and allocated amenable land according to the existing management regime in each county [12], with no-till modified to continuous no-till using a factor defined by the ratio of major commodity-crop farms adopting no-till for four years or more [44]. We randomly sampled ~300 crop field locations per major land-resource area, which were regionally representative of diverse climate, parent material, and soil types in US croplands [45]. This amounted to 37,283 samples across the country in croplands growing corn, wheat, cotton, soybean, oats, barley, sorghum grain, hay, and peanuts. The DayCent process model simulated county-level biogeochemical responses to cover cropping, perennial field borders, and no-till using representative local historical land-management and Earth-system model future climate projections as inputs. The SALUS model simulated county and sub-county biogeochemical response of low-productivity cropland to switchgrass, a representative perennial carbon crop. SALUS was run using historical climate data and an assumed annual corn-soy crop rotation. We aggregated biogeochemical outputs from each

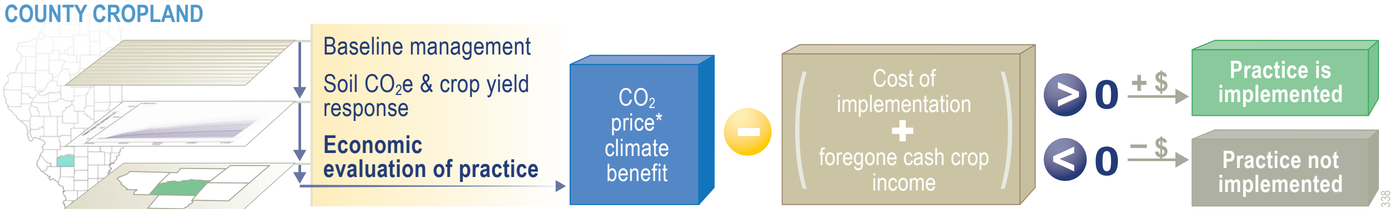


Figure 3-6. *Economic evaluation: A management practice was assumed to be continuously implemented for cropland in a given county when mean annual income outweighed mean annual costs between 2025 and 2050, which in turn depended on baseline management and the county-specific soil carbon and crop yield response to each practice.*

site for each model at the county level prior to economic evaluation.

Potential land area for each practice was constrained by economic models (Figure 3-6; see **Appendix 3** for details) and allocated wherever income from a carbon price outweighed the cost of implementation, including foregone income from any reduced commodity-crop yield. We chose practices that could be implemented such that they did not (or minimally in the case of field borders) interfere with land designated for commodity-crop production. To prioritize total decarbonization of the agricultural system, the economic models awarded income for any climate benefit above the baseline management, including both avoided emissions and true CO_2 removal. We report climate benefit in units of CO_2e, which also accounts for the climate-forcing effects of N_2O (which has 273 times the 100-year global warming potential of CO_2 [46]). We report true atmospheric CO_2 removal from time of practice implementation, less any positive N_2O emissions or positive baseline soil-carbon accrual, which in most cases is smaller in magnitude than the total climate benefit. We calculated the cost of the practice to the incentivizer (public or private) by subtracting the climate benefit for a practice at a price of $0/tonne from the climate benefit of the same practice at a price of $40/tonne to get only additional climate benefit, then multiplied by the $40/tonne carbon price to obtain cost of additional climate benefit.

Technical potential estimates for soil-based CO_2 removal from cropland management are 500%–700% higher [47, 48] than the spatially explicit economically constrained estimates that we present in this report. The primary differences imposed in this report are the stricter economic and land-use constraints, which reduce the fraction of amenable land area that will adopt the practices relative to other reports, even for the same practices [48].

Opportunities for Growth of Cropland Soil-Based CO_2 Removal

Cover Crops

Cover cropping has a relatively high potential contribution to national soil-based CO_2-removal efforts due mainly to the large extent of land area that can be cover-cropped without interfering with cash-crop production. Cover cropping extends the duration of plant growth in croplands over the year by planting vegetation during periods when fields would otherwise be fallowed. We simulated the planting of an unfertilized cereal-rye cover crop during otherwise fallow periods. We chose cereal rye because it is by far the most widely planted cover crop currently in the United States [9], though regionally or locally specific cover crops, including legume mixes, may have greater benefits in some climates and soil conditions [49]. Nation-wide, implementing cover crops increased overall annual net primary productivity by an average of ~5 tonnes of CO_2/ha, of which approximately one fourth of the newly photosynthesized carbon was transferred to and stored in soil and the rest was respired back to the atmosphere. Notably, most studies that show increased soil carbon as an effect of cover crops were not designed to fully quantify changes in SOC (e.g., to an adequate depth and with proper experimental controls) [50], leaving substantial uncertainty regarding the effect of cover crops on soil carbon.

Cover cropping increased soil CO_2 removal by an average of 0.9 tonnes of CO_2/ha per year across all land amenable without a carbon price, 1.5 tonnes of CO_2/ha per year with a $40 carbon price, and up to 1.6 tonnes CO_2/ha per year across all land amenable with an $80/tonne CO_2e carbon price. CO_2 removal-potential from cover cropping is sensitive to carbon prices and has higher potential as more productive land becomes economically amenable (**Figure 3-7 and 3-8**). The climate benefit of cover cropping on economically viable land is almost entirely CO_2 removal rather than avoided emissions, which explains why potential CO_2 removal from cover-crop implementation is highly sensitive to the value of the CO_2e price and is cheaper per tonne of CO_2 removed than other practices. In accounting for whether cover cropping is economically viable in a given county, we weighed the income from a CO_2 price against the cost of seed, the cost of planting and terminating the cover crop, and the cost or income due to any change in yield of the cash crop planted on either side of the cover-crop rotation. Importantly, this analysis assumes that farmers will only adopt the practice when profitable, and will maintain a cover crop rotation through 2050 (given continued CO_2 payments), as maintenance of a practice over time is key to the durability of soil-based CO_2 removal. However, a recent survey of farmers who cover crop in the United States suggested that managers are highly likely to continue cover cropping even after the end of payments subsidizing the practice [9], indicating that the true total cost of cumulative soil-based CO_2 removal from cover-cropping is less expensive than our reported results. Our economic evaluation also did not account for potential income from grazing or harvesting and selling the cover crop during termination, a practice followed by approximately 25% of current cover-crop practitioners [9].

In practice and in this analysis, including cover crops in a rotation depends on the rhythm of the commodity-crop rotation and would not occur every year in most places, particularly not in years when winter wheat is planted as a cash crop. Planting cover crops may also impact commodity-

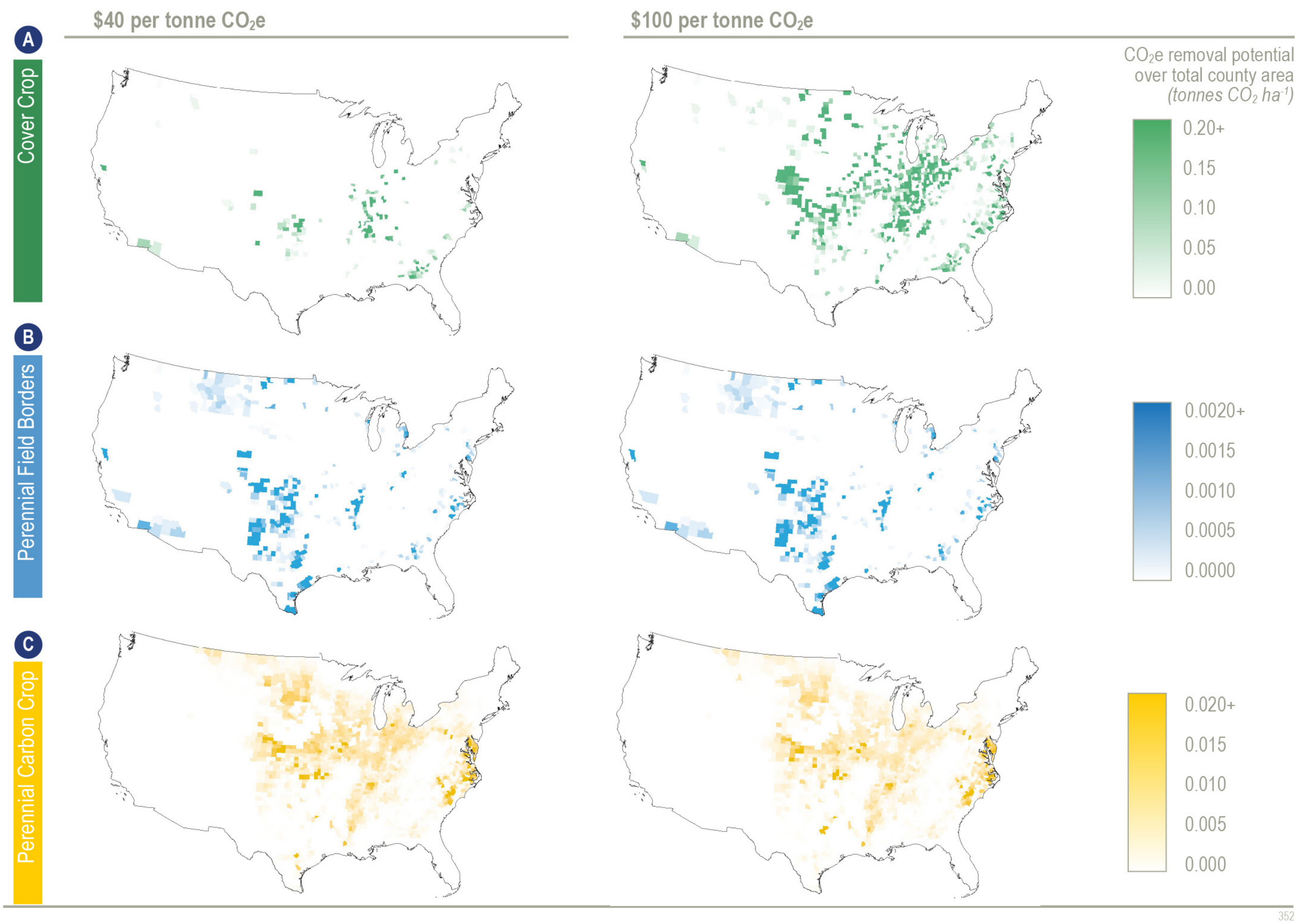


Figure 3-7. *Maps of economically viable potential for conservation agriculture practices. Counties with cropland area where implementing a new soil-management practice is economically viable are highlighted in color—(A) Cover crop, (B) Perennial field border, and (C) perennial carbon crop—in units of tonnes of CO_2 removed/ha of total county area. Colors are darkest where the annual rate of soil-based CO_2 removal due to that practice are high relative to the total land area of the county, indicating high potential for viable adoption in the county. The proportion of available cropland is limited for (B) field borders (blue) and (C) perennial carbon crops (yellow), as indicated by the reduced scale bars in panels B and C.*

crop yields positively or negatively (**Appendix 3, Figure A3-2**) and is more likely to have a negative impact on yields when timing of implementation and termination is not optimized [51]. This analysis assumes correctly timed implementation to avoid negative-yield effects and accounts for changes in yield through county soil and climate-specific modeling of both soil carbon and yield responses. Commodity-crop yield responses to cover cropping varied by county, with country-wide average yield decreasing by less than 1 tonne/ha per year under full-till cropping regimes and remaining the same as the baseline under no-till cropping regimes. (**Appendix 3, Figure A3-2**).

