Natural Resources Conservation Service and Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Northern Research Station | General Technical Report NRS-217 | May 2024

Economics of Soil Health Management Systems that Sequester Carbon: Key Research Needs for the Northeastern United States

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Citation

Rejesus, Roderick M.; Aglasan, Serkan; Knight, Lynn G.; Cavigelli, Michael A.; Dell, Curtis J.; Lane, Erin D.; Hollinger, David Y. 2024. **Economics of soil health management systems that sequester carbon: key research needs for the northeastern United States.** Gen. Tech. Rep. NRS-217. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service; Madison, WI: U.S. Department of Agriculture, Forest Service, Northern Research Station. 27 p. https://doi. org/10.2737/NRS-GTR-217.

Abstract

Agricultural practices such as cover crops and no-till systems can maintain and improve soil health and productivity and help to address climate change by sequestering carbon. However, economic costs and returns to farmers influence the rate of adoption of these practices. This paper reviews published studies that address the economic factors associated with using cover crops and no-till systems in the northeastern United States. Farmers typically bear all of the costs of adopting soil health practices, while both the farmer and society receive benefits. Variability of economic outcomes for soil health practices over time and the number of years such practices have been used have been shown to be factors influencing long-term economic benefits of the practices. Recent studies for the northeastern United States have been limited and have largely been done at the plot-scale, pointing to the need for studies using datasets from a broader land base and with a broader range of economic analysis tools. Further examination is also needed to evaluate the potential benefit of public and private financial incentives that encourage adoption of carbon-sequestering soil health practices.

Keywords: soil health, cover crops, no-till, economic benefits

Cover Photograph: Research plots using no-till, cover crops, and other soil health practices at the USDA Beltsville Agricultural Research Station in Beltsville, MD. USDA Agricultural Research Service photo by Michael A. Cavigelli.

Manuscript received for publication October 2021

Published by:
USDA Forest Service
One Gifford Pinchot Drive
Madison, WI 53726
May 2024

Visit our homepage at: http://www.nrs.fs.usda.gov

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EXECUTIVE SUMMARY

Management practices that maintain and improve soil health, such as cover cropping and no-till systems, are essential to the continued productivity of agriculture in the United States and are key strategies for increasing carbon sequestration and helping to address climate change. In this paper, we describe different economic dimensions associated with the decision to adopt soil health practices. Recent literature examining the environmental and economic benefits and costs of cover crops and no-till systems are reviewed for the United States in general and for the northeastern United States in particular. Key research directions are identified that would advance understanding of the economics of soil health practices and provide insights on policies to encourage adoption of these carbon-sequestering soil health practices.

The economic framework conceptualizes soil health as encompassing the physical, chemical, and biological characteristics of the soil, and does not simply equate soil health with soil fertility. Three key factors–initial soil conditions, agricultural management practices, and uncontrollable environmental factors–interact and eventually influence the three main soil health properties. Of these three key factors, only agricultural management practices are directly under the control of the farmer. Moreover, specific adoption of agricultural management practices that influence soil health depends on the economic benefits and costs associated with using these practices. Soil health is also linked to environmental outcomes that society values, such as reduced nitrogen and phosphorus runoff to waterbodies and lower carbon emissions to the atmosphere. Hence, an important dimension when considering the economics of soil health is balancing private costs and benefits with external (or societal) costs and benefits. Farmers typically bear all the costs of adopting soil health practices, even though both the farmer and society benefit from these practices. This mismatch of who bears the costs and who receives benefits suggests that the rate of adoption of soil health-enhancing practices may have limited the achievement of soil health benefits. This potential market failure points to a role for public policy to help compensate landowners for the cost of practice adoption by designing interventions, such as subsidies, to maximize achievement of soil health outcomes that benefit all.

Another important dimension in the economics of soil health is the inherently dynamic nature of economic outcomes that follow the adoption of soil health management practices. The action to adopt a soil health management practice in one period influences economic outcomes in the same period as well as in future periods. Evolving environmental and soil conditions will influence the selection of management practices in each future period, but those evolving conditions could also influence how soil health responds to each management practice. Therefore, economic outcomes from the adoption of soil health management practices dynamically evolve depending on the number of years the particular management practices are used. Variability of economic outcomes over time (e.g., yield risk) is also a factor when considering the dynamic processes involved in the economics of soil health management practices.

Much of the literature that examines the economics of soil health practices in the United States focuses on the private benefits and costs associated with adopting a particular soil health practice. Long-term studies that account for the dynamic aspects and external dimensions of soil health management practices have been very limited. For cover crops, recent economic studies have used partial budget type analysis and have found, in general, that short-run, private benefits from adoption of cover crops typically are not higher

than the initial costs of implementation. Long-term use of cover crops is likely needed to generate positive private net economic returns. In addition, an aspect of cover crop economics that has not been thoroughly investigated is the economic value associated with the potential external benefits of cover crop use. For no-till systems, the economic literature indicates that private net economic benefits from adoption of this practice are variable and site specific (i.e., private benefits and costs depend on factors such as soil characteristics, local climatic conditions, cropping patterns, and other attributes of the overall farming operation). However, the observed increase in no-till adoption rates over the last few decades (approximately 37 percent of U.S. cropland acres) suggests that farmers are adopting these no-till systems and implies that these systems generally pay off for U.S. farmers.

