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REGENERATIVE FARMING PRACTICES: HOW MUCH CARBON DO THEY SEQUESTER?

by

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REGENERATIVE FARMING PRACTICES: HOW MUCH CARBON DO THEY SEQUESTER?

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Along with the recent rise of voluntary carbon markets comes potential carbon credit producers seeking reliable information on how much carbon they can expect to sequester. In this thesis a distribution of expected sequestration outcomes is constructed using cost-benefit analysis and data gathered from agronomic experiments and land-grant university crop budgets for cover crops and no-till practices. The inverse cumulative distribution of carbon sequestration outcomes from adopting a regenerative agricultural practice is visualized and the net social benefit of paying farmers to produce carbon credits is estimated. Results show that on average there is between \$29.02 and \$37.20 of social benefit produced per ton of CO_2e sequestered using no-till, and between -\$8.68 and \$26.82 of social benefit produced per ton of CO_2e sequestered using cover crops. Information uncertainty about the sequestration potential for individual fields means that the outcome for an individual farmer's field lies somewhere within these ranges, but the results are firmly positive for no-till carbon credit production.

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Introduction

Many solutions have been proposed in response to the rapidly worsening climate crisis. Some appear to be more feasible than others, and one such realistic contribution is adapting already widespread agricultural systems to sequester greater amounts of atmospheric carbon dioxide. When an agricultural producer reduces tilling or starts planting cover crops when a field would otherwise lay fallow, more atmospheric carbon dioxide is converted to soil organic carbon (SOC). This soil carbon can no longer contribute to the greenhouse effect (Lal 2004) and therefore offsets new carbon emissions. While a rapid reduction of carbon emissions to the atmosphere is necessary (USGCRP 2017), increased sequestration allowing more time for change is simultaneously needed.

Voluntary carbon markets incentivize and facilitate transactions between producers of agricultural carbon credits (offsets) and buyers who desire to reduce their own carbon footprint. These programs enroll farmers to adopt no-till or cover crop practices and calculate an estimate of the amount of carbon sequestered using representative physical tests and algorithms based on historical data. They pay the producers to adopt the practice, as it usually costs the farmer additional financial resources in the form of a new seed drill or additional seeds and pesticides/herbicides, so payment is both compensation for these expenses and incentive to participate in the program (Giller et al 2021). Credits for the carbon sequestered are verified by a third party, which are then sold to individual or corporate consumers online. These voluntary carbon markets have been increasing in recent years in the United States, and some examples include Nori, IndigoAg, and Land'O'Lakes' Truterra.

However, voluntary carbon markets are not a new phenomenon. The Chicago Climate Exchange (CCX) operated from 2003-2010 and was the first main carbon market in the United States. Unfortunately, the market collapsed in 2008-2010 when the global financial crisis hit and demand for credits fell. An excess supply ensued, resulting in the price of credits dropping dramatically to near zero and the end of the market (Spaargaren and Mol 2013). The European Union also ran a carbon market (a compliance market rather than a voluntary market) called the Emissions Trading System (ETS) during this period. The ETS survived the financial crisis largely in part due to the creation of the Market Stability Reserve (MSR) by the EU, which purchased the excess supply of credits to keep prices from bottoming out at zero. An important regulatory step accompanied this action: the MSR severely curtailed the production of future credits until the excess credits could be auctioned off, which occurred incrementally over a 10-year period (European Commission 2017). The market continued operating and is notably still active today.

How can observation of these past experiences assist policymakers in ensuring recently new voluntary carbon markets do not meet a similar fate as the Chicago Climate Exchange? First, accurate knowledge of the distribution of carbon sequestration outcomes for no-till and cover crops is needed. The goal of this research is to gather sequestration data from the existing academic literature to present an inverse cumulative distribution of outcomes, then use a cost-benefit analysis including crop budgets and the social cost of carbon to estimate the distribution of potential net benefits of a program that registers farmers to produce carbon credits.

Literature Review

There are attributes of carbon credits that complicate the way they are treated in a cost-benefit analysis compared to normal goods. First, carbon offsets are credence goods. Even after a consumer purchases a carbon offset, they cannot determine the offset's quality to measure how much utility they gain from the transaction (Bonroy and Constantatos 2008). Consumers may find the offset producer reputable and if so are more likely to make a repeat purchase in the future, but no physical product or service is provided to the consumer that they can measure the quality of in order to render judgment.

Additionally, carbon sequestration is a public good. The sequestration of carbon dioxide from the atmosphere and subsequent lessening of the effects of climate change provide a benefit to all people on Earth that is not excludable and not rival in consumption. In most transactions, consumers pay money to receive a product or service for their personal use exclusively. In the case of individuals purchasing carbon offsets, the benefits of the good are enjoyed universally even though the cost is privatized. Therefore, when examining the costs and benefits for farmers to produce carbon credits the public benefit of the good must be considered. To account for this social benefit, in this study the social cost of carbon (SCC) is used.

Agronomic studies regarding the carbon sequestration rate of both no-till and cover crops are vital to answering the research question of how much carbon is actually sequestered by these practices. In this study, search procedures followed standard meta-analysis guidelines (Hansen et al 2021) and included using the AgEcon Search database and Google Scholar. For no-till, a meta-analysis by West and Post (2002) provided references to tens of additional studies that were deemed useful. The authors identified experiments with a distribution of outcomes, but obviously they did not include the more than two decades worth of results that have been published since. More recently published studies that provided sequestration observations included Valkama et al (2020), Ruis and Blanco-Canqui (2017), Lal (2015), and Poeplau and Don (2015).

Methods

Literature reporting results of scientific studies of the effects of no-till and cover crops on changes in soil-sequestered carbon is abundant. The review here has identified multi-year experiments for 77 no-till sequestration observations and 189 cover crop sequestration observations. These data were aggregated and used to form an inverse cumulative distribution to use in the cost-benefit analysis. The practice of gathering and combining data from existing literary sources is called meta-analysis. One must be cautious when doing a meta-analysis to ensure the data being collected are recorded or converted into the appropriate units (DeSimone et al. 2021). Results of all studies are presented here in metric tons CO_{2e} sequestered per year per acre.

Selection bias presents another potential challenge. Multiple scholars encourage data collection from studies published in both well-known journals and their lesser known counterparts in an attempt to avoid over-representing data that appear in the top journals (Steel et al. 2021). While there are some possible outliers in the compiled data, no values were removed in order to prevent potential selection bias.