We simulated cover crops across both rainfed and irrigated croplands (though the cover crop itself was not irrigated), and the model captured any commodity-crop yield impacts. Cover-crop impacts on irrigated cropland may improve carbon stocks and water-holding capacity [52, 53] but may also decrease yields as cover crops compete for water [54]. Planting cover crops in croplands in the lower Mississippi, Lower Great Lakes, and Southeast regions has the highest potential soil-based CO_2 removal at lower carbon prices (**Figure 3-9**). For a climate-benefit price of $40/tonne CO_2e, soil-based CO_2-removal rates would be as high as 0.6 million tonnes of CO_2 per year in the Lower Great Lakes and Lower Mississippi regions and 0.5 million tonnes of CO_2 per year in the Southeast and West Texas regions. Per-area CO_2-removal rates are highest in the Lower Midwest (2.2 tonnes/ha per year) and Lower Great Lakes regions (2.0 tonnes/ha per year), but the land area that would be converted to cover crops in these regions is limited to less than 0.3 million ha. In contrast, the Southeast region has a wide land area economically amenable to cover cropping (more than 0.7 million ha) but a relatively low CO_2-removal rate (0.74 tonnes/ha per year). Cover crops also have moderate potential CO_2-removal rates

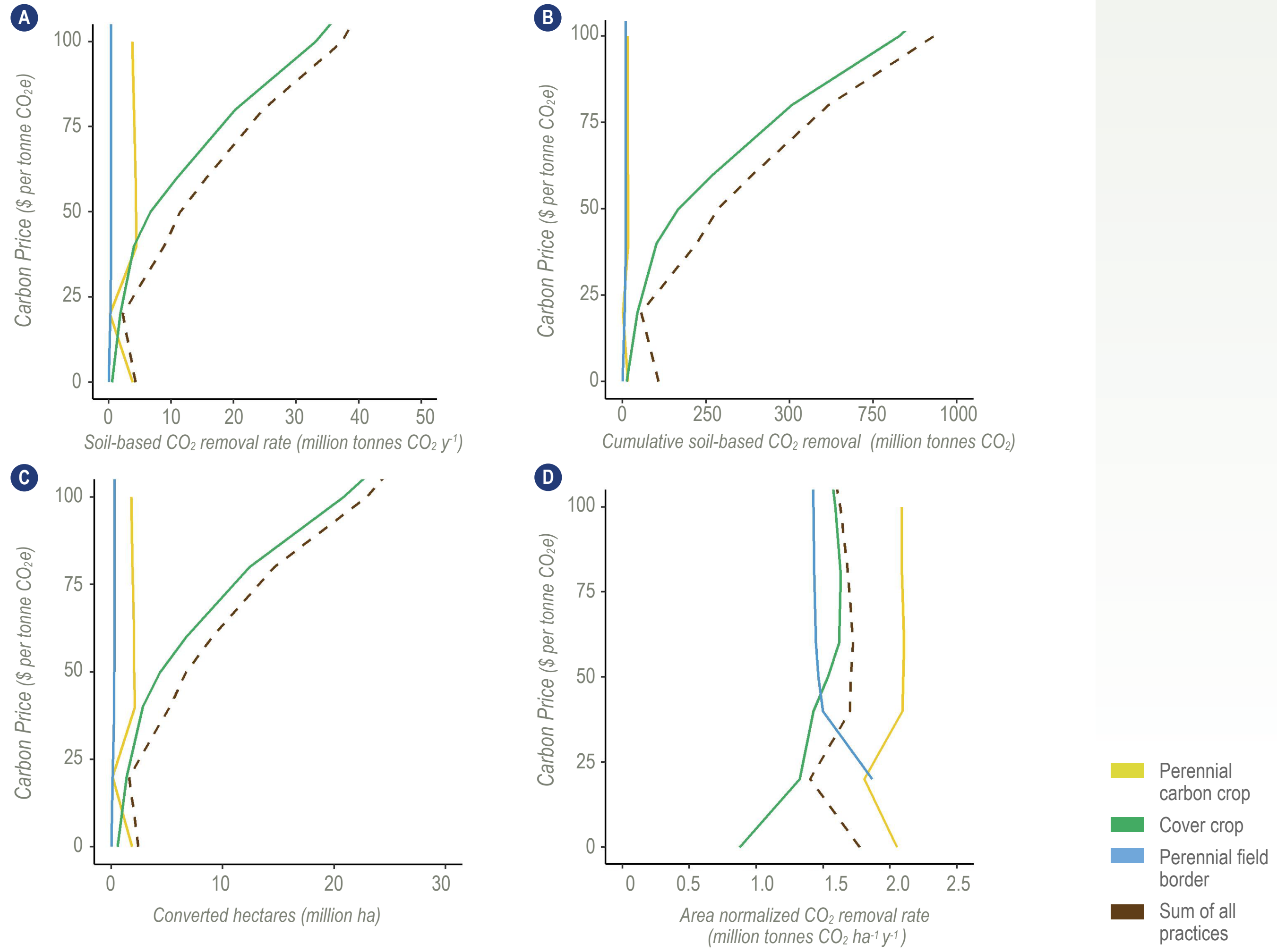


Figure 3-8. *Sensitivity of soil-based CO_2 removal to the price of climate-benefit carbon incentives (y-axis). The x-axis supply represents (A) cumulative economically viable CO_2 removal between 2025 and 2050, (B) projected annual rate of soil-based CO_2 removal in 2050, (C) the national cropland area economically amenable to each practice at each incentive value, and (D) mean annual soil-based CO_2-removal rate in each hectare where the practice was adopted.*

in a number of major commodity-crop growing counties the Lower Midwest, California Central Valley, Appalachia, and South-Central regions. Cover cropping on orchards, vineyards, and specialty crops is not represented in this report but will contribute additional opportunities for soil-based CO_2 removal in regions including the California Central Valley and Florida Peninsula.

Perennial Field Borders

Planting native perennial grasses or tree species along the borders of a cropland field helps reduce erosion, contain water runoff, provide habitat for pollinators, and contribute to soil-based CO_2 removal. Perennial grasses and trees remove atmospheric CO_2 by increasing the annual duration of photosynthetic plant biomass building, a portion of which can be stored in soil through decomposition and allocation of photosynthetically fixed carbon to belowground roots and root exudates. Perennial-switchgrass root systems are both denser and deeper than annual crops, such as maize [55, 56], with three times the fine-root biomass at the surface [57]. Cropland field edges—including edges that would otherwise be bare plus approximately 1% of the annual crop field—are the only areas we considered amenable to perennial field borders. We assigned area limitations based on the proportion of typical area of field border implementation to the typical area of a cropland field, as defined by the USDA EQIP [35]. Of the 114 million ha of annual cropland we considered in this study, a maximum of approximately 1.1 million ha could possibly be planted as perennial field borders according to these limitations. We found that 0.14 million ha would be economically viable for field borders with a $20/tonne CO_2e price, which equates to field borders around 12% of amenable cropland. Economically viable land increases to 0.28 million ha, or field borders on 25% of amenable

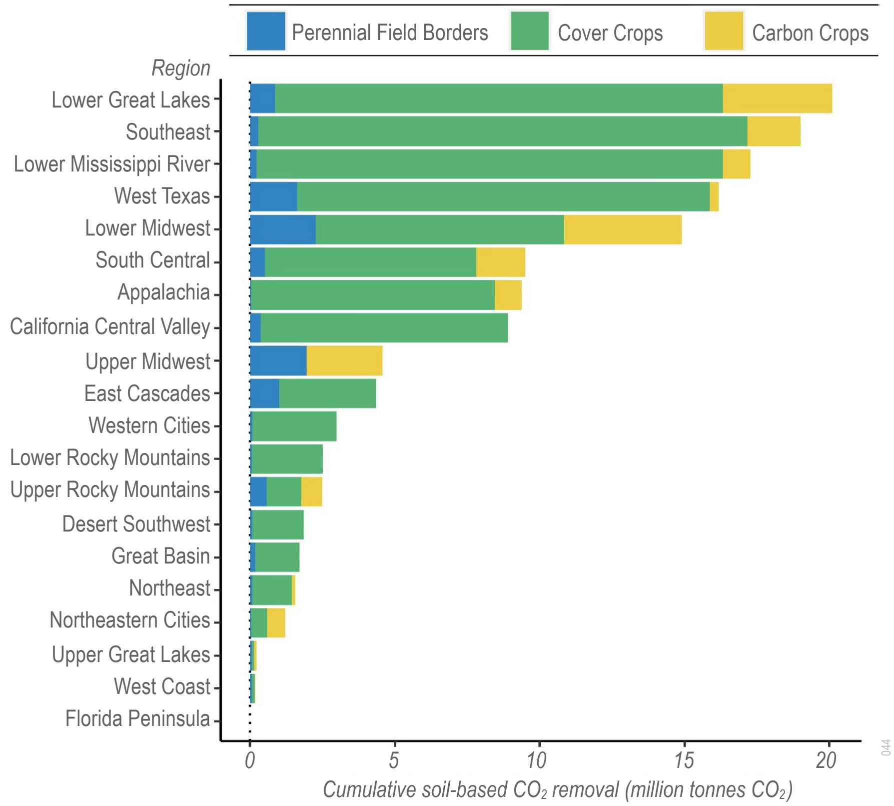


Figure 3-9. *Cumulative regional soil-based CO_2-removal potential between 2025 and 2050 at an incentive rate of \$40/tonne CO_2e. Economically and technically viable soil-based CO_2-removal potential for perennial carbon crops (yellow), cover crops (green), and perennial field borders (blue) in each region.*

cropland, with a \$40/tonne CO_2e price (Figure 3-4B; Figure 3-8). Without a carbon price, the upfront implementation cost is too high to be economically viable (Appendix 3, Table A3-1). However, perennial field borders have high per-hectare annual CO_2-removal potential. Counties with the highest per-hectare annual rate of CO_2 removal are the most likely to implement the practice for a low price: \$20/tonne CO_2e could fund field borders removing an average of 1.9 tonnes of CO_2/ha per year on the first 0.14 million ha, with diminishing returns from higher carbon prices.

Across the United States, planting perennial field borders for a price of \$40 per tonne CO_2e has the highest overall potential throughout the Great Plains, specifically in the Lower Midwest, Upper Midwest, and West Texas regions (Figure 3-4B). In the West Texas region, higher per-area rates of soil-based CO_2 removal (1.6 tonnes CO_2/ha per year) more than offset costs of implementation. In the Upper and Lower Midwest regions, both soil-based CO_2 removal (with mean rates of 1.5 and 1.4 tonnes CO_2/ha per year, respectively) and payments for avoided N_2O emissions and soil CO_2 loss compensate for implementation costs of planting field borders. The East Cascades and Lower Great Lakes Regions also have relatively moderate potential for CO_2 removal from perennial field borders. Sub-regions, such as the California Delta in the California Central Valley region and the Lower Mississippi River region, have high per-area rates of soil-based CO_2 removal (1.7 tonnes CO_2/ha per year) but relatively low available land, with baseline conditions consistent with model requirements for where implementation of field borders (i.e., corn, wheat, cotton, soybean, oats, barley, sorghum grain, hay, and peanut crops) could occur. Notably, we did not have a way to estimate present day prevalance of field borders, so our assumptions about available land area for expansion of field borders represent an upper bound (see definition of Additionality above).