The economics literature focusing on soil health practices in the northeastern United States generally follows the trends and patterns described in the preceding paragraph for studies conducted in other parts of the United States. However, many of the economic studies of cover cropping and no-till systems in the Northeast were conducted prior to 2010. In addition, aside from partial budget type analysis (usually using plot-level experimental data), studies in this region have used models to simulate crop production and economic factors to examine long-term soil, environmental, and economic outcomes. Moreover, a majority of the cover cropping and no-till economic studies were conducted in Maryland, New York, and Pennsylvania; research in other states has been limited.

Hence, more economic studies in other northeastern states may lead to higher adoption in those states. Notwithstanding the limited economic studies in this region, several states in the Northeast rank among the top in terms of adoption of cover cropping and no-till systems based on the 2017 U.S. Census of Agriculture.

Given the current state of the soil health economics literature, long-term studies that apply statistical analysis of data observed at multiple time points to identify relationships among soil health practices, soil health indicators, and economic outcomes are needed. Dynamic issues associated with cover crops and no-till systems (e.g., risk effects and investment analysis under uncertainty) are also topics that need further study. Geographical heterogeneity of soils and agricultural production systems need to be recognized, and economic evaluations of cover crop use should be conducted for different regions, such as the northeastern United States, where recent economic evaluations have been limited. Use of more aggregated data sets, such as county-level, satellite-based data, needs to be explored to allow further study of a variety of economic issues (e.g., risk and dynamics) over a longer period of time and covering a wider geographical scale that plot-level experimental data cannot adequately address. Use of nonmarket valuation techniques to estimate the societal external contributions of soil health practices is another research avenue that is likely to be fruitful. Lastly, further examination of the role and design of different conservation payment programs is important to better understand how public policy can best be developed to incentivize the adoption of soil health practices. Separately examining the impact of different government payment programs, as well as private carbon market initiatives, would aid in the design of effective programs that encourage adoption of carbon-sequestering soil health practices.

CONTENTS

INTRODUCTION

Soil health is a key element in enhancing agricultural production, environmental sustainability, and food system resilience (Farnsworth 2015, Stevens 2018). The Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA) defines soil health as “the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans” (USDA NRCS 2023). A common theme in the scientific literature points to soil health as an indicator of the soil’s ability to support life, withstand environmental stresses, and endure as an important part of a resilient ecosystem. Because one of the key individual components of soil health is carbon in organic matter (Idowu et al. 2009, Morrow et al. 2016), enhancing soil health also has a prominent role to play in addressing climate change (Paustian et al. 2016, Schipanski et al. 2014, Stockmann et al. 2013). Improving soil health is a natural climate solution for increasing carbon storage in soils and building resilient systems (Griscom et al. 2017, Jian et al. 2020, Poeplau and Don 2015).

Given the key role of soil health in sustaining agricultural productivity and enhancing carbon storage, there is significant interest in promoting agricultural management decisions, practices, and production systems that can help maintain or improve soil health. These include practices such as cover cropping, no-till residue and tillage management, conservation crop rotations, mulching, and nutrient management. There are two overarching issues related to the adoption of practices that improve soil health. First, the adoption of soil health practices by farmers is inextricably linked to whether private economic benefits from adopting these practices (i.e., benefits to the farmer) outweigh the associated private adoption costs. Second, understanding the environmental benefits from adopting these soil health practices (i.e., external benefits to society through ecosystems services) can help inform the design of public policies seeking to align private incentives with public environmental goals (for example, designing of subsidy payments to farmers).

In this paper, we describe the economic dimensions associated with the decision to adopt soil health practices. These are important concepts that will help soil and water conservation practitioners further encourage adoption of soil health practices. We summarize recent literature that examines the economic benefits and costs of cover crops and no-till systems for the United States in general, and for the understudied northeastern United States region in particular.[1] Adoption of cover crops and no-till varies widely across the United States (Fig. 1). We identify key research directions that would both enhance understanding of the economics of soil health practices and provide insights into policies to encourage adoption of carbon-sequestering soil health practices.

[1] The northeastern United States was chosen because several states in this region (e.g., Maryland, Pennsylvania, Delaware) are among the top states in terms of percentage cover crop and no-till adoption (Zulauf and Brown 2019a, 2019b). Even so, few economic studies of soil health practices have been conducted for this region. The states in this study include Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont.