Most of the no-till observations were identified from a meta-analysis completed in 2002 (West and Post 2002). This reference served as a guide on how to aggregate and sort data for the rest of the data collection in this study. In the article, the authors explained how they accounted for fluxes caused by variable precipitation amounts and temperatures by comparing observations taken in the same year. The research for this thesis examined each original reference in West and Post (2002) and standardized calculations. Seventy-four unique observations were gathered from West and Post (2002). Valkama et al. (2020) report sequestration rates for no-till test plots in Kazakhstan, Finland, and Italy, bringing the total number of no-till observations to 77. The mean value for no-till carbon sequestration in these studies is 0.77 metric tons of CO_2e per acre per year, and the median value is 0.55 metric tons of CO_2e per acre per year.

Carbon sequestration observations using cover crops were gathered from three main studies. Ruis and Blanco-Canqui (2017) provided 33 observations, Lal (2015) provided 15 observations, and Poeplau and Don (2015) provided 140 observations. To avoid double-counting, locations and dates attached to the observations were compared. The mean value for cover crop carbon sequestration in these studies is 0.76 metric tons of

CO_2e per acre per year, and the median value is 0.48 metric tons of CO_2e per acre per year.

Land grant university crop budgets proved to be the best resources for data on the cost of adopting no-till or cover crops. Six budgets were found for implementation of no-till with an average cost of $16.67 per acre per year, and a range of $8.17 to $23.75. Most of this cost is due to the need for a no-till seed drill. Eight budgets were found for planting cover crops with an average of $44.84 per acre per year, and a range of $21.51 to $69.11. The large range in cover crop cost estimates is due to the type of seed used with cereal rye being the cheapest and hairy vetch being the most expensive.

Results

The results of data collection are summarized in Figures 1 & 2. Each figure is an inverse cumulative distribution of outcomes with respect to the amount of carbon sequestered. Sequestration outcomes on the horizontal axis increase from lowest to highest, and Figures 1 and 2 show that there is a large range of potential outcomes hidden by the average values. For purposes of this analysis, it is assumed that the experimental conditions are representative samples of farmers’ fields, so that a randomly selected farmer’s field could fall anywhere along the distribution according to the probabilities on the y axis. The curve in each figure indicates the percent of plots that yielded sequestration above the level indicated on the horizontal axis.

For example, in Figure 1 for no-till experiments, the worst outcome was a plot on which no-till *decreased* soil carbon by slightly greater than 2 tons of CO_2e per acre per year. As revealed on Figure 1, 89.6% of the no-till experimental plots recorded positive carbon sequestration, while 28% of them recorded sequestration above 1 ton per acre per year. Only 6.5% of no-till plots achieved sequestration greater than 2 tons of CO_2e annually. Thus, the average increase of 0.77 tons sequestered per year hides a large range of outcomes.

Figure 2 indicates a similar result from the cover crop experiments. The inverse cumulative distribution shows that 89.9% of cover crop plots recorded positive sequestration with 28% of plots recording sequestration over 1 ton per acre per year. Only 8% of cover crop plots achieved sequestration greater than 2 tons of CO_2e per acre per year. The range of outcomes for cover crops is even larger than the no-till range, with a minimum observation of approximately -3 tons per acre per year and a maximum observation of almost 5 tons per acre per year.

As shown in the inverse cumulative distributions for both practices, about 10% of plots resulted in negative changes in soil carbon. Because of this loss, buyers would not be willing to pay for a change in practice on these sites, or for any site for which the cost exceeds the benefits, if they could avoid it.

Figure 1: Percentage of no-till plots that showed carbon sequestration above the amount on the horizontal axis. Any point along the curve can be interpreted as "Y% of plots have greater than X amount of sequestration".

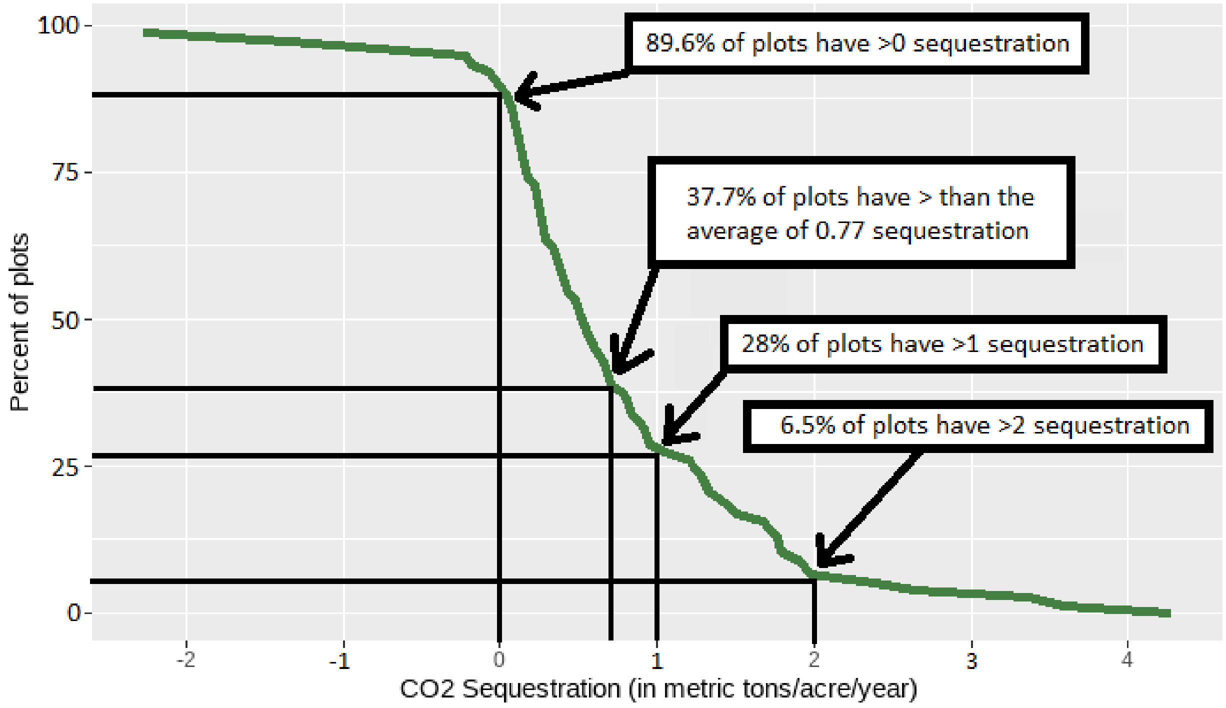
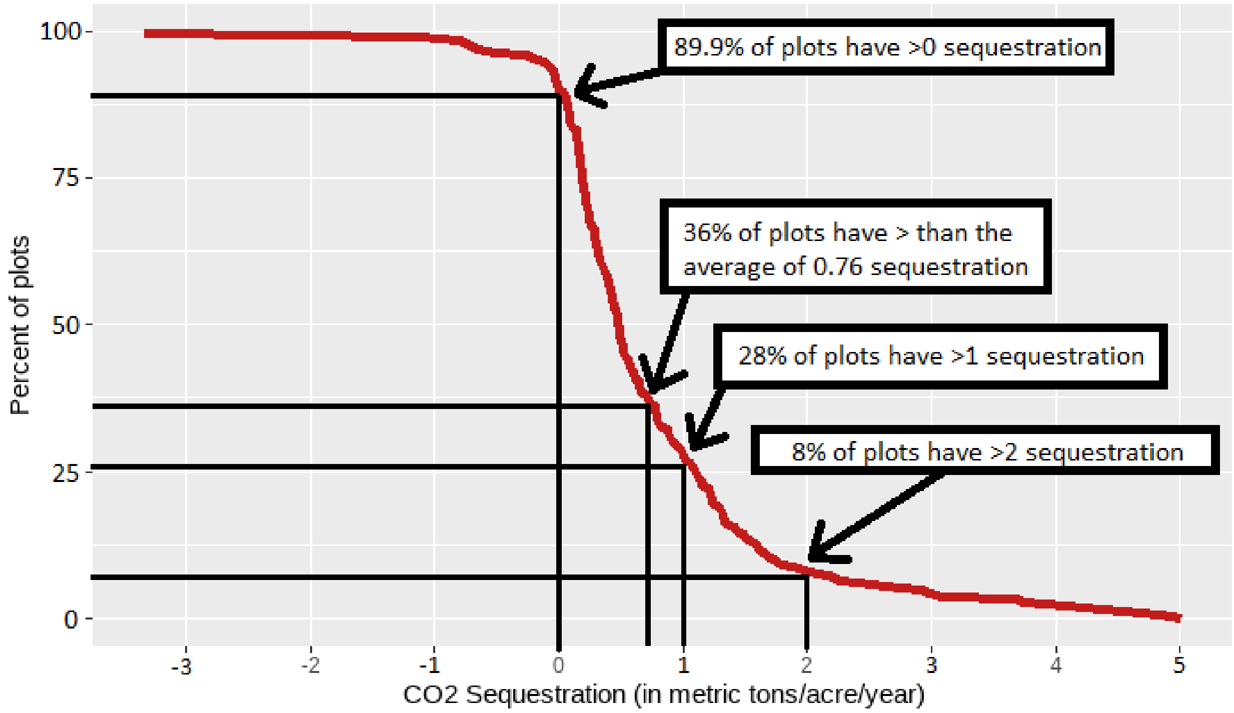