Perennial Carbon Crops

Deep-rooted perennial crops have high potential for simultaneous soil-based CO_2 removal and harvesting for biomass inputs for BiCRS (biomass carbon removal and storage) pathways. Currently, the demand for biofuels from corn ethanol drives more than 40% of annual maize grain production [58]. However, full electrification of US light-duty vehicles sold by 2050 could significantly reduce the demand for ethanol in the next decades, which could free up cropland presently used for maize production. The zero-cropland-change economic approach (see **Appendix 3 – Methods** for details) identified annual commodity-cropland area where native perennial carbon crops, such as switchgrass, could planted on cropland that may become available with reduced ethanol demand, without impacting land area used for food and feed production. The goal of this land-use constraint is to minimize potential indirect land-use change. In **Box 3-3**, we also present an analysis of potential soil-based CO_2 removal for a future in which carbon crops could compete for land without any constraints. Details on biomass production, commodity-crop price impacts, and methods can be found in Chapter 6 – BiCRS. This analysis assumed perennial carbon crops are harvested sustainably and sold for industrial conversion to BiCRS pathways at a price commensurate with the per-tonne CO_2 removal price. We analyzed the balance of soil-carbon accrual and N_2O emissions due to perennial carbon crop switchgrass, which received annual inputs of 50 kg of nitrogen/ha sourced from either legume planting or fertilizer. If perennial carbon crops were to be planted on low-productivity annual commodity croplands (the land most likely to be freed up from reduced ethanol demand), the shift from annual grain production to perennial carbon crops would remove on average 0.7 tonnes of CO_2/ha per year for at least 25 years (Figure 3-4), with a mean climate benefit ranging from 1.4 to 2.0 tonnes of CO_2e/ha depending on baseline tillage regime.

Much like perennial field borders, the per-area CO_2-removal rate of planting perennial carbon crops is relatively high, but land-use constraints keep the area available for implementation relatively low. The zero-cropland-change economic approach to land allocation also considers the harvest and sale of ≤50% (depending on the county) of commodity-crop residues (e.g., corn stover) as inputs to BiCRS pathways. As both biomass and CO_2 prices increase, residue removal from corn and wheat becomes an important revenue source alongside the sale of grain. Thus, farmers have some incentive to expand the area of those crops even if revenue

BOX 3-3

Maximum Economic Potential Assessment Approach

Perennial carbon crops could theoretically be planted on any existing cropland. Farmers could choose to plant a perennial carbon crop through the same decision making as choosing to plant any other crop, likely motivated by differences between profit and cost of implementation. The maximum economic potential approach allowed perennial carbon crops to compete for available agricultural land with all other commodity food and feed crops and pasture, to allow markets to determine where carbon crops would be planted. This approach impacts the cropland area growing commodity crops, and thus could increase commodity crop prices by 7 to 12% for a CO_2 price of $40 per tonne, as detailed in **Chapter 6** "Biomass and BiCRS conversion technologies." This chapter includes carbon crops planted only on commodity cropland (not pastures, rangeland, or natural vegetation) in calculations for potential soil-based CO_2 removal. Without the "zero cropland change" land limitation, carbon crops could expand to more than four times the land area (**Figure 3-10**), and remove a cumulative 117 million tonnes CO_2 between 2025 and 2050 for a carbon price of $40 tonne CO_2e combined with an equivalent harvested biomass price of $73 dry tonne for inputs to the biomass-based CO_2 removal and storage industry. The biomass price of $73 per dry tonne on its own, without any soil carbon incentive, could lead to 103 million tonnes CO_2 of soil carbon storage.

This assessment of carbon crop expansion is presented separately, as the land area considered is not additive with the other soil-based CO_2 removal practices considered in this chapter. This approach found the highest potential for soil-based CO_2 removal from planting carbon crops in cropland in the western great plains of the lower midwest region, with a cumulative soil-based CO_2 removal of 30 million tonnes by 2050. Another 26 million tonnes of cumulative soil-based CO_2 removal comes from planting perennial carbon crops in the west texas region of the lower great plains.

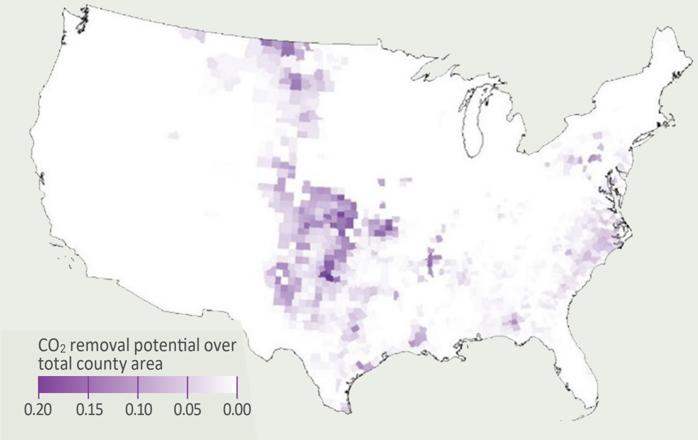


Figure 3-10. *Intensity of soil-based CO_2 removal, normalized by total county area, for perennial carbon crops given $73 per dry tonne biomass price combined with a $40 per tonne soil CO_2e incentive within the maximum economic potential approach. In this assessment, perennial carbon crops, where competitive, may be planted on any agricultural land, though only cropland was included as the baseline for soil-based CO_2 removal in this report.*

for grain falls due to lower commodity prices and they receive zero soil-carbon benefits and revenue. This incentive results in an increase and then slight decrease in land area that converts to perennial carbon crops as CO_2 prices increase (see Figure 047). The choice of which carbon crops to plant and harvest may depend not only on biomass payments but also on ecosystem functions that could be gained (Box 3-2).

Regions of the United States that have the greatest soil-based carbon-removal potential through planting perennial carbon crops are regions with both high per-area productivity and high rates of land made available due to electrification of light vehicles. At a \$40/tonne CO_2e price commensurate with a \$73/tonne biomass price, the Lower Midwest region has the highest soil-based CO_2-removal potential, with a mean annual rate of 2.5 tonnes CO_2 per hectare over 0.4 million hectares for an annual rate of 1.0 million tonnes CO_2 removed per year in 2050 (Figure 044). The Lower Great Lakes region and Upper Midwest regions both also have high potential contributions, with high available land area (0.4 and 0.5 million ha, respectively) but slightly lower per-area soil-carbon accrual rates (2.0 and 2.1 tonnes of CO_2/ha, respectively) relative to the Lower Midwest region. The Southeast and South-Central regions have moderate potential for soil carbon accrual through carbon crops, each storing an additional 0.3 million tonnes of CO_2 per year by 2050.

Additionality: Biomass Price Versus Soil-Carbon Price

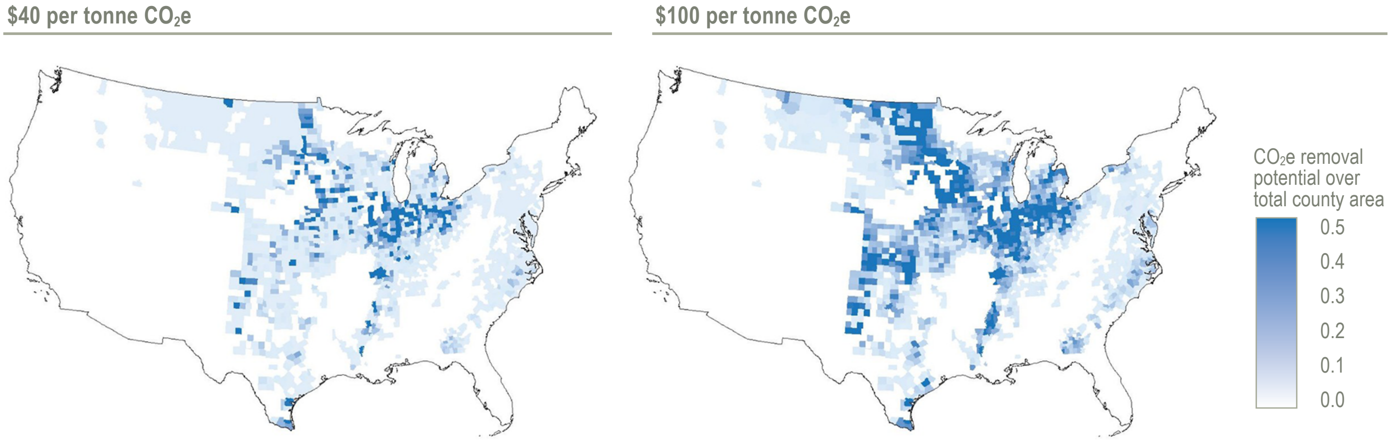
As the demand for BiCRS grows, market rates for biomass alone could be enough to offset costs and foregone income of planting perennial carbon crops. Deep-rooted perennial carbon crops, particularly native plants, such as switchgrass, have benefits far beyond their value as BiCRS inputs, including providing habitat for wildlife [7], reducing synthetic fertilizer and water requirements, and increasing soil-carbon stocks [55, 56]. We compare the soil-carbon supply assuming the same biomass price both with and without a soil-carbon price to understand how a soil-based CO_2 price can lead to additional CO_2 removal. Table 1 shows that payment for biomass from carbon crops at the rate of \$73/dry tonne provides enough market incentive to convert either 1.9 or 8.2 million ha to carbon crops using the zero-cropland-change and maximum-economic-potential approaches, respectively. In an assessment that explicitly avoids impacting food prices, providing a second, commensurate price for soil-based CO_2 removal (\$40/tonne) expands the economically viable land by 11% relative to the land area converted to carbon crops due to biomass price alone. Though challenging to fully decouple the market carbon-crop biomass price from a soil-based CO_2-removal price, this assessment demonstrates that the majority of soil-based climate and CO_2-removal benefits from planting perennial carbon crops would occur as an unincentivized co-benefit of establishing robust demand for carbon-crop biomass and that providing a soil-specific incentive can provide a modest expansion of the practice.

Uncertain Potential for CO_2 Removal with No-Till Management

No-till and reduced-till practices require cropland managers to switch from conventionally managed cropland that is tilled prior to planting to a system that totally or partially eliminates tillage, respectively. Conversion to no-till reduces the vertical mixing of soil and crop residues and reduces disruption of carbon-containing soil aggregates [62, 63]. Meta-analyses of field studies typically show higher soil-carbon stocks in no-till systems relative to full-till systems [64, 65], but the effect is not universal. Further, carbon changes at depth in response to no-till are uncertain [66] due to high spatial variability and low carbon concentrations. Moreover, no-till must be continuous for captured carbon to be durable [67, 68].