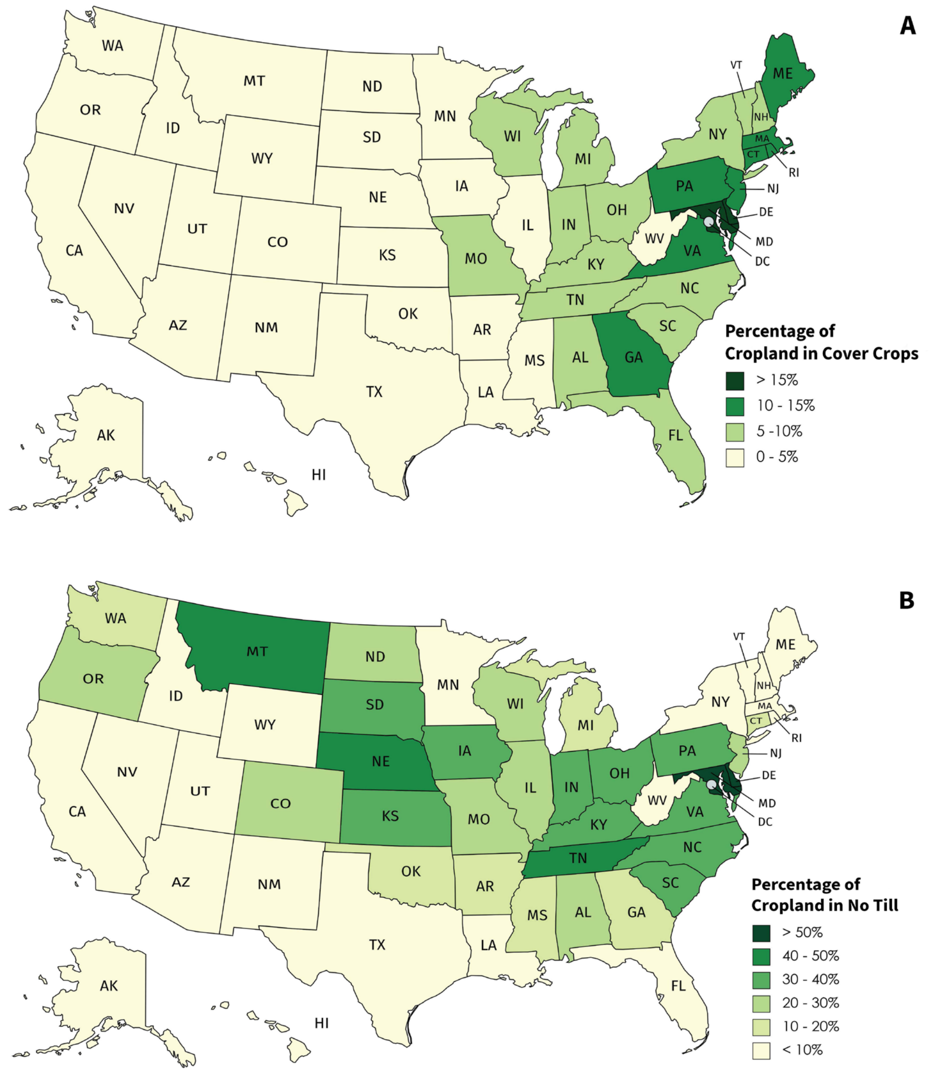

Figure 1.—Cover crop acres (A) and no-till acres (B) as a percent of state total crop acres in the United States based on the 2017 U.S. Census of Agriculture. Map created via mapchart and licensed under a Creative Commons Attribution/ShareAlike 4.0 International License.

ECONOMICS OF SOIL HEALTH MANAGEMENT PRACTICES: A FRAMEWORK

Economic considerations are the main elements that an individual farmer typically assesses when making decisions to adopt soil health management practices. In this section, we use an economic framework as a lens for discussing how to assess the various factors influencing the decision to adopt soil health practices and how to evaluate the overall economic impacts of these practices.

Building on the ecosystem-centered NRCS definition of soil health—the ability of the soil to continue to support plants, animals, and humans—Stevens (2018) asserts that the health of a soil depends on its physical, chemical, and biological components, noting that soil health is now conceptualized broadly and is no longer simply equated with soil fertility. The physical properties of soil typically refer to the structure of the soil matrix.

Specific physical properties typically considered are aggregate stability (the soil's ability to maintain structure when exposed to stress), soil penetrometer resistance (an indication of compaction), and available water capacity (how much plant-available water is held within the soil matrix). The chemical components of the soil are measures of the soil's acidity (pH), salinity, organic matter, and nutrient content. The nutrient content includes the macronutrients nitrogen (N), phosphorus (P), and potassium (K); the secondary nutrients calcium (Ca), magnesium (Mg), and sulfur (S); and the micronutrients zinc (Zn) and copper (Cu). These chemical properties help determine what nutrients are available to plants and other living things. The biological properties of the soil are typically characterized by the size and composition of the biological community and the rate of biological processes like mineralization (i.e., conversion from organic to mineral forms) of carbon and nitrogen from soil organic matter. Good biological soil health is associated with high rates of mineralizable nitrogen because nitrogen in soil organic matter is only available to plants and soil microbes after it is mineralized. High rates of mineralizable carbon reflect high soil microbial activity, and soils with healthy microbial communities are generally considered more productive and resilient to stress. Soil organic matter also helps prevent soil compaction and erosion. The biological component of soil health is directly linked to climate change mitigation because an increase in soil carbon represents a decrease in atmospheric carbon dioxide.

Along with the key physical, chemical, and biological components that determine soil health, it is important to recognize that three key factors—initial soil conditions, agricultural best management practices, and uncontrollable environmental factors—interact and eventually influence the three main soil health properties (Farnsworth 2015). A simplified framework of how these three properties affect soil health is shown in Figure 2, which also provides a conceptual framework to assess soil health relative to a benchmark healthy soil by using indicators that encompass the key physical, chemical, and biological measures of soil heath. Of the three key factors that can alter soil conditions, only the adoption of agricultural best management practices is directly under the control of the farmer. Planting cover crops and using no-till systems are examples of management practices that improve a variety of soil properties and enhance soil health. Conversely, conventional tillage and other practices with a high degree of soil disturbance often negatively impact soil properties and lead to lower soil health.