Figure 2: Percentage of cover crop plots that showed carbon sequestration above the amount on the horizontal axis. Any point along the curve can be interpreted as "Y% of plots have greater than X amount of sequestration".



The distributions of outcomes for no-till and for cover crop observations are nearly identical, even though the experimental reports the distributions are created from are entirely unique. Because the cover crops dataset contains more than twice the number of observations than the no-till data set, the cover crop distribution line is smoother than its no-till counterpart. Additionally, the cover crop observations show a larger range of outcomes than the no-till observations.

As explained in the methods section, land-grant university crop budgets were used to estimate the cost for a farmer to adopt no-till or cover crop practices. The average budget cost of switching to no-till was found to be $16.67 per acre, ranging from $8.17 to $23.75. Based on the average sequestration rate of no-till of 0.766 metric tons of CO_2e/acre/year and the cost values above, the expected average cost to sequester one metric ton of CO_2e using no-till is $21.76. When calculated in excel using the precise average sequestration value with an increased number of significant figures, the expected average cost is $21.98, which is the value used in the remainder of the analysis.

The average cost of planting a cover crop is $44.84 with a range of $21.51 to $69.11. Based on the average sequestration rate of cover crops of 0.758 metric tons of CO_2e/acre/year and the cost values above, the expected average cost to sequester one metric ton of CO_2e using cover crops is $59.16. When calculated in excel using the precise average sequestration value with an increased number of significant figures, the expected average cost is $59.68, which is the value used in the remainder of the analysis.

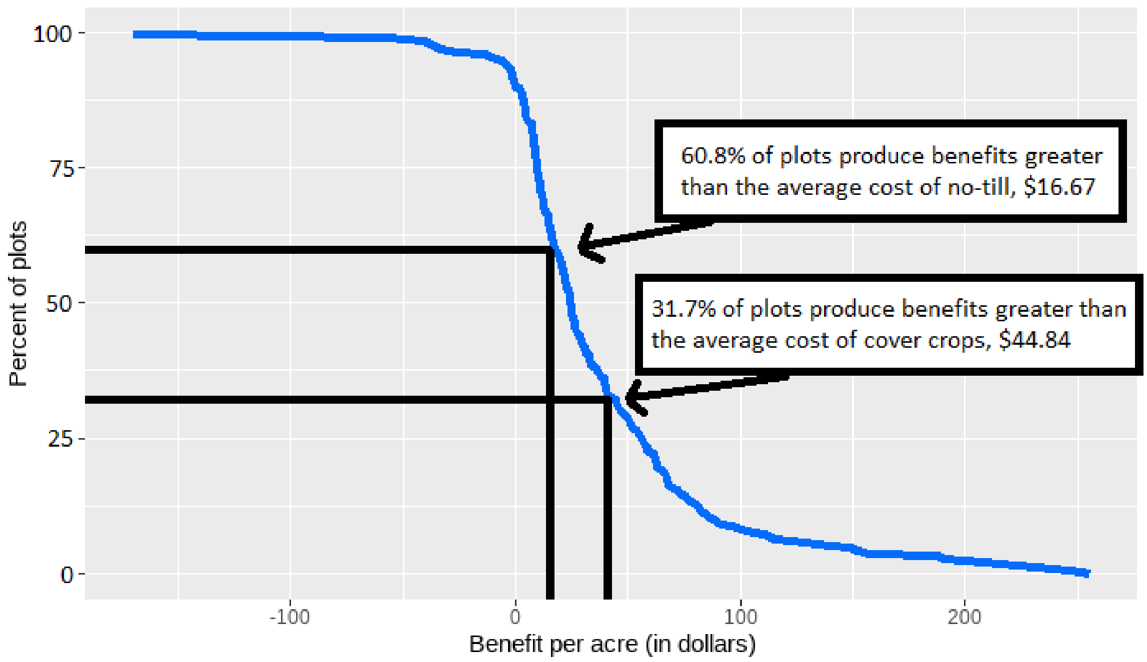
As for estimating benefits, the social cost of carbon (SCC) is used here. There are private benefits attained by buyers of credits apparently equal to approximately $15-20 per ton, which is the typical price at which voluntary carbon credits are sold. However, apart from the private value those buyers receive, there is a social benefit to the entire world society of reducing atmospheric carbon because it reduces future damages from climate change. Thus, any action that can be taken to slow or reverse climate change is socially valuable. The present value (discounted) of future costs to society of an additional ton of CO_2

emitted today is known as the social cost of carbon (SCC). In this analysis the SCC is used as the social benefit achieved by the sequestration of carbon. Because buyers of credits may experience private benefits in addition to this social benefit, the social cost of carbon is a lower bound estimate of total benefit.