The modeling approach we used in this study assumes that increases in SOC following tillage reduction represent a flux from the atmosphere to the soil. This assumption is highly uncertain, hence we separate results related to tillage reduction from the rest of the practices analyzed in this chapter. More specifically, the models we used in this study were not able to address three major uncertainties related to tillage management: vertical carbon redistribution, changes in bulk density, and changes in erosion and subsequent lateral redistribution of soil carbon. First, the DayCent biogeochemical model simulations were limited to the top 30 cm of soil, which may miss changes in carbon at deeper depths and overestimate (or possibly underestimate) the full-profile soil-carbon benefit of no-till [66, 69]. Second, DayCent simulates a fixed soil depth and was not able to account for changes in soil bulk density. Changes to bulk density following tillage reduction tend to yield overstimates of carbon sequestration unless soil-carbon accounting is performed on a mass-equivalent basis [68, 70]. Third, the change in soil carbon predicted in our analysis could not account for erosion-mediated lateral transport of carbon. Erosion drives lateral movement of soil carbon within a landscape and enhances export of organic carbon, but losses of soil carbon due to erosion do not necessarily represent a net flux of carbon to the atmosphere [71]. Biogeochemical models that do account for lateral transport of SOC suggest that a significant amount of the soil-carbon loss observed under conventional tillage is due to erosion [72, 73], which complicates landscape-scale soil-carbon accounting following tillage reduction. Even with accurate soil-carbon accounting, identifying whether increased soil carbon is a flux from the atmosphere (e.g., through increased photosynthesis) or from a reduction in decomposition or lateral transport of carbon [64] is not straightforward.

Bearing these caveats in mind, our analysis suggests that tillage reduction can yield moderate increases in soil carbon over a large land area, potentially yielding a relatively large amount of soil-carbon accrual. DayCent model results indicate a moderate, almost always positive increase in soil-based CO_2 removal from switching to continuous no-till **(Appendix 3, Figure A3-3**). No-till is relatively inexpensive to implement, at approximately a quarter of the cost of cover-crop implementation (**Appendix 3, Table A3-1**), resulting in high potential for inexpensive soil-based CO_2 removal. Our economic trade-off simulation found virtually all available cropland area not already under no-till could be converted to continuous no-till management at prices above $50/tonne CO_2e (**Figure 3-11, Table A3-1**). The large extent of cropland area converting to no-till provides significant potential for soil-carbon increases (Figure 3-6). If increased soil carbon from no-till yields true removal of atmospheric carbon, the practice could remove a cumulative 950 million tonnes of CO_2 between 2025 and 2050 for a price of $40/tonne CO_2e, as well as an additional 2 million tonnes for conversion to reduced tillage. For a price of $40/tonne CO_2e, the Lower Great Lakes region has the highest potential for soil-based CO_2 removal, at a rate of 9.8 million tonnes per year. The Upper and Lower Midwest regions also have relatively high potential for expansion of continuous no-till management for soil-based CO_2 removal.


$40 per tonne CO_2e

$100 per tonne CO_2e

Figure 3-11. *Intensity of CO_2-removal potential through implementation of no-till management, normalized by total county land area, given a \$40/tonne CO_2e incentive (left) and a \$100/tonne CO_2e incentive (right). Areas of opportunity for no-till management were constrained to land area where continuous no-till was not already practiced in 2017 [11, 38] (see Appendix 3, Figure S1).* [351]

Table 3-3. *Economically constrained potential for implementing continuous no-till as a soil-based CO_2 strategy.*

Practice	Carbon Price	Economically Viable Land Area	Soil-based CO_2 Removal Rate	Soil-Based Climate Benefit *(incl. Avoided Emissions)*	Cumulative Soil-Based CO_2 Removal 2025–2050	Cumulative Soil-Based Climate Benefit *(incl. Avoided Emissions)* 2025–2050
	\$USD/ tonne CO_2e	*Million hectares*	*Million tonnes CO_2/ y*	*Million tonnes CO_2/ y*	*Million tonnes CO_2*	*Million tonnes CO_2e*
No till	0	0.2	0.2	0.3	6.0	8.2
No till	40	30.5	38.0	53.3	948.8	1331.8
No till	100	78.9	81.7	112.4	2043.5	2809.6
Reduced till	0	0.1	0.0	0.1	0.8	1.5
Reduced till	40	0.2	0.1	0.1	1.7	3.6
Reduced till	100	4.3	2.1	3.7	51.5	91.5

Effect of Future Climate Projections on CO_2-Removal Potential

Soil-carbon accrual and plant growth both depend on temperature and precipitation and will likely be sensitive to future climate change. We ran the DayCent biogeochemical model projecting soil-carbon, N_2O, and crop-yield responses across each county under spatially explicit future climates projected by five different downscaled Earth-system models [74, 75]. We report data outputs driven by gridded climate data from the MIROC_ES2L Earth-system model, which we chose as a reference model because it best represents historic temperature and precipitation data aggregated across the contiguous United States. To understand how sensitive our results are to Earth-system model variability, we also compared the coupled biogeochemical and economic outcomes driven by climate from four other future-climate projections (see **Appendix 3** for details). National soil-based CO_2 removal for a \$40/tonne CO_2 price varied by up to 32% (range of all models divided by the MIROC_ES2L-derived value) relative to the reference climate-model output for planting cover crops and by 9% for planting perennial field borders. For a higher CO_2 price of \$100/tonne, national soil-based CO_2 removal simulated with other climate models varied by 21% relative to the reference climate model for planting cover crops and by 8% for planting perennial field borders. Variability is likely lower for perennial field border implementation due to the greater area limitations imposed on this practice. We did not analyze the future-climate variability effect on perennial carbon crop implementation using the SALUS model.

Variability presented here captures only future-climate uncertainty due to variation in Earth-system model predictions and does not include uncertainty related to the parameters or assumptions of the DayCent biogeochemical model. All future model projections assumed a moderate future-emissions scenario (IPCC shared socioeconomic pathway), which project a continuation of historic trends of slow and uneven progress toward decarbonization [76]. We did not analyze the range of potential from future-emissions trajectories for different shared socioeconomic pathways, which will also certainly affect potential for soil CO_2 removal and storage, especially in the latter half of the century.

Soil-Based CO_2-Removal Practices through Socioeconomic and Environmental Perspectives

The soil-carbon management case studies examined in this chapter—cover cropping, perennial borders, and perennial carbon crops—each have opportunities for co-benefits and potential negative impacts. In this section, we compare the trade-offs for each and make recommendations to maximize co-benefits and avoid or minimize potential negative impacts (**Table 3-4 A-C**). Key co-benefits for soil-based CO_2-removal methods include preserving productive farmland through erosion reduction, decreasing nitrate and herbicide pollution in local waters, and providing alternative carbon-crop income for low-productivity farmland operators (e.g., [63-66]). By prioritizing counties with the highest erodibility, nitrate pollution, and herbicide applications and the lowest farm net income, policymakers could maximize these environmental and economic co-benefits of soil-based CO_2 removal. The overarching potential negative impacts that soil-based CO_2-removal methods risk, however, is increasing disparities in cropland ownership, operatorship, and income in the United States, caused by entrenched structural drivers [67]. Historic and ongoing injustices have resulted in an agricultural industry composed of 98% white landowners, 94% white farm operators, and 63%–87% male cropland owner/operatorship [67]. Furthermore, the abundance of family farms in the United States is decreasing (-4%, 2012–2017; [16]), which presents a challenge for equitable soil CO_2-removal scale-up, since small family farms (gross cash farm income <\$350,000) are more likely to have diverse farm operatorship. However, they account for a much smaller percentage of land area in the United States (and thus CO_2 removal) than large, corporate farms [16]. *Without equity enhancements that design credit or incentive programs and/or policies to support small, family-owned and historically marginalized farmers (who are already less likely to participate in financial assistance programs), soil CO_2-removal investments could disproportionately benefit populations and corporations that do not reflect the diversity of United States* [16, 67-69]. Project developers could slow or reverse past land loss from historically marginalized populations and small, family-owned farms by designing or reforming agricultural financial

Table 3-4 *A. Soils-based CO_2 community benefits and negative impacts trade-off table.*

Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Reduced nitrate runoff Cover cropping reduces nitrate runoff in most instances and should be preferentially implemented where nitrate runoff is particularly serious. Sandier soils, tilled soils, and soils hosting horticultural crops should be targeted first for cover cropping. Non-legume cover crops are generally more effective than legume cover crops at reducing nitrate runoff [77]. Cover cropping also supports split-N fertilization (e.g., multiple smaller applications of fertilizer), where it has been seen to further reduce nitrate runoff without impacting yields [78]	Increased herbicide use to terminate cover crop To the extent feasible, mechanical methods (e.g., mowing, tillage, roller-crimping, grazing) should be used instead of herbicide tocontrol weeds and terminate the cover crop [85]. Especially avoid herbicide applications in regions with high application rates currently
Reduced air pollution from wind erosion Cover cropping should be applied in regions with existing high soil-erosion rates to achieve the greatest benefit. Cover cropping with small winter grains has been shown to reduce wind erosion by ~2–3 orders of magnitude compared to fallow fields [86]	Risk of voiding cover-crop insurance Historical rigidity of crop-insurance programs around the timing of cover-crop termination has been somewhat alleviated with the 2018 farm bill but remains a minor barrier to adoption of cover crops [87]. Cost-sharing and/or economic incentives to utilize cover cropping should be implemented as farmers indicate that cost is the primary barrier to adopting cover cropping practices [88]
Increased soil water storage Cover cropping should be used to help retain water in working fields. Cover cropping with winter rye, in both wet and dry years, increased topsoil water storage by ~10% and plant-available water by ~22% without negatively impacting maize or soybean production [89]. This benefit is especially helpful in counties with unsustainably high water draft rates currently	Economic risks for farmers (cost of cover crop vs. economic viability) Cost sharing for cover cropping should be further developed. Roughly three quarters of US farmers have consistently indicated for the last 15 years that cost share would help them adopt cover cropping [88, 90]. Tax credits for planting cover crops are not viewed by farmers as being as helpful as cost share
Erosion control Plant a mix of cover-crop species to maximize erosion control. Cover cropping decreases runoff losses (by 13%–78%) and sediment losses (by 39%–96%) [91]. Soils prone to erosion should be prioritized to maximize benefits	Delayed or unrealized benefits Guaranteed, long-term incentive programs could be implemented so that farmers can be confident that cover cropping will lead to a net economic gain. In general, the varied improvements from cover cropping are cumulative and may take several years to overcome the upfront costs [92]. Perform baseline assessment such that results can be compared against a rigorous counterfactual [93]
Production of silage for nearby animal operations or biofuels Plant cover crops that can be grazed or harvested for biofuels, since this may in some cases be possible without negatively mpacting their soil carbon benefits or other co-benefits (e.g. air and water quality) [91]. The revenue from the use of cover crops could be significant but need to be considered against cover-cropping definitions in cost-share programs [94]	Increased nitrate runoff Fertilizer application to cover crops is not needed and may undo the reductions in nitrate runoff provided by cover crops [77]. Field experience shows that cover cropping reduces total fertilizer usage [90]
Improved soil organic matter Cover crops should be preferentially applied to soils with low organic matter. Increases in soil organic matter have been found whether left on the surface or turned under [85]	Increased socioeconomic division Regional maps of historically marginalized and female land ownership/farm operations should be consulted pre-investment to assess equitable distribution potential [81, 95]. Do not develop, disturb, or restrict access to land that the community has identified as culturally or ecologically valuable [93]
Improved crop yield Cover cropping should be targeted for humid and sub-humid regions where it generally increases crop yields. In semiarid regions, careful selection of cover crops should be made to ensure that crop yields do not decrease [91]. Cover cropping should be continued for multiple years as yields tend to improve over time [96]. Cover cropping should be combined with no-till practices to maximize benefits [85]	Competitive disadvantage on small farms Identify counties with a high proportion of small farms and provide equity enhancements for cover cropping

Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Decreased herbicide usage and herbicide-resistant weeds Use cereals or cover crops with high biomass to maximize weed suppression and reduce herbicide usage, especially in regions with high herbicide application rates currently. When using broadleaf species or legumes, mix with a productive grass species to increase weed suppression [79, 97]	Increased cost to farmer Use a single cover crop instead of a mixture to reduce seed costs or participate in a rebate program for cover-crop seed [79]

Table 3-4 *B. Perennial Field Borders: Conserving land between fields to improve ecosystem health.*

Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Reduces wind erosion Where climatic conditions allow, tall woody species with substantial leaf coverage should be planted to reduce wind erosion of soils [98], especially in regions of high soil-erodibility risk]	Land opportunity costs Field borders should be focused to areas most vulnerable to wind erosion—typically, semiarid and arid portions of the farm—such that equipment size and irrigation-system design are not overly constrained [98]
Reduces water erosion Use wide barriers (1–10 m) that combine woody species with native grasses to reduce soil erosion [99, 100], especially in regions of high soil erodibility risk	Education costs Education efforts should not be exclusively centered on the proper design and maintenance of field borders but should also help farmers utilize existing economic incentives [101]
Reduces nutrient runoff Use wide barriers (typically 6–10 m) that combine woody species with native grasses to increase nutrient capture [99, 100], especially in regions with high nutrient pollution risk	Unrealized benefits Focus perennial field borders to farms without tile drainage. For farms with tile drainage, alternative erosion and runoff control measures should be considered [102]
Increased ecological diversity Plant a variety of native species, in particular woody vegetation, to maximize species diversity. Well-connected, wide corridors should be made to allow wildlife to move between fragmented habitats [101]	Rejection on aesthetic grounds Design "neat" or "manicured" perennial field borders, preferably including trees, to better align with the generally preferred aesthetic of farmers [101]
Reduced pesticide runoff Application should particularly focus on farms that use pesticides that tightly bind to soil, as these are effectively removed by field borders. On farms using less tightly bound pesticides, design the buffers to slow water movement to maintain removal efficiencies [103]	Increased socioeconomic division Regional maps of historically marginalized and female land ownership/farm operations should be consulted pre-investment to assess equitable distribution potential [81, 95]. Do not develop, disturb, or restrict access to land that the community has identified as culturally or ecologically valuable [93]
Pathogen reduction Consider pathogen vector (i.e., residue or insect) when designing field border geometry and vegetation to reduce pathogen transport [104]	Competitive disadvantage of small farms Identify counties with a high proportion of small farms and provide equity enhancements for conservation borders

Table 3-4 *C. Perennial Carbon Crops.*

Potential **Co-benefits** to Communities & Recommendations for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Recommendations for Minimizing Potential Negative Impacts
Income retention for farmers/ranchers In counties where traditional farming is at risk (e.g., climatic, environmental, or economic forces), producers may consider perennial carbon crops as an alternative to land retirement [105]	Incomplete income retention for farmers/ranchers Focusing carbon cropping transitions in counties with already marginal crop income yields may reduce risk of producers experiencing incomplete income retention
Reduces nutrient runoff Transition conventional, fertilized croplands to perennial carbon crops in counties with exceptionally high nitrate concentrations for the greatest human health benefits [61, 106]	Loss of/conflict with farmer identity Identifying farmers with innate productivist, conservationist, or naturalist identities might increase carbon-cropping practice uptake, without instigating identity clashes [107]
Increased biodiversity and abundance Plant a switchgrass polyculture, instead of a monoculture, to increase flower and pollinator diversity and abundance [59, 61]	Competitive disadvantage for small farms Identify counties with a high proportion of small, financially struggling farms and engage in equity-enhanced outreach to small farm operators
Water conservation For maximal water conservation, prioritize the conversion of croplands with high irrigation needs to non-irrigated, drought-tolerant carbon crops in counties currently facing (or forecasted to face) drought conditions [108]	Land opportunity costs Prioritizing the conversion of croplands to perennial carbon crops in counties that are not especially land limited may reduce conflict with broader community land needs (e.g., for residential, commercial, industrial, or conservation activities)

incentives. Targeted incentives such as crop-insurance modifications or subsidies to credit soil-based CO_2-removal opportunities toward small, family-owned and historically marginalized farmers (including tribal governments who represent a majority share of non-white-operated agricultural acreage in the United States) (**Chapter 9**) could help support land access to new and existing farmers in these communities.

To efficiently synthesize socioeconomic and environmental data relevant to DOE's energy equity and environmental justice (EEEJ) goals [60], we constructed an average EEEJ Index value for each US county (**Chapter 9 – EEEJ**). In these indices, values closer to 1 represent high opportunities for co-benefits, and values closer to 0 represent lower likelihood for co-benefits and potentially greater challenges pertinent to EEEJ considerations. The impact of each variable, positively or negatively, on the overall EEEJ Index value for each county is presented in **Figure 3-12**. Following the construction of the EEEJ index, we conducted a comparison to the Center for Disease Control's (CDC's) Social Vulnerability Index (SVI) to facilitate a comprehensive evaluation of regional disparities and potential areas for targeted interventions *(***Figure 3-13***).* Evaluating SVI alongside this report's EEEJ index may be useful for agencies and project developers in determining potential priorities, such as protecting a region's most vulnerable communities from water pollution or careful considerations around developing an industrial presence (e.g., a carbon-crop-based BiCRS facility) in a county least-equipped to respond to potential negative impacts, should they occur. Further examination of the socioeconomic and environmental contexts considered for each county identified in the chapter can be found in the dedicated EEEJ chapter (**Chapter 9**).

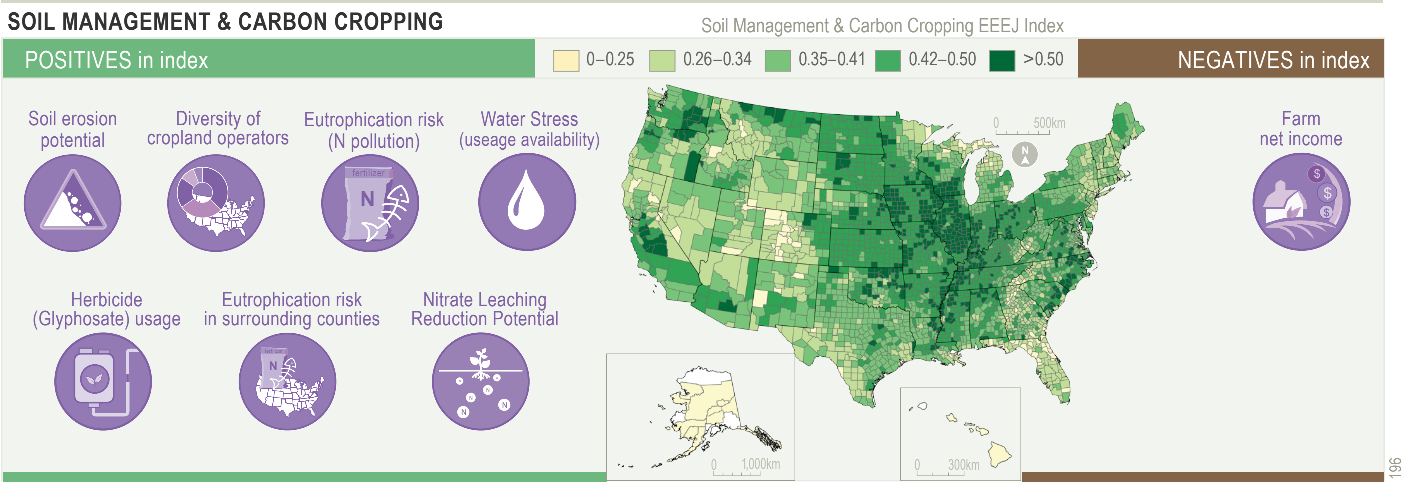


Figure 3-12. *Map of the EEEJ index for increased soil management, alongside each variable that contributed, positively or negatively, to the index. The index is normalized from 0 to 1, where values higher values represent a potentially greater opportunity for socio-economic co-benefits, including reducing water pollution and preserving farmland through decreased soil erosion. Higher values also represent a smaller potential for negative impacts, such as disproportionately benefitting large, industrial farms over small, family- or minority-owned farms.*