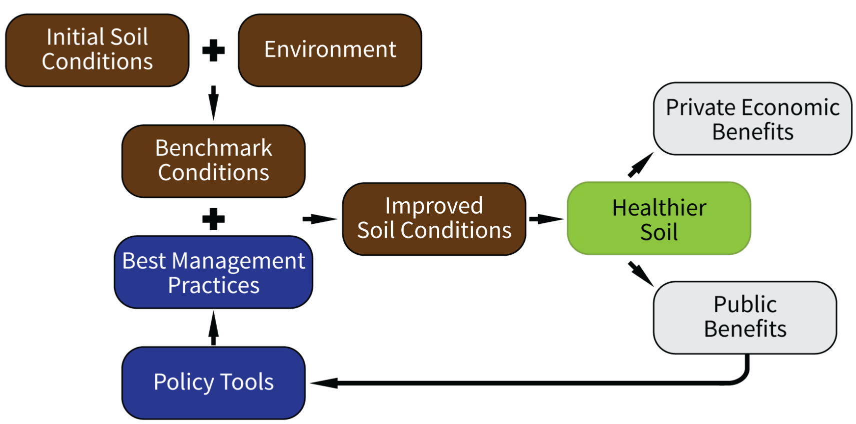

Figure 2.—Feedbacks from analysis of the economics of soil health practices. Analyzing the impact of management practices could improve understanding of policies designed to encourage best soil management practices. Use of these best management activities can improve soil conditions (relative to a benchmark) and may lead to improved private economic benefits and public environmental benefits such as carbon sequestration (Table 1). Further enhancements and analysis of the benefits of soil health practice then create feedback loops.

Adopting agricultural management practices that improve soil health provides beneficial environmental outcomes such as reduced soil erosion, reduced nitrogen or phosphorus runoff to waterbodies, and sequestration of atmospheric carbon in the soil from use of cover crops (Jian et al. 2020, Poeplau and Don 2015). Both the farmer and the general public benefit from these outcomes. However, the decision to adopt a particular soil health practice is largely influenced by the net economic benefits to the farm from adopting the practice. If a soil practice does not provide an adequate (and consistent) private benefit relative to the cost of implementing it, then it is unlikely that farmers will consistently adopt or continue this practice (Table 1) (Boyer et al. 2018, Suri 2011).

One of the fundamental tools used in farm business management is a partial budget, a tool rooted in the economic tradition of conducting marginal analyses to determine optimal decisions that maximize an objective function, which is typically to maximize profit. A partial budget is a method for calculating the expected change in profit resulting from a proposed change and therefore considers only those income and expense items that will likely change if the proposed modification in the farm business (e.g., using new

Table 1.—Economic dimensions of the soil health management practice decision

	Potential Benefits (revenue increasing or cost decreasing)	Potential Costs (revenue decreasing or cost increasing)
Private (e.g., individual)	**Agronomic** • Increased yields (and revenues) • Reduced fertilizer expenses • Reduced fuel cost (in no-till) • Better resilience to extreme weather events • Yield stability over time • Grazing opportunities (from cover crops) **Environmental** • Reduced soil erosion in farmer fields • Decreased soil compaction • Reduced nitrogen and phosphorus losses increasing nutrient use efficiency • Better moisture retention in-season	**Agronomic** • Increased cover crop seed costs • Increased labor and machinery cost (e.g., for planting cover crops) • Increased herbicide costs (e.g., for cover crop termination) • Decreased yield (e.g., if delayed planting due to delayed cover crop termination, among other reasons) • Opportunity cost of labor for planting cover crops in the winter • Decreased moisture available for cash crop (after planting cover crops) • May recruit unwanted wildlife (for cover crops) **Environmental** • None
External (e.g., societal)	**Agronomic** • Reduced pest and disease outbreak incidence (e.g., due to beneficial insects) **Environmental** • Reduced soil erosion on landscape • Carbon sequestration (e.g., cover crops remove carbon dioxide from the air and store it in the form of carbon in the plant and soil) • Improved water quality (e.g., from reduced nitrate leaching) • Increased biodiversity (e.g., better environment for beneficial insects and pollinators)	**Agronomic** • Increased pest or disease incidence for neighbors due to cover crops being a possible host **Environmental** • None

soil health practices) is adopted (Kay et al. 2015). It does not include benefits and costs that do not change with the modification in practice. The key elements of a partial budget are identifying (1) profit-increasing components and (2) profit-decreasing components that are associated with the proposed change. In Table 1, the profit-increasing components are given in the column labeled Potential Benefits and include revenue-increasing and cost-decreasing changes that result from adoption of a particular soil health management practice. Profit-decreasing components are in the column labeled Potential Costs and include revenue-decreasing and cost-increasing changes that result from adopting a particular soil health management practice. The two columns provide a structure for thinking about and identifying the different factors that determine net economic benefits from a particular soil health management practice.