The federal government maintains estimates of the social cost of carbon (Executive Order 13990) based on academic studies of likely additional damages in the future due to an additional ton of emissions in the present. The 2021 estimate of the social cost of carbon by Interagency Working Group on Social Cost of Greenhouse Gases is $51.00 per metric ton of CO_2 (Interagency Working Group on Social Cost of Greenhouse Gases, 2021). Notably, the average cost of sequestering CO_2 via no-till is $21.98 per ton, below the $51 benefit, while the average cost via cover crops, $59.68 per ton, is higher than the $51 benefit.

Figure 3 plots the same distribution of outcomes as Figure 2, but with the horizontal axis CO_2 values multiplied by $51 to convert from sequestration per acre per year to benefit per acre per year. It also identifies the fraction of observations at which each practice results in a net benefit. (Because the inverse cumulative distributions are so similar, Figure 3, which is plotted from the cover crop distribution, represents both no-till and cover crop sequestration distributions.) The graph shows that 60.8% of plots are expected to produce carbon sequestration benefits greater than the $16.67 average cost of adopting no-till. For cover crops, only 31.7% of plots are expected to produce benefits greater than the average cost of cover crops, which is $44.84.

Figure 3: Percentage of plots that showed benefits above the amount on the horizontal axis. Any point along the curve can be interpreted as "Y% of plots produce greater than X amount of benefit".



60.8% of plots produce benefits greater than the average cost of no-till, $16.67

31.7% of plots produce benefits greater than the average cost of cover crops, $44.84

If these experimental plots do represent the distribution of outcomes on farm fields, it would be reasonable for society to enroll and reimburse only the top 60.8% of fields for no-till, and only the top 31.7% of cover crop fields, as these fields are expected to sequester enough carbon to return a net benefit. To implement that, however, would require identifying which farmers' fields are represented by which experimental plots. If it could be known ahead of time exactly which of the experimental plots reflect the outcome for a given farm field, a "perfect information" policy could be implemented to enroll only fields with positive net benefits. For the 60.8% of fields that would be enrolled for no-till under a perfect information policy, the average sequestration would be 1.21 tons per acre, providing an average benefit of $61.71 per acre and an average cost of $13.80 per ton sequestered. For a policy of open enrollment where *all* no-till fields are enrolled (a "no information" policy), the cost per ton sequestered rises to $21.98, still well below the social benefit of $51.00.

Under a perfect information policy for a cover crop program, the average sequestration for the 31.7% of fields enrolled would be 1.85 tons per acre, resulting in an average cost of $24.18 per ton sequestered, well below the social benefit. However, a program enrolling *all* fields in cover crops would include many fields with adverse outcomes, resulting in the average sequestration cost rising to $59.61 per ton, above the social benefit of $51. This result is reflected in the second to last row of Table 1 where the net benefit of enrolling all cover crop fields is revealed to be -$8.68.

Table 1: Average costs and benefits expected by practice and enrollment criterion

Outcome	**No-till**		**Cover crops**	
	Enroll all fields	**Enroll only fields with social benefit greater than cost**	**Enroll all fields**	**Enroll only fields with social benefit greater than cost**
Percent of fields enrolled	100%	60.8%	100%	31.7%
Average sequestration (tons CO_2e per acre enrolled)	0.77	1.21	0.76	1.85
Average cost per acre enrolled ($ per acre)	$16.67	$16.67	$44.84	$44.84
Expected cost of sequestration ($ per ton CO_2e)	$21.98	$13.80	$59.68	$24.18
Social benefit of sequestration ($ per ton CO_2e)	$51.00	$51.00	$51.00	$51.00
Expected net benefit of sequestration ($ per ton CO_2e)	$29.02	$37.20	-$8.68	$26.82
Expected net benefit of sequestration ($ per acre)	$22.01	$44.94	-$6.52	$49.73

Realistically, the market will be able to operate somewhere in the realm between no information and perfect information (the pairs of columns in Table 1). Computer models and satellite imagery are able to predict expected carbon sequestration on a piece of land, although certainly not with 100% accuracy (Plastina 2022). The two estimates of this study provide a lower and upper bound for the expected net benefits. Based on the results of this analysis, between $29.02 and $37.20 of social benefit would be produced per metric ton of CO_2e sequestered if farmers were paid to adopt no-till. Notably, while this estimate is a range it is substantially positive.

The same cannot be said of the estimate of net benefits from cover crops. If farmers were paid to sequester carbon using cover crops, the estimated net benefit is between -$8.68 and $26.82. Zero is included in this range, and because it is not known precisely how much information market participants will have access to, it is uncertain whether the average net benefit would be negative or positive.

Because more information available about potential sequestration on given fields could lead to higher net benefits, there is value in addressing the issue of information uncertainty. Farmers may be required to divulge data about the type of crops they grow and other management practices as part of the application process of submitting acres to be considered. That information could be used to produce a better carbon sequestration outcome estimate, but only if sequestration models are capable of using the information to produce accurate sequestration predictions. Satellite imagery could also be used in the same way if sequestration models could use the information. Ultimately, satellite imagery may be used to monitor carbon sequestration amounts by observing crop cover, biomass, growth stages, and tillage practices. Investment in advancing the ability of satellite imagery to reliably estimate carbon sequestration would speed up the process, but the current technology's capabilities are limiting.

Implications

Policymakers are likely to be interested in the net benefits of a program that incentivizes carbon credit production, which includes the variability caused by the amount of available information. As shown in Table 1, higher amounts of information about potential sequestration by particular fields would lead to less costly sequestration because the fields that will provide a clear net social benefit can be identified and included in the program. Less information about potential sequestration leads to the inclusion of the fields that do not produce a net social benefit, resulting in a more costly policy. For no-till however, even if all fields were enrolled and reimbursed, there is an expected average net benefit of $29.02 per ton of CO_2 sequestered. Thus, a potential public program to pay farmers to produce carbon credits using no-till is expected to provide a positive public benefit with no information available about individual fields. For cover crops, however, more information is needed to help identify fields with positive net benefits, if the expected social benefit of a program is to be positive.