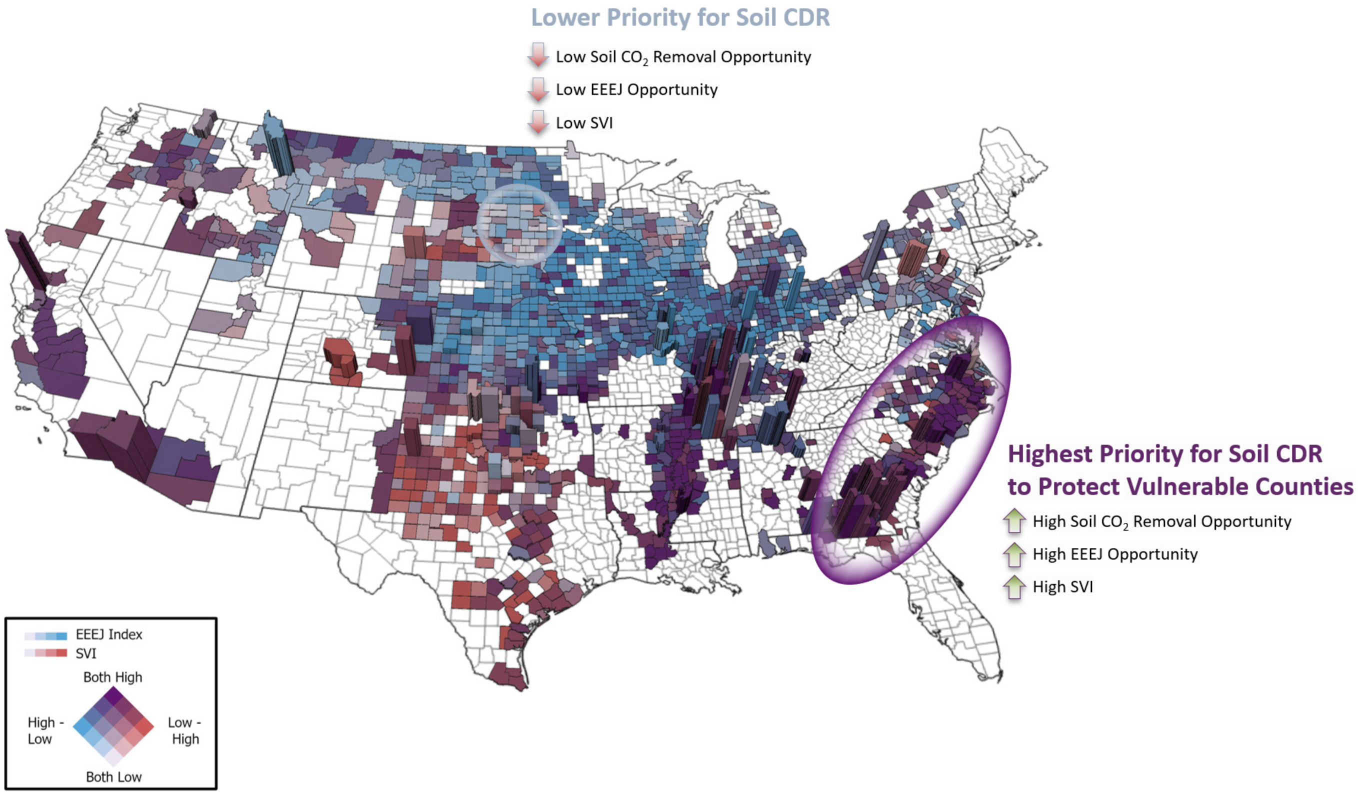


Figure 3-13. *Map of EEEJ index data (blue) and the CDC's Social Vulnerability Index (red) for the United States in counties whose CDR costs were analyzed in this report. The height of counties in this map represents potential for CO_2 removal (CDR) through cropland soil management where taller counties have the greatest cumulative capacity for CDR through 2050. In this report, we categorize soil management as a 'protective' CDR practice, which exhibits outsized potential for protection of people from agricultural pollution, but the key reason for the management practices not being implemented currently is likely funding or capacity. Therefore, our premise is that: if a county has high opportunity for co-benefits and high social vulnerability, then they may benefit from equity enhanced outreach for soil management practices. Conversely, counties with high opportunity for co-benefits, but low social vulnerability may similarly benefit from cropland soil management, but perhaps there is less urgent need for outreach, given that these counties are more likely to have secondary protective measures in place (e.g. in-home water filtration or access to regular medical care).*

Conclusions

The low-cost and fast near-term deployability of soil-based CO_2-removal practices is important context for their contribution to targets for climate-change mitigation. If cover cropping, perennial field borders, and carbon crops were implemented starting in 2025 across all economically viable cropland in the contiguous United States (Figure 3-1), the cumulative CO_2 removed by 2050 could reach more than 130 million tonnes at a moderate \$40/tonne CO_2e price, in addition to 55 million tonnes of CO_2e of avoided GHG emissions (**Figure 3-14**). Cover cropping on annual croplands contribute over 75% of this CO_2-removal potential due to the greater area of cropland amenable to the practice relative to perennial field borders and carbon crops. The durability of an enhanced soil-carbon stock is a key uncertainty toward its contribution to targets for climate-change mitigation and depends in part on whether future cropland managers choose to maintain management. Without a guarantee of long-term maintenance, soil-based CO_2 removal and storage should be considered a near-term strategy that bridges immediate action to highly durable storage. A strategy involving soil-based CO_2 removal must continue to invest in maintenance of soil-storage and eventually “re-locate” an equivalent amount of stored CO_2 to storage in geologic reservoirs once technology and regulations develop.

The primary benefits of soil-conservation practices contribute to the longevity and productivity of food-producing systems and communities. Enhanced periods of plant growth on croplands—as implemented through the cropland-management practices analyzed in this chapter—benefit communities and agroecosystems by managing erosion, creating habitat for wildlife, improving water management, and reducing pollution. Together with the co-benefit of soil-based CO_2 removal, these practices contribute to both climate-change adaptation of food systems and mitigation of future climate change.

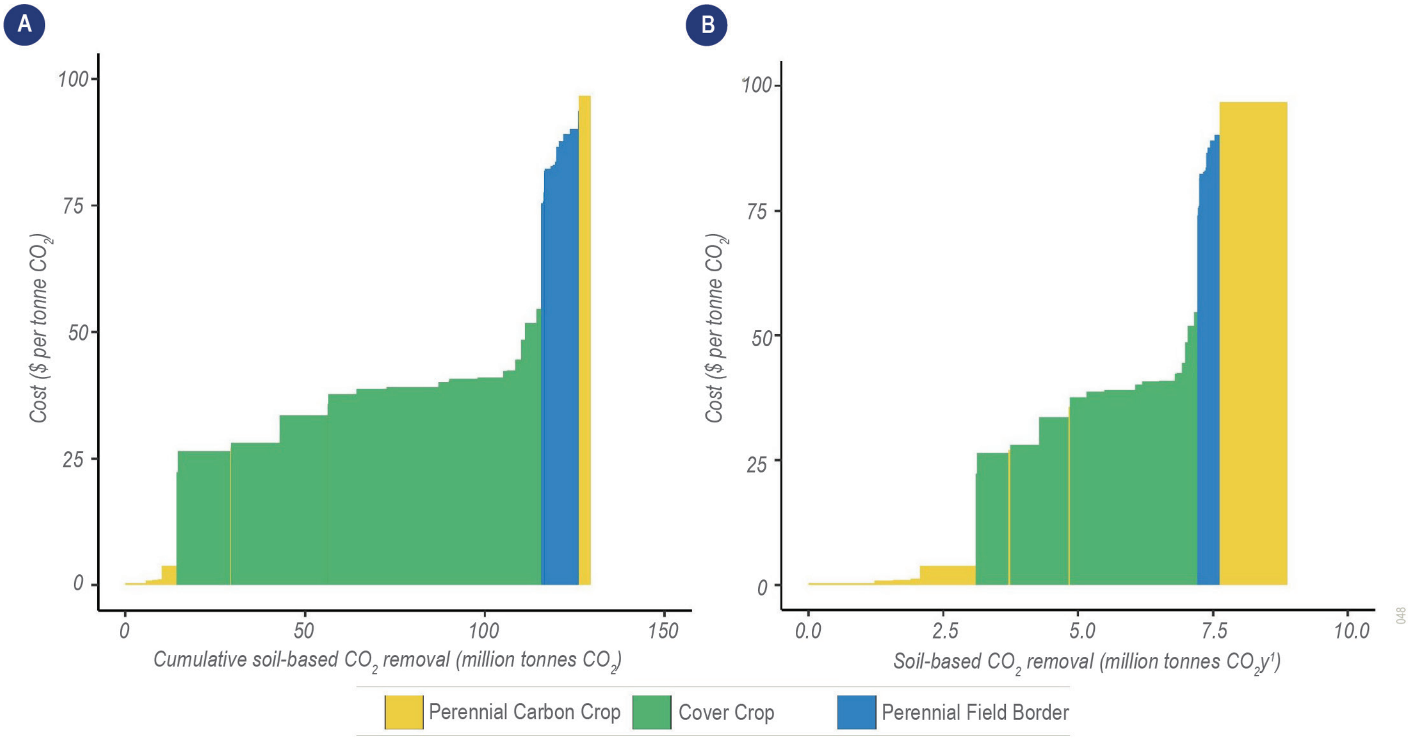


Figure 3-14. *The cost per additional tonne of atmospheric CO_2 removal for each region, varied by practice for a constant climate-benefit price of \$40/tonne CO_2e. Additive effects of each practice are shown on the x-axis for (A) cumulative soil-based CO_2 removal and (B) annual rate of CO_2 removal. Each dollar spent toward soil-based CO_2 removal goes further when also accounting for avoided soil-carbon losses and N_2O emissions (i.e., the total climate benefit). We calculated additional cost by subtracting the climate benefit that would occur at a carbon price of \$0 from the climate benefit that would occur given a \$40 carbon price and then multiplied the resulting additional climate benefit by the \$40 incentive price*

References

1. J. Padarian, et al., *Monitoring changes in global soil organic carbon stocks from space. Remote Sensing of Environment, 2022*. 281: p. 113260, https://doi.org/10.1016/j.rse.2022.113260.
2. Jonathan Sanderman, Tomislav Hengl, and Gregory J. Fiske, *Soil carbon debt of 12,000 years of human land use. Proceedings of the National Academy of Sciences, 2017*. 114(36): p. 9575-9580, https://doi.org/10.1073/pnas.1706103114.
3. Dolly Autufuga, et al., *Distribution of Soil Nutrients and Ancient Agriculture on Young Volcanic Soils of Ta'ū, American Samoa. Soil Systems*, 2023. 7(2): p. 52, https://doi.org/10.3390/soilsystems7020052.
4. Peter Potapov, et al., *Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nature Food*, 2022. 3(1): p. 19-28, https://doi.org/10.1038/s43016-021-00429-z.
5. Xuan Du, et al., *Conservation management decreases surface runoff and soil erosion. International Soil and Water Conservation Research*, 2022. 10(2): p. 188-196, https://doi.org/10.1016/j.iswcr.2021.08.001.
6. Oskar Englund, et al., *Strategic deployment of riparian buffers and windbreaks in Europe can co-deliver biomass and environmental benefits. Communications Earth & Environment*, 2021. 2(1): p. 176, https://doi.org/10.1038/s43247-021-00247-y.
7. Sara A. Berges, et al., B*ird species diversity in riparian buffers, row crop fields, and grazed pastures within agriculturally dominated watersheds. Agroforestry Systems*, 2010. 79(1): p. 97-110, https://doi.org/10.1007/s10457-009-9270-6.
8. *USDA Natural Resources Conservation Service. A Brief History of NRCS*. Accessed July 2023 Published by U.S. Department of Agriculture; Available from https://www.nrcs.usda.gov/about/history/brief-history-nrcs.
9. *Conservation Technology Information Center (CTIC) Sustainable Agriculture Research and Education (SARE), and American Seed Trade Association (ASTA). National Cover Crop Survey Report 2022–2023. 2023. SARE, CITC, ASTA*, https://www.sare.org/wp-content/uploads/2022-2023-National-Cover-Crop-Survey-Report.pdf.
10. Christopher Poeplau and Axel Don, *Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. Agriculture, Ecosystems & Environment*, 2015. 200: p. 33-41, https://doi.org/10.1016/j.agee.2014.10.024.
11. Ziqi Qin, et al., *Assessing long-term impacts of cover crops on soil organic carbon in the central US Midwestern agroecosystems. Global Change Biology*, 2023. 29(9): p. 2572-2590, https://doi.org/10.1111/gcb.16632.
12. *U. S. Department of Agriculture. Census of Agriculture*. 2017 Published by Natinal Agricultral Statistics Service; Available from www.nass.usda.gov/AgCensus.
13. Lisa A. Schulte, et al., *Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands*. Proceedings of the National Academy of Sciences, 2017. 114(42): p. 11247-11252, https://doi.org/10.1073/pnas.1620229114.
14. Douglas A. Landis, *Designing agricultural landscapes for biodiversity-based ecosystem services*. Basic and Applied Ecology, 2017. 18: p. 1-12, https://doi.org/10.1016/j.baae.2016.07.005.
15. Amy L. Lewis, et al., *Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. Applied Geochemistry, 2021*. 132: p. 105023, https://doi.org/10.1016/j.apgeochem.2021.105023.
16. Rebecca Ryals, et al., *Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. Soil Biology and Biochemistry, 2014*. 68: p. 52-61, https://doi.org/10.1016/j.soilbio.2013.09.011.
17. Marcia S. DeLonge, Rebecca Ryals, and Whendee L. Silver, *A Lifecycle Model to Evaluate Carbon Sequestration Potential and Greenhouse Gas Dynamics of Managed Grasslands*. Ecosystems, 2013. 16(6): p. 962-979, https://doi.org/10.1007/s10021-013-9660-5.