A second important dimension in the economics of soil health management practices pertains to private and external benefits. The potential benefits and costs of soil health adoption are either private, where the benefits and costs accrue directly to the individual farmer implementing the practice, or external where the benefits and costs are experienced by society more broadly (Table 1).[2] For example, the private benefits are related to the positive outcomes that farmers receive from adopting soil health management practices, such as increasing revenue with yield increases or the cost-reducing effects of decreased soil erosion (Table 1, upper left quadrant). Similarly, the private costs of adopting soil health practice, such as increased seed and herbicide costs, are mostly taken on by the farmer (Table 1, upper right quadrant). The external benefits, such as reduced carbon emissions, are typically related to positive environmental outcomes valued by society (Table 1, lower left quadrant). Thus, in the context of soil health practice adoption, a key insight into the private versus external delineation is that the costs of adopting soil health practices are primarily borne by individual farmers, while the benefits are received by both the farmer and society. The benefit to society is known as the positive externality effect. A mismatch in who bears the costs and who receives benefits suggests that the rate of adoption of practices that enhance soil health may be limiting development of soil health benefits. This failure to directly match recipients of the benefits to those who bear the costs (i.e., a market failure) points to a role for public policy to help expand the adoption of soil health practices by designing interventions (e.g. subsidies) for optimal societal provision of soil health benefits (Stevens 2018).

Another important dimension of the economics of soil health management practices is the delineation of agronomic and environmental benefits and costs within each quadrant of Table 1. The private agronomic benefits pertain primarily to the profit-increasing outcomes that affect the farm production operations, such as increasing yields and reducing fertilizer and pesticide applications. The private agronomic costs relate to the profit-decreasing outcomes that affect the agricultural production process, such as increased seed cost due to cover cropping. The private environmental benefits are improved environmental outcomes that accrue to the individual producer operation, such as a reduction in soil erosion on a farmer's fields that in turn maintains or improves productivity. The external environmental benefits from enhanced soil health can positively affect society in general and overlap with the individual producer. For example, reduced nitrate leaching from a farmer's field improves nutrient use efficiency and improves water quality in nearby waterbodies is valued by non-farmers residing near these waterbodies.

[2] Detailed lists of private and external benefits and costs for several soil health practices can be found on the USDA's Natural Resources Conservation Service webpage, Conservation Practice Benefit-Cost Templates (also known as the NRCS T-charts) at https://www.nrcs.usda.gov/resources/guides-and-instructions/conservation-practice-benefit-cost-templates (accessed September 9, 2023).

An economic dimension not explicitly shown in Table 1 is the dynamic nature of the economic outcomes that arise from adoption of soil health management practices (Stevens 2018). Simply put, the action to adopt a soil health management practice in one period influences economic outcomes in that period as well as in future periods. The management practice effects in each future period are governed by evolving environmental and soil conditions and by the natural processes by which soil health responds to each management practice. For example, soil organic matter response to a 1-year planting of cover crops is usually below the existing technical ability to measure changes; therefore the observable soil health response to cover cropping may take more than one planting of cover crops (Myers et al. 2019). Thus the economic outcomes from soil health management practice adoption dynamically evolve depending on the number of years the particular management practices are used. In this dynamic context, the economic concept of discount rates—how much individuals value the present returns relative to future returns—plays a central role. Variability of economic outcomes over time (e.g., yield risk) is also a factor when thinking about the dynamic process involved in the economics of soil health management practices. In turn, farmers' attitudes towards risk (i.e., how much year-to-year variability in yields/profits one can tolerate) also plays a role in the long-term value of soil health practice adoption.

ECONOMICS OF SOIL HEALTH PRACTICES: A SELECTIVE LITERATURE REVIEW FOR THE UNITED STATES

Much of the literature that examines the economics of soil health practices focuses on the private benefits and costs associated with adopting a particular soil health practice. Long-term studies that account for the dynamic aspects and external dimensions of soil health management practices and studies on the combined effects of various soil health management practices have been very limited.

Cover Crops

Cover crops are grasses, legumes, brassicas, and other forbs (or mixtures of these) that are planted in the late summer or fall around harvest and before spring planting of the following year's regular cash crops. Cover crops are planted for a variety of reasons: to provide erosion control; to improve soil structure, moisture retention, and nutrient content by increasing soil organic matter; to increase nutrient cycling and retention; to increase beneficial soil biota; to suppress weeds; to provide habitat for wildlife and beneficial predatory insects; to facilitate crop pollinators; and to provide forage for farm animals (Bergtold et al. 2017, Singer et al. 2007).

Use of cover crops in the United States is increasing but is still a minor practice. The USDA National Agricultural Statistics Service (NASS) reported that cover crop acres increased from 10.3 million acres in 2012 to 15.4 million acres in 2017, representing about 3.9 percent of all cropland in the United States (USDA NASS 2019, Zulauf and Brown 2019a). However, in Delaware and Maryland, where state subsidies for cover crops are available, use is well above the national average at about 19 percent (DE) and 29 percent (MD), respectively (Fig. 1).