Included in the cost-benefit analysis of this study are private costs of adopting a conservation practice and the possible social benefits from any resulting carbon sequestration. However, there are additional public and private benefits from both no-till and cover crops. These potential benefits include increased biodiversity, reduced runoff, less soil erosion, improved ecosystem resilience, and increased water filtration (White

2020). Less fertilizer and less water than normal are other potential benefits. Reduced soil erosion helps farmers retain healthy and productive soils for longer. Some of these benefits accrue to people in the surrounding areas as well. Increased water filtration and greater biodiversity improve nearby communities by providing cleaner drinking water and a healthier local ecosystem.

However, these private and local external benefits are difficult to quantify. No convenient metric such as the SCC exists for quantifying the local benefits of better groundwater quality or a more diverse ecosystem, and estimation of these benefits is beyond the scope of this work. They are not included in the analysis and thus the estimated net benefits in this study are minimums.

An important aspect of carbon sequestration credits is additionality. Essentially, an agricultural carbon credit satisfies additionality if it was produced by a change in practice that would not or did not otherwise occur. Under this definition, a farmer who began using no-till 10 years ago would not be eligible for payment for those past changes in practice; only present and future actions satisfy additionality. Over half of all farmed acres in the United States are already managed using no-till (USDA-NASS 2017), so any farmers submitting fields for inclusion in carbon credit production would need to be currently using standard tillage and be willing to adopt no-till.

Paying farmers to adopt no-till or cover crops but neglecting to reimburse farmers who have already begun sequestering carbon on their own without the cash incentive brings up issues of fairness and equity. However, the demand side of the voluntary carbon credit market almost universally requires additionality in order to satisfy buyers' goals and net-zero promises. While fairness to earlier adopters may be important for public support of a program, little can be done to accommodate it in the voluntary carbon market because purchasers of credits are likely to insist on additionality because they want assurance that the sequestration is due to their own action (their own payment).

A final consideration of the results of this study is the value of the social cost of carbon used. This analysis employs the $51/metric ton (in 2020 USD) as currently evaluated by the federal government to be the social value of avoiding emitting a ton of carbon dioxide (or, equivalently, the benefit of sequestering a ton of carbon dioxide equivalent). Some recent research suggests the value is too low and should be set higher. Work by Rennert et al. (2022), for example, suggests the social cost of carbon should be $185/metric ton (in 2020 USD) based on updated models and novel discoveries about the future damages of climate change.

Using a higher SCC value would significantly change the results of the analysis. The net benefit values for both no-till and cover crops would be much higher. With an increased estimate of social benefits, farmers might have greater leverage in negotiating higher prices paid for their sequestration efforts.

Conclusion

While the initial goal of this research was to investigate evidence-backed average sequestration rates for the conservation practices of no-till and cover crops, one of the most important findings is that there is significant variation in sequestration outcomes throughout the existing scientific literature. An inverse cumulative distribution of these outcomes provides useful information on the probability of a particular acre producing an expected sequestration amount, but with current technology it is impossible to predict exactly how much carbon will be sequestered on a field randomly selected from fields that farmers might offer for enrollment in a program.

Using the gathered data, it was estimated that if farmers were paid to stop using conventional tillage methods and adopt no-till practices the net social benefit would be between $29.02 and $37.20 per ton of CO_2e sequestered. If there was zero information about the expected sequestration rates of potential plots to enroll, the expected net social benefit would be the lower value, while perfect information about potential plots would result in the higher value.

For cover crops, under the assumption of no useful information (enrolling everyone), the expected net social benefit per ton of sequestered CO_2e is -$8.68 per ton sequestered. If perfect information were available (it is known exactly how much each potential acre will sequester), a net benefit of $26.82 per ton of sequestered CO_2e could be achieved. Notably, there is a wider range of expected values for the cost of adopting cover crops which can be attributed to the significantly more expensive cost of planting a cover crop compared to the adoption of no-till.

Despite the uncertainty caused by the issue of information availability, these results provide important conclusions. By combining data available in the literature, the range of outcomes on any random plot of farmland has been visualized. The knowledge that costs of adopting conservation agriculture practices are highly variable is also useful, as is the inverse cumulative distribution of sequestration outcomes produced. Cover crop costs are the most variable due to the wide variety of available seeds as well as possible potential economic uses of the cover crop.

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Van Kooten, G. C., Schmitz, A., & Furtan, W. H. (1988). The economics of storing a non-storable commodity. The Canadian Journal of Economics, 21(3), 579. https://doi.org/10.2307/135439

West, T. O., & Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. Soil Science Society of America Journal, 66(6), 1930–1946. https://doi.org/10.2136/sssaj2002.1930

White, C. (2020). Why regenerative agriculture? American Journal of Economics and Sociology, 79(3), 799–812. https://doi.org/10.1111/ajes.12334

Appendix A. Experimental Sequestration Outcomes for No-till and Sources

NT observations CO2/acre/year	Source 1	Source 2
0.07	West	Aase, J. K., & Pikul, J. L. (1995). Crop and soil response to long-term tillage practices in the northern Great Plains. Agronomy Journal, 87(4), 652–656. https://doi.org/10.2134/agronj1995.00021962008700040008x
0.29		Angers, D. A., N'dayegamiye, A., & Côté, D. (1993). Tillage-induced differences in organic matter of particle-size fractions and microbial biomass. Soil Science Society of America Journal, 57(2), 512–516. https://doi.org/10.2136/sssaj1993.03615995005700020035x
1.32		Arshad, M. A., Schnitzer, M., Angers, D. A., & Ripmeester, J. A. (1990). Effects of till vs no-till on the quality of soil organic matter. Soil Biology and Biochemistry, 22(5), 595–599. https://doi.org/10.1016/0038-0717(90)90003-i
0.7		Balesdent, J., Marriotti, A., & Boisgontier, D. (1990). Effect of tillage on soil organic carbon mineralization estimated from 13c abundance in maize fields. European Journal of Soil Science, 41(4), 587–596. https://doi.org/10.1111/j.1365-2389.1990.tb00228.x
0.77		Bayer, C., Mielniczuk, J., Amado, T. J. C., Martin-Neto, L., & Fernandes, S. V. (2000). Organic matter storage in a sandy clay loam acrisol affected by tillage and cropping systems in southern Brazil. Soil and Tillage Research, 54(1-2), 101–109. https://doi.org/10.1016/s0167-1987(00)00090-8
1.06		op. cit.
0.11		Buyanovsky, G. A., & Wagner, G. H. (2002). Carbon cycling in cultivated land and its global significance. Global Change Biology, 4(2), 131–141. https://doi.org/10.1046/j.1365-2486.1998.00130.x
0.11		Campbell, C. A., McConkey, B. G., Zentner, R. P., Dyck, F. B., Selles, F., & Curtin, D. (1995). Carbon sequestration in a brown chernozem as affected by tillage and rotation. Canadian Journal of Soil Science, 75(4), 449–458. https://doi.org/10.4141/cjss95-065
0.29		op. cit.
0.18		op. cit.
0.18		op. cit.
0.84		Chagas, C. I., Santanatoglia, O. J., Castiglioni, M. G., & Marelli, H. J. (1995). Tillage and cropping effects on selected properties of an Argiudoll in Argentina.