18. David J. Beerling, et al., *Farming with crops and rocks to address global climate, food and soil security*. Nature Plants, 2018. 4(3): p. 138-147, https://doi.org/10.1038/s41477-018-0108-y.

19. Jonathan Sanderman and Jeffrey A. Baldock, *Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective*. Environmental Research Letters, 2010. 5(3): p. 034003, https://dx.doi.org/10.1088/1748-9326/5/3/034003.

20. Mathew Williams, Dave Reay, and Pete Smith, *Avoiding emissions versus creating sinks—Effectiveness and attractiveness to climate finance*. Global Change Biology, 2023. 29(8): p. 2046-2049, https://doi.org/10.1111/gcb.16598.

21. Barbara Haya, et al., *Managing uncertainty in carbon offsets: insights from California's standardized approach*. Climate Policy, 2020. 20(9): p. 1112-1126, https://doi.org/10.1080/14693062.2020.1781035.

22. Allegra Mayer and Whendee L. Silver, *The climate change mitigation potential of annual grasslands under future climates*. Ecological Applications, 2022. 32(8): p. e2705, https://doi.org/10.1002/eap.2705.

23. Phil Renforth and Gideon Henderson, *Assessing ocean alkalinity for carbon sequestration*. Reviews of Geophysics, 2017. 55(3): p. 636-674, https://doi.org/10.1002/2016RG000533.

24. David J. Beerling, et al., *Potential for large-scale* CO^2 *removal via enhanced rock weathering with croplands*. Nature, 2020. 583(7815): p. 242-248, 10.1038/s41586-020-2448-9.

25. David J. Beerling, et al. *Enhanced weathering in the U.S. Corn Belt delivers carbon removal with agronomic benefits*. 2023. arXiv:2307.05343 DOI: https://doi.org/10.48550/arXiv.2307.05343.

26. Iris Holzer, et al. Quantifying *Enhanced Weathering. 2023 Published by (Carbon)plan*; Available from https://carbonplan.org/research/ew-quantification-explainer.

27. Lauren Gifford, *"You can't value what you can't measure": a critical look at forest carbon accounting*. Climatic Change, 2020. 161(2): p. 291-306, https://doi.org/10.1007/s10584-020-02653-1.

28. Lambert Schneider, *Assessing the additionality of CDM projects: practical experiences and lessons learned*. Climate Policy, 2009. 9(3): p. 242-254, https://doi.org/10.3763/cpol.2008.0533.

29. Timothy Searchinger, et al., *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science*, 2008. 319(5867): p. 1238-1240, https://doi.org/10.1126/science.1151861.

30. Philippe C. Baveye, et al., *From Dust Bowl to Dust Bowl: Soils are Still Very Much a Frontier of Science*. Soil Science Society of America Journal, 2011. 75(6): p. 2037-2048, https://doi.org/10.2136/sssaj2011.0145.

31. Susan Trumbore, *Age of soil organic matter and soil respiration: radiocarbon constraints on belowground c dynamics*. Ecological Applications, 2000. 10(2): p. 399-411, https://doi.org/10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2.

32. Jens Leifeld and Sonja G. Keel, *Quantifying negative radiative forcing of non-permanent and permanent soil carbon sinks*. Geoderma, 2022. 423: p. 115971, https://doi.org/10.1016/j.geoderma.2022.115971.

33. H. Damon Matthews, et al., *Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. Communications Earth & Environment*, 2022. 3(1): p. 65, https://doi.org/10.1038/s43247-022-00391-z.

34. USDA Farm Service Agency (FSA). *Conservation Reserve Program*. 2023 Published by USDA FSA; Available from www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2023/crp_general_signup_main_fact_sheet_2023.pdf.

35. USDA Natural Resources Conservation Service Service (NRCS). *Environmental Quality Incentives Program (EQIP)*. 2022 Published by Available from https://www.nrcs.usda.gov/programs-initiatives/eqip-environmental-quality-incentives.

36. Susan M. Capalbo, et al., *Sensitivity of Carbon Sequestration Costs to Economic and Biological Uncertainties*. Environmental Management, 2004. 33(1): p. S238-S251, https://doi.org/10.1007/s00267-003-9134-1.

37. John Antle, et al., *Spatial heterogeneity, contract design, and the efficiency of carbon sequestration policies for agriculture*. Journal of Environmental Economics and Management, 2003. 46(2): p. 231-250, https://doi.org/10.1016/S0095-0696(02)00038-4.

38. G. Cornelis van Kooten, *Biological carbon sequestration and carbon trading re-visited*. Climatic Change, 2009. 95(3): p. 449-463, https://doi.org/10.1007/s10584-009-9572-8.

39. Tingting Liu, Randall J. F. Bruins, and Matthew T. Heberling, *Factors Influencing Farmers' Adoption of Best Management Practices: A Review and Synthesis. Sustainability*, 2018. 10(2): p. 432, https://doi.org/10.3390/su10020432.

40. Ram B. Gurung, et al., *Bayesian calibration of the DayCent ecosystem model to simulate soil organic carbon dynamics and reduce model uncertainty*. Geoderma, 2020. 376: p. 114529, https://doi.org/10.1016/j.geoderma.2020.114529.

41. William J. Parton, et al., *DAYCENT and its land surface submodel: description and testing*. Global and Planetary Change, 1998. 19(1): p. 35-48, https://doi.org/10.1016/S0921-8181(98)00040-X.

42. Bruno Basso and Joe T Ritchie, *Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model*, in The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability, S.K. Hamilton, J.E. Doll, and G.P. Robertson, Editors. 2015, Oxford University Press: New York, NY, USA (https://api.semanticscholar.org/CorpusID:6109747).

43. Bruno Basso, et al., *Simulation of tillage systems impact on soil biophysical properties using the SALUS model*. Italian Journal of Agronomy, 2006. 1(4): p. 677-688, https://doi.org/10.4081/ija.2006.677

44. Roger Claassen, et al. *Tillage Intensity and Conservation Cropping in the United States*. 2018. EIB 197; http://dx.doi.org/10.22004/ag.econ.277566.

45. United States Department of Agriculture (USDA) *Natural Resources Conservation Service. Land resource regions and major land resource areas of the United States, the Caribbean, and the Pacific Basin*. 2022. USDA, Agriculture Handbook 296, https://www.nrcs.usda.gov/sites/default/files/2022-10/AgHandbook296_text_low-res.pdf.

46. Intergovernmental Panel on Climate Change (IPCC). AR6 WGI Report – List of corrigenda to be implemented. 2021. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf.

47. Amy Swan, et al. *Princeton's Net-Zero America study Annex Q: Potential for Negative Emissions from Carbon Sequestration on US Agricultural Land*. 2020. https://netzeroamerica.princeton.edu/img/NZA%20Annex%20Q%20-%20Agricultural%20carbon%20sink.pdf.

48. G. Philip Robertson, et al., *Land-based climate solutions for the United States*. Global Change Biology, 2022. 28(16): p. 4912-4919, https://doi.org/10.1111/gcb.16267.

49. Isaac Vendig, et al., *Quantifying direct yield benefits of soil carbon increases from cover cropping*. Nature Sustainability, 2023. 6(9): p. 1125-1134, 10.1038/s41893-023-01131-7.

50. Vincent Chaplot and Pete Smith, *Cover crops do not increase soil organic carbon stocks as much as has been claimed: What is the way forward?* Global Change Biology. n/a(n/a), https://doi.org/10.1111/gcb.16917.

51. Jillian M. Deines, et al., *Recent cover crop adoption is associated with small maize and soybean yield losses in the United States*. Global Change Biology, 2023. 29(3): p. 794-807, https://doi.org/10.1111/gcb.16489.

52. Irene García-González, et al., *Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. Geoderma*, 2018. 322: p. 81-88, https://doi.org/10.1016/j.geoderma.2018.02.024.

53. Jeffrey P. Mitchell, et al., *Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley*, USA. Soil and Tillage Research, 2017. 165: p. 325-335, https://doi.org/10.1016/j.still.2016.09.001.

54. Ismail I. Garba, Lindsay W. Bell, and Alwyn Williams, *Cover crop legacy impacts on soil water and nitrogen dynamics, and on subsequent crop yields in drylands: a meta-analysis*. Agronomy for Sustainable Development, 2022. 42(3): p. 34, https://doi.org/10.1007/s13593-022-00760-0.

55. M. A. Liebig, et al., *Soil carbon under switchgrass stands and cultivated cropland*. Biomass and Bioenergy, 2005. 28(4): p. 347-354, https://doi.org/10.1016/j.biombioe.2004.11.004.

56. Andrea Nocentini and Andrea Monti, *Comparing soil respiration and carbon pools of a maize-wheat rotation and switchgrass for predicting land-use change-driven SOC variations*. Agricultural Systems, 2019. 173: p. 209-217, https://doi.org/10.1016/j.agsy.2019.03.003.

57. A. Tufekcioglu, et al., F*ine root dynamics, coarse root biomass, root distribution, and soil respiration in a multispecies riparian buffer in Central Iowa, USA*. Agroforestry Systems, 1998. 44(2): p. 163-174, https://doi.org/10.1023/A:1006221921806.

58. USDA ERS. *Feed Grains Sector at a Glance*. 2023 Published by Available from https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance/.

59. Lindsey R. Kemmerling, Sean R. Griffin, and Nick M. Haddad, *Optimizing pollinator conservation and crop yield among perennial bioenergy crops*. GCB Bioenergy, 2021. 13(7): p. 1030-1042, https://doi.org/10.1111/gcbb.12826.

60. Ben P. Werling, et al., *Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes*. Proceedings of the National Academy of Sciences, 2014. 111(4): p. 1652-1657, https://doi.org/10.1073/pnas.1309492111.

61. G. Philip Robertson, et al., *Cellulosic biofuel contributions to a sustainable energy future: Choices and outcome*s. Science, 2017. 356(6345): p. eaal2324, https://doi.org/10.1126/science.aal2324.

62. Márcio R. Nunes, et al., *Biological soil health indicators respond to tillage intensity: A US meta-analysis. Geoderma*, 2020. 369: p. 114335, https://doi.org/10.1016/j.geoderma.2020.114335.

63. J. Six, E. T. Elliott, and Keith Paustian, *Soil Macroaggregate Turnover and Microaggregate Formation: A Mechanism for C Sequestration under No-Tillage Agriculture*. Soil Biology and Biochemistry, 2000. 32: p. 2099-2103, https://doi.org/10.1016/S0038-0717(00)00179-6.