According to Farnsworth (2015), many of the economic studies that examine soil health practices have compared private economic benefits and costs of a treatment production system that has used a soil health practice (e.g., cover crops) to a control system that has not used a soil health practice (e.g., no cover crops). If yields were statistically higher for the soil health treatment group, then improved soil health was considered to be the main reason for the difference in yields. Several other economic studies have followed this logic but have instead utilized the partial budget concept and examined how a soil health treatment, like cover crops, influences the profit-increasing components and profit—decreasing components of a farm budget. Farnsworth (2015) noted that few studies have estimated explicitly how a soil health management practice directly influences actual soil health indicators (e.g., physical, chemical, and biological measures) and then measured how the change in soil health eventually influenced yields and other economic outcomes of interest.

To determine the net change in profits when cover crops were used, Plastina et al. (2018a, 2018b, 2020) used a partial budget analysis to calculate the difference in annual net returns for farmers who used cover crops compared to those who did not. Using data collected from row crop producers in Illinois, Iowa, and Minnesota, the authors found that, in general, the average difference in annual net returns for farmers who used cover crops versus those who did not was usually negative. In other words, for midwestern row crops, the profits for farms that did not use cover crops tended to be higher than for those that did. Specifically, the average change in annual net returns tended to be negative for corn operations that used cover crops terminated with herbicides relative to operations that did not use cover crops. Moreover, change in net profits for cover crop users (relative to non-cover crop users) was generally negative when these cover crop adopters did not use cover crops for grazing livestock or forage. This negative result was consistent across different planting and termination methods, tillage practices, and experience levels (Plastina et al. 2018b). Only those farmers who used cover crops for grazing livestock or forage and those that received cost-share incentive payments from government programs tended to derive higher net returns relative to non-cover crop users. In contrast to corn farmers, the average change in net return typically was positive for soybean farmers who used cover crops terminated with herbicides compared to those who did not use cover crops (Plastina et al. 2018a).

Consistent with Plastina et al. (2018a, 2018b, 2020), the partial budget analysis results based on national survey data and presented in Myers et al. (2019) also indicate that the change in annual net returns for farmers who use cover crops is usually negative. This finding is especially true for farmers who have adopted the practice for only 1 or 2 years. The authors point out that the following situations can increase the likelihood of getting a positive change in net returns from cover crop use: (1) when herbicide resistant weeds are a problem, (2) when cover crops are grazed, (3) when soil compaction is an issue, (4) when cover crops are used to facilitate transition to no-till, (5) when there are soil moisture deficits, (6) when fertilizer costs are high or there is a need to sequester nutrients (e.g., nitrogen) that are left at the end of a cash crop season (e.g., from manure), and (7) when government incentive payments, such as cost-share or subsidy payments, are received for planting cover crops.

An issue highlighted by Myers et al. (2019) is that short-term use of cover crops (1 to 2 years) does not usually result in an immediate positive change in net economic returns because upfront costs in the short run outweigh the benefits. Medium- to long-term use of cover crops (3 years or more) is necessary in order to see a positive change in net returns. This finding is largely consistent with the results of other studies that explore the private economic benefits and costs of cover crop adoption and show that the use of cover crops and other soil health practices does not typically result in immediate (short-term) improvements in soil health (Bergtold et al. 2017, Snapp et al. 2005). Over time, with at least 3 or more years of cover cropping, improvements in soil health are expected to result in yield benefits that can overcome these costs (Cai et al. 2019, Myers et al. 2019). Note, however, that even a recent long-run economic simulation study of cotton indicates that the net present value of returns to a long-term investment in cover crop use may still not be higher than a no-cover crop practice (Boyer et al. 2018), a conclusion that may be based on the specific discount rate used. More long-term analyses of the various dimensions of cover crop economics are needed.

Field experiment data, usually at the plot level, can also be used to assess the effects of cover cropping on private economic benefits and costs. For example, Mahama et al. (2016), Reddy (2003), and Roberts et al. (1998) evaluate economic returns to cover crop use (and other conservation practices) using field experiment data from Kansas, Mississippi, and Tennessee, respectively, and each study shows that the additional expense of cover crops reduced profits. Findings from studies that explore the profit effects of cover crops using experimental data are mixed, with some reporting positive profit effects and others reporting negative effects (Boquet et al. 2004, Cai et al. 2019, Dunn et al. 2016, Foote et al. 2014, Larson et al. 2001, Miguez and Bollero 2005, Snapp et al. 2005, Varco et al. 1999, Zhou et al. 2017). Whether a result is positive or negative generally depends on the relative magnitudes of the revenue and cost changes associated with cover crop use.

An aspect of cover crop economics that has not been thoroughly investigated is the economic value associated with the potential external benefits of cover crop use (Bergtold et al. 2017). Valuing these external benefits is difficult, largely because they benefit society at large as well as the farmers who deploy the practices. These external benefits are also hard to quantify from the biophysical measurement perspective. As with most positive externalities, there are as yet no established markets for environmental cover crop benefits that accrue to society.

In summary, much of the recent literature that uses partial budget type analysis indicates that short-term, private benefits from adoption of cover crops typically are not higher than the initial costs of implementation. The literature that utilizes field experiments is largely mixed regarding the private profitability impact of cover crop use. Long-term use of cover crops is likely needed to generate positive, private, net economic returns. Benefits to society in the form of ecosystem services may be a significant element that has not yet been included in many previous economic studies.