	Communications in Soil Science and Plant Analysis, 26(5-6), 643–655. https://doi.org/10.1080/00103629509369325
0.84	Chan, K. Y., Roberts, W. P., & Heenan, D. P. (1992). Organic carbon and associated soil properties of a red earth after 10 years of rotation under different stubble and tillage practices. Soil Research, 30(1), 71–83. https://doi.org/10.1071/sr9920071
0.55	Chaney, K., Hodgson, D. R., & Braim, M. A. (2009). The effects of direct drilling, shallow cultivation and ploughing on some soil physical properties in a long-term experiment on Spring Barley. The Journal of Agricultural Science, 104(1), 125–133. https://doi.org/10.1017/s0021859600043069
0.29	Dalal, R. C., Henderson, P. A., & Glasby, J. M. (1991). Organic matter and microbial biomass in a vertisol after 20 yr of zero-tillage. Soil Biology and Biochemistry, 23(5), 435–441. https://doi.org/10.1016/0038-0717(91)90006-6
0.33	op. cit.
0.29	op. cit.
1.72	Dao, T. H. (1998). Tillage and crop residue effects on carbon dioxide evolution and carbon storage in a paleustoll. Soil Science Society of America Journal, 62(1), 250–256. https://doi.org/10.2136/sssaj1998.03615995006200010032x
3.37	Deibert, E. J., & Utter, R. A. (1989). Growth and NPK uptake by soybean cultivars in northern U.S.A. under reduced tillage systems. Canadian Journal of Plant Science, 69(4), 1101–1111. https://doi.org/10.4141/cjps89-133
1.98	Dick, W. A. (1983). Organic Carbon, nitrogen, and phosphorus concentrations and ph in soil profiles as affected by tillage intensity. Soil Science Society of America Journal, 47(1), 102–107. https://doi.org/10.2136/sssaj1983.03615995004700010021x
1.28	op. cit.
1.79	op. cit.
-0.22	Dickey, E. C., Jasa, P. J., & Grisso, R. D. (1994). Long term tillage effects on grain yield and soil properties in a soybean/grain sorghum rotation. Journal of Production Agriculture, 7(4), 465–470. https://doi.org/10.2134/jpa1994.0465
0.44	op. cit.
1.5	Edwards, J. H., Wood, C. W., Thurlow, D. L., & Ruf, M. E. (1992). Tillage and crop rotation effects on fertility status of a hapludult soil. Soil Science Society of America Journal, 56(5), 1577–1582. https://doi.org/10.2136/sssaj1992.03615995005600050040x

2.38	op. cit.
1.76	op. cit.
0.95	Francis, G. S., & Knight, T. L. (1993). Long-term effects of conventional and no-tillage on selected soil properties and crop yields in Canterbury, New Zealand. Soil and Tillage Research, 26(3), 193–210. https://doi.org/10.1016/0167-1987(93)90044-p
0.48	Franzluebbers, A. J., & Arshad, M. A. (1996). Soil Organic Matter Pools during early adoption of conservation tillage in northwestern Canada. Soil Science Society of America Journal, 60(5), 1422–1427. https://doi.org/10.2136/sssaj1996.03615995006000050019x
0.15	Hendrix, P. F. (1996). Long-Term Patterns of Plant Production and Soil Carbon Dynamics in a Georgia Piedmont Agroecosystem. In Soil organic matter in temperate agroecosystems: Long-term experiments in North America. essay, CRC Press.
4.28	Hermawan, B., & Cameron, K. C. (1993). Structural changes in a silt loam under long-term conventional or minimum tillage. Soil and Tillage Research, 26(2), 139–150. https://doi.org/https://doi.org/10.1016/0167-1987(93)90040-V
0.81	Horne, D. J., Ross, C. W., & Hughes, K. A. (1992). Ten years of a maize/oats rotation under three tillage systems on a silt loam in New Zealand. 1. A comparison of some soil properties. Soil and Tillage Research, 22(1-2), 131–143. https://doi.org/10.1016/0167-1987(92)90027-9
0.15	Hossain, S. A., Dalal, R. C., Waring, S. A., Strong, W. M., & Weston, E. J. (1996). Comparison of legume-based cropping systems at Warra, Queensland. 1. soil nitrogen and organic carbon accretion and potentially mineralisable nitrogen. Australian Journal of Soil Research, 34(2), 273–287. https://doi.org/10.1071/sr9960273
0.29	op. cit.
0.4	op. cit.
1.98	Hunt, P. G., Karlen, D. L., Matheny, T. A., & Quisenberry, V. L. (1996). Changes in carbon content of a Norfolk loamy sand after 14 years of conservation or conventional tillage. Journal of Soil and Water Conservation, 51(3), 255–258. Retrieved from https://www.webofscience.com/wos/woscc/full-record/WOS:A1996UH70500017?SID=USW2EC0CD7wbRfQAWPac7FDPrZtqk.
1.32	Hussain, I., Olson, K. R., & Ebelhar, S. A. (1999). Long-term tillage effects on soil chemical properties and organic matter fractions. Soil Science Society of America Journal, 63(5), 1335–1341. https://doi.org/10.2136/sssaj1999.6351335x