64. Stephen M. Ogle, et al., *Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions*. Scientific Reports, 2019. 9(1): p. 11665, https://doi.org/10.1038/s41598-019-47861-7.

65. Rodrigo S. Nicoloso and Charles W. Rice, *Intensification of no-till agricultural systems: An opportunity for carbon sequestration*. Soil Science Society of America Journal, 2021. 85(5): p. 1395-1409, https://doi.org/10.1002/saj2.20260.

66. John M. Baker, et al., T*illage and soil carbon sequestration—What do we really know?* Agriculture, Ecosystems & Environment, 2007. 118(1): p. 1-5, https://doi.org/10.1016/j.agee.2006.05.014.

67. A. N. Kravchenko and G. P. Robertson, *Whole-Profile Soil Carbon Stocks: The Danger of Assuming Too Much from Analyses of Too Little*. Soil Science Society of America Journal, 2011. 75(1): p. 235-240, https://doi.org/10.2136/sssaj2010.0076.

68. Liangang Xiao, et al., *Evaluating soil organic carbon stock changes induced by no-tillage based on fixed depth and equivalent soil mass approaches*. Agriculture, Ecosystems & Environment, 2020. 300: p. 106982, https://doi.org/10.1016/j.agee.2020.106982.

69. Zhangliu Du, et al., *The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis*. Agriculture, Ecosystems & Environment, 2017. 236: p. 1-11, https://doi.org/10.1016/j.agee.2016.11.007.

70. J. W. Wendt and S. Hauser, *An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers*. European Journal of Soil Science, 2013. 64(1): p. 58-65, https://doi.org/10.1111/ejss.12002.

71. Sebastian Doetterl, et al., *Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes*. Earth-Science Reviews, 2016. 154: p. 102-122, https://doi.org/10.1016/j.earscirev.2015.12.005.

72. Papanicolaou T. Wacha K., Wilson C. *Redistribution Effects on Changes in Soil Carbon Storage Potential in Intensely Managed Landscapes*. (2014). pgs. 1262-1271. World Environmental and Water Resources Congress 2014. https://doi.org/10.1061/9780784413548.127.

73. Verena Dlugoß, et al., *Model based analysis of lateral and vertical soil carbon fluxes induced by soil redistribution processes in a small agricultural catchment*. Earth Surface Processes and Landforms, 2012. 37(2): p. 193-208, https://doi.org/10.1002/esp.2246.

74. Bridget Thrasher, et al., *NASA Global Daily Downscaled Projections*, CMIP6. Scientific Data, 2022. 9(1): p. 262, https://doi.org/10.1038/s41597-022-01393-4.

75. B. Thrasher, et al., *NEX-GDDP-CMIP6*. 2021, Center for Climate Simulation. https://doi.org/10.7917/OFSG3345.

76. Keywan Riahi, et al., *The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change*, 2017. 42: p. 153-168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.

77. Amin Nouri, et al., *When do cover crops reduce nitrate leaching? A global meta-analysis*. Global Change Biology, 2022. 28(15): p. 4736-4749, https://doi.org/10.1111/gcb.16269.

78. Giovani Preza-Fontes, et al., S*plit-nitrogen application with cover cropping reduces subsurface nitrate losses while maintaining corn yields*. Journal of Environmental Quality, 2021. 50(6): p. 1408-1418, https://doi.org/10.1002/jeq2.20283.

79. Vipan Kumar, et al., I*ntegrating cover crops for weed management in the semiarid U.S. Great Plains: opportunities and challenges*. Weed Science, 2020. 68(4): p. 311-323, https://doi.org/10.1017/wsc.2020.29.

80. Evan A. Thaler, et al., *Rates of Historical Anthropogenic Soil Erosion in the Midwestern United States*. Earth's Future, 2022. 10(3): p. e2021EF002396, https://doi.org/10.1029/2021EF002396.

81. Megan Horst and Amy Marion, *Racial, ethnic and gender inequities in farmland ownership and farming in the U.S. Agriculture and Human Values*, 2019. 36(1): p. 1-16, https://doi.org/10.1007/s10460-018-9883-3.

82. Anil K Giri, et al. *Participation of Agricultural Producers in the Economic Injury Disaster Loan Program*. (2023). pgs. Presentation 25501. 2023 Agricultural & Applied Economics Association Annual Meeting. Washington D.C., USA https://ageconsearch.umn.edu/record/335596?ln=en.

83. Kelli Russell, Leslie Hossfeld, and Gina Rico Mendez, "*Not a new pattern": Black farmers' perspectives on barriers to participating in federal farm programs*. Journal of Agriculture, Food Systems, and Community Development, 2021. 10(4): p. 195–209, https://doi.org/10.5304/jafscd.2021.104.007

84. U.S. DOE Office of Energy Efficiency & Renewable Energy (EERE). *Energy Equity and Environmental Justice*. Accessed July 2023 Published by EERE; Available from https://www.energy.gov/eere/energy-equity-and-environmental-justice.

85. Jerry V Mannering, David R Griffith, and Keith D Johnson. Winter cover crops—their value and management. 2000. Cooperative Extension Service, Department of Agronomy, Purdue University. AY-247, West Lafayette, IN, USA; http://www.browncountyswcd.com/wp-content/uploads/2018/06/winter-cover-crops.pdf.

86. RS Van Pelt and TM Zobeck. *Effect of polyacrylamide, cover crops, and crop residue management on wind erosion*. (2004). pgs. 1-4. 13th International Soil Conservation Organization (ISCO) Conference. Brisbane, Australia (https://topsoil.nserl.purdue.edu/isco/isco13/PAPERS%20R-Z/VAN%20PELT.pdf).

87. Lawson Connor, Roderick M. Rejesus, and Mahmut Yasar, *Crop insurance participation and cover crop use: Evidence from Indiana county-level data*. Applied Economic Perspectives and Policy, 2022. 44(4): p. 2181-2208, https://doi.org/10.1002/aepp.13206.

88. J. W. Singer, S. M. Nusser, and C. J. Alf, *Are cover crops being used in the US corn belt?* Journal of Soil and Water Conservation, 2007. 62(5): p. 353-358, http://www.jswconline.org/content/62/5/353.abstract.

89. Andrea D. Basche, et al., *Soil water improvements with the long-term use of a winter rye cover crop*. Agricultural Water Management, 2016. 172: p. 40-50, https://doi.org/10.1016/j.agwat.2016.04.006.

90. Conservation Technology Information Center (CTIC) Sustainable Agriculture Research and Education (SARE), and American Seed Trade Association (ASTA). *National Cover Crop Survey Annual Report* 2019–2020. 2020. SARE, CTIC, ASTA, https://www.sare.org/wp-content/uploads/2019-2020-National-Cover-Crop-Survey.pdf.

91. Humberto Blanco-Canqui, et al., *Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils*. Agronomy Journal, 2015. 107(6): p. 2449-2474, https://doi.org/10.2134/agronj15.0086.

92. NSAC. *Cover Crops – Good for Crop Yields, Soil Health, and Bottom Lines*. 2019 Published by National Sustainable Agriculture Coalition; Available from https://sustainableagriculture.net/blog/cover-crops-good-for-crop-yields-soil-health-and-bottom-lines/.

93. Carbon Direct. *Criteria for High-Quality Carbon Dioxide* Removal. 2023. https://www.carbon-direct.com/research-and-reports/criteria-for-high-quality-carbon-dioxide-removal.

94. Jason Bergtold, et al., *A review of economic considerations for cover crops as a conservation practice*. Renewable Agriculture and Food Systems, 2017. 34: p. 1-15, https://doi.org/10.1017/S1742170517000278.

95. Gilbert Jess, Wood Spencer, and Sharp Gwen, *Who Owns the Land?* Agricultural Land Ownership by Race/Ethnicity. Rural America, 2002. 17(4): p. 55-62, http://dx.doi.org/10.22004/ag.econ.289693.

96. Sustainable Agriculture Research and Education (SARE). *Cover Crop Economics Opportunities to Improve Your Bottom Line in Row Crops*. 2019. https://www.sare.org/wp-content/uploads/Cover-Crop-Economics.pdf.

97. Alexandros Tataridas, et al., *Sustainable Crop and Weed Management in the Era of the EU Green Deal: A Survival Guide. Agronomy*, 2022. 12(3): p. 589, https://doi.org/10.3390/agronomy12030589.

98. Karl F. Nordstrom and Shintaro Hotta, *Wind erosion from cropland in the USA: a review of problems, solutions and prospects*. Geoderma, 2004. 121(3): p. 157-167, https://doi.org/10.1016/j.geoderma.2003.11.012.

99. Richard Lowrance, Seth Dabney, and Richard Schultz, *Improving water and soil quality with conservation buffers. Journal of Soil and Water Conservation*, 2002. 57(2): p. A36-A43, https://www.jswconline.org/content/jswc/57/2/36A.full.pdf.

100. K. H. Lee, T. M. Isenhart, and R. C. Schultz, *Sediment and nutrient removal in an established multi-species riparian buffer. Journal of Soil and Water Conservation*, 2003. 58(1): p. 1, https://www.jswconline.org/content/58/1/1.

101. Sarah Taylor Lovell and William C. Sullivan, *Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions*. Agriculture, Ecosystems & Environment, 2006. 112(4): p. 249-260, https://doi.org/10.1016/j.agee.2005.08.002.

102. Lewis L. Osborne and David A. Kovacic, *Riparian vegetated buffer strips in water-quality restoration and stream management*. Freshwater Biology, 1993. 29(2): p. 243-258, https://doi.org/10.1111/j.1365-2427.1993.tb00761.x.

103. J Bagdon, et al. *Conservation buffers to reduce pesticide losses*. 2000. United States Department of Agriculture & Natural Resources Conservation Service, https://efotg.sc.egov.usda.gov/references/public/va/ConservationBuffertoReducePesticideLosses.pdf.

104. Karen L Bailey and Bruce D Gossen, *Boundary areas and plant diseases, in Field boundary habitats: implications for weed, insect and disease management*, A.G. Thomas, Editor. 2005, Canadian Weed Science Society: Sainte-Anne-de-Bellevue, Quebec, Canada. p. 165-169 (https://www.weedscience.ca/wp-content/uploads/2021/04/Boundary_livre_with_cover.pdf#page=176).

105. Shruti K. Mishra, et al., *Performance-Based Payments for Soil Carbon Sequestration Can Enable a Low-Carbon Bioeconomy. Environmental Science & Technology*, 2021. 55(8): p. 5180-5188, 10.1021/acs.est.0c06452.

106. Elke Brandes, et al., *Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production*. GCB Bioenergy, 2018. 10(3): p. 199-212, https://doi.org/10.1111/gcbb.12481.

107. Jean M. McGuire, et al., *Farmer identities and responses to the social–biophysical environment*. Journal of Rural Studies, 2015. 39: p. 145-155, https://doi.org/10.1016/j.jrurstud.2015.03.011.

108. Sarah M. Lewis, et al., *A fuzzy logic-based spatial suitability model for drought-tolerant switchgrass in the United States*. Computers and Electronics in Agriculture, 2014. 103: p. 39-47, https://doi.org/10.1016/j.compag.2014.02.006.