No-Till Systems

Conventional tillage is typically implemented to prepare the soil for planting, to control weeds, to incorporate manure or fertilizer spread on the soil surface, and to mix crop residues into the soil. Soils that are conventionally tilled in the fall typically absorb more heat and warm up more quickly in the spring (Larney et al. 2003, Licht and Al-Kaisi 2005). This practice allows for earlier planting for some crops (particularly corn) in regions where spring weather is often cool and wet (Claassen et al. 2018a). However, conventional tillage also disrupts and exposes the soil, leading to greater erosion risk, accelerated decomposition of organic matter, soil degradation, structural breakdown, aggregate instability, and compaction issues (Pagliai et al. 2004). In addition, there are concerns about the effects of intensive tillage on long-term soil health and productivity.

From a societal perspective, intensive conventional tillage can also lead to sediment and nutrient runoff, resulting in pollution of surface water and possibly increased emission of greenhouse gases (Hodde et al. 2019).

Similar to cover crops, no-till production systems are viewed as a key method for enhancing soil health and for mitigating or avoiding the negative effects associated with conventional tillage methods. No-till refers to the practice of refraining from tilling the soil from harvest of the previous crop to harvest of the current crop (Claassen et al. 2018a). The no-till practice, along with mulch-till, strip-till, and reduced-till, are all types of conservation tillage practices. In contrast to conventional tillage systems, which leave less than 30 percent crop residue, conservation tillage is traditionally defined as tillage systems that leave at least 30 percent of crop residue on the soil surface after planting (Wade et al. 2015). In a no-till system, farmers plant directly into the undisturbed residue of the previous crop. The weed control benefits of conventional tillage are replaced with additional herbicide applications in no-till systems.

Profitability, or the private net economic returns derived from the practice, is an important factor influencing adoption of a no-till system. The private economic benefits with regard to the private economic costs of implementing no-till systems relative to other tillage systems critically depend on yield and input cost differentials. No-till systems can lead to savings in labor, machinery, and fuel costs due to a reduction in the number of field equipment passes (Weersink et al. 1992). Residue cover, however, may increase the prevalence of pests and diseases, which can result in higher costs for chemical inputs (Fuglie 1999). A study by Kaval (2004) comparing the profitability and production costs of 198 no-till and conventional till systems found that no-till production was the least costly system.[3] Many American farmers seem to have agreed with this finding. A 2019 report based on U.S. Census of Agriculture data indicated that the total area under no-till (104 million acres) in the United States exceeded the area under conventional tillage (80 million acres), with another 98 million acres under other types of conservation tillage. The report also noted that conventionally tilled acres dropped by 26 million from 2012 to 2017, while the area in conservation tillage increased by 29 million acres (Zulauf and Brown 2019b).

Conservation tillage (including no-till systems) affects soil health and crop yields. Studies show that it improves soil structure (Blanco-Canqui and Ruis 2018, Gál et al. 2007), enhances the biological and chemical characteristics of the soil (Karlen et al. 1994, Lewis et al. 2018, Obour and Holman 2017), and increases soil moisture (Díaz-Zorita et al. 2004). Studies on yields report mixed results. Some show that conservation tillage practices can adversely affect yields by delaying warming and drying of soil and slowing plant emergence (Bowman et al. 2016, Doster et al. 1983) and decreasing overall crop yields (Vyn and Raimbult 1993). West et al. (1996) report that corn yield reductions with no-till were more likely in continuous corn production than in the more common corn-soybean rotation. Phillips et al. (1997) report that an experiment on a sloping, erodible site in southern Illinois showed increased yield and economic returns in no-till versus conventional till over several seasons of corn-soybean rotations. A recent study that compared a continuous no-till corn system to conventional till over a 29-year period on a site in southwestern Michigan suggests that the probability of higher profits for the no-till system increases with longevity of use (Cusser et al. 2020). Overall, evidence suggests that

[3] Older studies such as Uri (1999) argue that input costs associated with no-till systems, including labor, fertilizer, pesticides, seeds, and machinery, are so dependent on site-specific factors that general inferences about the effect of no-till adoption on production costs are simply not possible.

yields under different tillage scenarios vary by cropping system, soil properties, land slope, longevity of adoption, and climatic conditions (Cusser et al. 2020, Ding et al. 2009, Toliver et al. 2012).

Similar to the published literature on yields and cost effects, the evidence on the profit effects of the no-till system is mixed. Some studies show that under favorable conditions (warm and dry weather early in the growing season), no-till systems can achieve profits comparable to conventional tillage methods (Kovar et al. 1992, Ogle et al. 2012). Other studies based on short-term and long-term field trials have shown that profits from using no-till systems can be similar to or greater than conventional tillage methods (Al-Kaisi and Yin 2005, Doster et al. 1983, Trlica et al. 2017). In a survey of Iowa farmers, Liu and Duffy (1996) report that most conservation tillage systems, such as no-till or reduced-till, had higher profits than conventional tillage due to lower production costs. In addition, the conservation tillage systems were shown to provide environmental benefits that were not typically quantified monetarily in the analysis. Other studies report that the profitability of no-till systems was lower than conventional systems. Marra and Kaval (2000) found lower profits in no-till systems, especially when the cost to control weeds chemically was high. Williams et al. (2000, 2012) found that the potential for an increase in diseases could result in higher chemical costs that could potentially offset savings in labor and machinery costs.