0.59	Ismail, I., Blevins, R. L., & Frye, W. W. (1994). Long-term no-tillage effects on soil properties and continuous corn yields. Soil Science Society of America Journal, 58(1), 193–198. https://doi.org/10.2136/sssaj1994.03615995005800010028x
0.29	op. cit.
0.29	op. cit.
0.51	op. cit.
0.66	Kladivko, E. J., Griffith, D. R., & Mannering, J. V. (1986). Conservation tillage effects on soil properties and yield of corn and soya beans in Indiana. Soil and Tillage Research, 8, 277–287. https://doi.org/10.1016/0167-1987(86)90340-5
1.39	op. cit.
1.46	Mielke, L. N., Doran, J. W., & Richards, K. A. (1986). Physical environment near the surface of plowed and no-tilled soils. Soil and Tillage Research, 7(4), 355–366. https://doi.org/10.1016/0167-1987(86)90022-x
0.88	op. cit.
0	op. cit.
-0.18	Miller, J. J., Larney, F. J., & Lindwall, C. W. (1999). Physical properties of a chernozemic clay loam soil under long-term conventional tillage and no-till. Canadian Journal of Soil Science, 79(2), 325–331. https://doi.org/10.4141/s98-053
-0.22	Paul, E. A., Paustian, K. H., Elliot, E. T., & Cole, C. V. (1997). Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press.
-1.35	op. cit.
-2.27	op. cit.
1.9	op. cit.
2.64	op. cit.
3.59	op. cit.
0.4	op. cit.
0.55	op. cit.
0.07	op. cit.
-0.07	op. cit.
0.59	op. cit.

0.7		op. cit.
0.44		op. cit.
0.22		op. cit.
0		op. cit.
0.95		op. cit.
1.21		op. cit.
1.24		op. cit.
0.7		Potter, K. N., Torbert, H. A., Jones, O. R., Matocha, J. E., Morrison, J. E., & Unger, P. W. (1998). Distribution and amount of soil organic C in long-term management systems in Texas. Soil and Tillage Research, 47(3-4), 309–321. https://doi.org/10.1016/s0167-1987(98)00119-6
0.4		op. cit.
0.4		op. cit.
0.66		Rhoton, F. E. (2000). Influence of time on soil response to no-till practices. Soil Science Society of America Journal, 64(2), 700–709. https://doi.org/10.2136/sssaj2000.642700x
0.92		op. cit.
1.79		Soane, B. D., & Ball, B. C. (1998). Review of Management and conduct of long-term tillage studies with special reference to a 25-yr experiment on Barley in Scotland. Soil and Tillage Research, 45(1-2), 17–37. https://doi.org/10.1016/s0167-1987(97)00070-6
1.68		op. cit.
0.11		Tebrügge, F., & Düring, R.-A. (1999). Reducing tillage intensity — a review of results from a long-term study in Germany. Soil and Tillage Research, 53(1), 15–28. https://doi.org/10.1016/s0167-1987(99)00073-2
0.04	Valkama	Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., Schillaci, C., Sacco, D., Moretti, B., Grignani, C., & Acutis, M. (2020). Can conservation agriculture increase soil carbon sequestration? A modelling approach. Geoderma, 369. https://doi.org/10.1016/j.geoderma.2020.114298
0.15		op. cit.
0.15		op. cit.

0.51	West	Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., Schillaci, C., Sacco, D., Moretti, B., Grignani, C., & Acutis, M. (2020). Can conservation agriculture increase soil carbon sequestration? A modelling approach. Geoderma, 369. https://doi.org/10.1016/j.geoderma.2020.114298

Appendix B. Experimental Sequestration Outcomes for Cover Crops and Sources

CC observations CO2/acre/year	Source 1	Source 2
0.33	Ruis	Acuña, J. C., & Villamil, M. B. (2014). Short-term effects of cover crops and compaction on soil properties and soybean production in Illinois. Agronomy Journal, 106(3), 860–870. https://doi.org/10.2134/agronj13.0370
0.15		op. cit.
0.48		op. cit.
1.02		op. cit.
0.66		op. cit.
0.48		Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., & Beaudoin, N. (2010). Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agriculture, Ecosystems & Environment, 135(4), 268–278. https://doi.org/10.1016/j.agee.2009.10.005
0.07		op. cit.
0.22		op. cit.
1.13		Ding, G., Liu, X., Herbert, S., Novak, J., Amarasiriwardena, D., & Xing, B. (2006). Effect of cover crop management on Soil Organic matter. Geoderma, 130(3-4), 229–239. https://doi.org/10.1016/j.geoderma.2005.01.019
1.54		op. cit.
1.21		op. cit.
0		op. cit.
0.44		Drinkwater, L. E., Wagoner, P., & Sarrantonio, M. (1998). Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396(6708), 262–265. https://doi.org/10.1038/24376
1.06		Higashi, T., Yunghui, M., Komatsuzaki, M., Miura, S., Hirata, T., Araki, H., Kaneko, N., & Ohta, H. (2014). Tillage and cover crop species affect soil organic carbon in Andosol, Kanto, Japan. Soil and Tillage Research, 138, 64–72. https://doi.org/10.1016/j.still.2013.12.010
1.76		op. cit.

0	Lal	Lal, R. (2015). Soil carbon sequestration and aggregation by cover cropping. Journal of Soil and Water Conservation, 70(6), 329–339. https://doi.org/10.2489/jswc.70.6.329
0.73		op. cit.
0		op. cit.
0		op. cit.
0.11		op. cit.
0.48		op. cit.
0.51		op. cit.
0.07		op. cit.
0.22		op. cit.
0.15		op. cit.
1.32		op. cit.
0.77		op. cit.
0.92		op. cit.
1.13		op. cit.
1.65		op. cit.
0.18	Ruis	Mazzoncini, M., Sapkota, T. B., Bàrberi, P., Antichi, D., & Risaliti, R. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil and Tillage Research, 114(2), 165–174. https://doi.org/10.1016/j.still.2011.05.001
0.4		op. cit.
0.48		op. cit.
0.51		Olson, K. R., Ebelhar, S. A., & Lang, J. M. (2010). Cover crop effects on crop yields and soil organic carbon content. Soil Science, 175(2), 89–98. https://doi.org/10.1097/ss.0b013e3181cf7959
0.51	Olson	op. cit.
0.4	Ruis	op. cit.

0.33	Poeplau	Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – a meta-analysis. Agriculture, Ecosystems & Environment, 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024
0.46		op. cit.
0.4		op. cit.
0.15		op. cit.
0.09		op. cit.
0.08		op. cit.
0.49		op. cit.
0.17		op. cit.
0.17		op. cit.
0.18		op. cit.
0.92		op. cit.
1.22		op. cit.
0.89		op. cit.
0.25		op. cit.
0.55		op. cit.
-0.05		op. cit.
-0.71		op. cit.
1		op. cit.
0.21		op. cit.
1.51		op. cit.
1.58		op. cit.
1.62		op. cit.
1.1		op. cit.
0.23		op. cit.
0.26		op. cit.
0.47		op. cit.
0.28		op. cit.

-0.71	op. cit.
0.04	op. cit.
-0.52	op. cit.
1.24	op. cit.
-0.65	op. cit.
0.18	op. cit.
1.01	op. cit.
0.18	op. cit.
0.36	op. cit.
0.44	op. cit.
2.92	op. cit.
4.09	op. cit.
0.88	op. cit.
-0.2	op. cit.
1.22	op. cit.
0.37	op. cit.
0.51	op. cit.
0.42	op. cit.
0.26	op. cit.
0.44	op. cit.
0.44	op. cit.
0.31	op. cit.
0.24	op. cit.
0.07	op. cit.
-0.07	op. cit.
1.42	op. cit.
0.3	op. cit.
1.14	op. cit.

2.17	op. cit.
0.15	op. cit.
1.09	op. cit.
0.99	op. cit.
0.69	op. cit.
0.2	op. cit.
0.3	op. cit.
0.79	op. cit.
1.43	op. cit.
0.64	op. cit.
0.44	op. cit.
0.79	op. cit.
0.25	op. cit.
1.28	op. cit.
0.2	op. cit.
0.79	op. cit.
0.74	op. cit.
1.23	op. cit.
1.93	op. cit.
0.15	op. cit.
0.59	op. cit.
0.1	op. cit.
1.68	op. cit.
0.99	op. cit.
0.79	op. cit.
0.09	op. cit.
0.47	op. cit.
1.33	op. cit.

1.23	op. cit.
0.93	op. cit.
-1.12	op. cit.
1.38	op. cit.
2.53	op. cit.
3.67	op. cit.
3.08	op. cit.
2.75	op. cit.
1.33	op. cit.
1.33	op. cit.
1.3	op. cit.
0.09	op. cit.
-0.12	op. cit.
0.21	op. cit.
0.21	op. cit.
-0.09	op. cit.
0.15	op. cit.
0.31	op. cit.
0.29	op. cit.
0.23	op. cit.
0.55	op. cit.
0.87	op. cit.
0.56	op. cit.
0.65	op. cit.
0.52	op. cit.
1.07	op. cit.
-0.27	op. cit.
1.62	op. cit.

1.81	op. cit.
0.29	op. cit.
0.6	op. cit.
0.8	op. cit.
0.58	op. cit.
1.49	op. cit.
0.44	op. cit.
0.58	op. cit.
-3.33	op. cit.
0	op. cit.
0.06	op. cit.
2.02	op. cit.
2.27	op. cit.
4.55	op. cit.
1.15	op. cit.
1.73	op. cit.
3.75	op. cit.
0.19	op. cit.
-0.8	op. cit.
2.99	op. cit.
2.27	op. cit.
4.36	op. cit.
5.01	op. cit.
0.14	op. cit.
0.35	op. cit.
0.26	op. cit.
0.31	op. cit.
0.42	op. cit.

4.83		op. cit.
0	Ruis	Sainju, U. M., Singh, B. P., & Whitehead, W. F. (2002). Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil and Tillage Research, 63(3-4), 167–179. https://doi.org/10.1016/s0167-1987(01)00244-6
0.81		op. cit.
0.66		op. cit.
0.62		op. cit.
0.07		op. cit.
0.18		op. cit.
0.4		op. cit.
0.73		op. cit.
0.48		op. cit.
0.62		op. cit.
0.18		op. cit.
0.15		op. cit.
0.33		op. cit.

Appendix C. Cost Estimates for No-till and Cover Crops

No-till:

Total cost	**Source**
$8.17	Epplin, F. M., Stock, C. J., Kletke, D. D., & Peeper, T. F. (2005). Cost of Conventional Tillage and No-till Continuous Wheat Production for Four Farm Sizes. Journal of American Society of Farm Managers and Rural Appraisers (ASFMRA), 69–76. https://doi.org/https://www.jstor.org/stable/10.2307/jasfmra.2005.69
$23.75	op. cit.
$20.19	Klein, R., & McClure, G. (2021). 2022 Nebraska Crop Budgets. Nebraska Extension. https://doi.org/https://cropwatch.unl.edu/Budgets/2022/2022-nebraska-crop-budgets-010322.pdf
$15.95	op. cit.
$20.34	op. cit.
$11.64	op. cit.

Cover crops:

Planting	Seed	Terminating	Other costs	Total cost	Source
$11.47	$12.06	$9.40	$0.99	$33.92	Edwards, W., & Plastina, A. (2018, March). Economics of cover crops: Ag Decision Maker. Iowa State University Extension and Outreach. Retrieved April 4, 2023, from https://www.extension.iastate.edu/agdm/crops/html/a1-91.html
$36.15	$20.00	N/A	$1.14	$57.29	Klein, R., & McClure, G. (2021). 2022 Nebraska Crop Budgets. Nebraska Extension. https://doi.org/https://cropwatch.unl.edu/Budgets/2022/2022-nebraska-crop-budgets-010322.pdf
$28.04	$14.78	N/A	$7.96	$50.78	Painter, K., & Jones, S. (2021). 2020 Direct Seed Budgets for Northern Idaho. University of Idaho Extension. https://doi.org/https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/cals/programs/idaho-agbiz/crop-budgets/northern/2021-ni-direct-seed-cover-crop-pdf.pdf?la=en&hash=3CE62F3E3A2DF574B62CB5AE613C94C86478B5C6
$28.04	$32.67	N/A	$8.40	$69.11	op. cit.
$13.68	$7.83	N/A	N/A	$21.51	Schnitkey, G., Coppess, J., & Paulson, N. (2018, July 6). Costs and benefits of cover crops: An example with cereal rye. farmdoc daily. Retrieved April 4, 2023, from https://farmdocdaily.illinois.edu/2016/07/costs-and-benefits-of-cover-crops-example.html
$14.13	$15.81	N/A	N/A	$29.94	Swanson, K., G. Schnitkey, J. Coppess and S. Armstrong. Understanding Budget Implications of Cover Crops (2018). farmdoc daily (8):119, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, June 28, 2018.
$14.13	$47.28	N/A	N/A	$61.41	op. cit.
$18.77	$15.96	N/A	N/A	$34.73	Zulauf, C., & Schnitkey, G. (2022, February 2). Policy budget for cover crops and the lesson of Crop Insurance. AgFax. Retrieved April 4, 2023, from https://www.agfax.com/2022/02/02/policy-budget-for-cover-crops-and-the-lesson-of-crop-insurance/