In addition to the private profitability and soil health benefits of no-till systems, the literature indicates that potential risk reduction is a factor in the decision to adopt no-till systems (Adusumilli et al. 2020, Archer and Reicosky 2009, Ding et al. 2009, Klemme 1985, Larson et al. 2001, Pendell et al. 2006, Williams et al. 2012). The risk associated with the tradeoff between upfront investment in no-till systems and the delay in benefits often plays a critical role in whether no-till systems are adopted (Fathelrahman et al. 2011). When no-till (with or without cover crops) is considered as a long-term investment, Boyer et al. (2018) found that risk-neutral, profit-maximizing southern cotton producers preferred conventional till planting without a cover crop (i.e., highest profit and yields for this practice combination). In contrast, risk-averse, profit-maximizing producers preferred no-till planting with no cover crops, which suggests that no-till planting can reduce cotton producers' exposure to risk. Given these findings from the long-term analysis, Boyer et al. (2018) indicate that the risk benefits associated with no-till might take many years of continuous use before they are received by producers.

In summary, the general economic literature on no-till systems suggests that the private net economic returns from adoption are variable and site specific. That is, private benefits and costs depend on such factors as soil characteristics, local climatic conditions, cropping patterns, and other attributes of the overall farming operation. However, the observed increase in no-till adoption rates over the last few decades (approximately 37 percent of U.S. cropland acres) suggests that farmers are adopting no-till systems and implies that these systems generally pay off for farmers (Fig. 1) (Zulauf and Brown 2019b). This revealed preference behavior may indicate that these systems generally pay off for most farmers, although there is still potential for better quantification of the value of ecosystem services from no-till systems.

ECONOMICS OF SOIL HEALTH PRACTICES IN THE NORTHEASTERN UNITED STATES

Cover Crops

The majority of the literature that examines the effects of cover crops on the environmental and economic outcomes in the northeastern United States is based primarily on field studies conducted in Maryland and to a lesser extent in New York and Pennsylvania. Most of these studies focus on the various environmental factors and soil properties associated with cover crop use (with the exception of cash crop yield effects) rather than on the economic outcomes.

Lu et al. (1999) evaluated the profitability and economic risk associated with four cropping systems established at the Sustainable Agriculture Demonstration site of the Beltsville Agricultural Research Center in Maryland from 1994 to 1997. The four cropping systems were (1) a no-till system with recommended fertilizer and herbicide inputs but no cover crops, (2) a no-till system with a crown vetch living mulch suppressed with herbicides, (3) a no-till system with winter wheat and hairy vetch cover crops, and (4) a minimum tillage manure-based system in which no chemicals were applied and animal and green manure were incorporated using a chisel plow. Each system followed a 2-year rotation of corn harvested in the first year and winter wheat and soybeans harvested in the second year. In this study, the no-till cropping system (number 3) with winter wheat and hairy vetch cover crops produced the largest average gross margin (calculated as revenues less variable costs). The no-till system with fertilizer and herbicide inputs but no cover crop (number 1) was next, followed by the minimum tillage manure-based system (number 4). The system with the smallest average gross margin was the no-till system with crown vetch living mulch (number 2). The study also considered risk (e.g., variability in yields and net returns over time) and found that the no-till system without cover crops (number 1) was the preferred system for risk-averse farmers, and the no-till system with winter wheat and hairy vetch cover crops (number 3) was the second choice. A follow-up study by Lu et al. (2000) examined similar grain crop systems, as well as tomatoes, and reported similar results. That study included comparison of the profitability of tomato production systems with an N-fixing cover crop (hairy vetch) compared to the conventional systems of black polyethylene mulch and bare soil. Tomatoes grown with hairy vetch cover crops were more profitable than those grown in conventional systems, mainly due to higher yields.

Hanson et al. (1993) and Lichtenberg et al. (1994), also in Maryland, examined the economic impact of cover crops in no-till corn systems. In both studies, planting corn following hairy vetch cover crops was the most profitable system (relative to corn following winter fallow). However, in contrast to results found in Lu et al. (1999, 2000), the risk analyses by Hanson et al. (1993) and Lichtenberg et al. (1994) found that the cover crop system (corn following hairy vetch) also had the lowest risk (e.g., variability in profits). These economic studies also emphasize that, for high N demanding cash crops such as corn, legume cover crops such as hairy vetch and crimson clover are likely to be more profitable than grass cover crops, such as rye, due to the ability of legumes to contribute N to the following crop. The ability of legume cover crops to enhance crop yields (through soil N contribution) is one of the factors that makes their use profitable.

Lu et al. (2000) and Watkins et al. (2002) investigated the potential long-term (60-year) environmental impacts of alternative cropping systems by using the Environmental

Policy Integrated Climate (EPIC) biological process simulation model. The simulated cropping systems were calibrated based on the experimental data from the Sustainable Agriculture Demonstration study described in the preceding paragraphs. Six cropping systems were simulated and compared: (1) a no-till system with recommended fertilizer and herbicide inputs (using the rotation in the experiment); (2) a no-till, 2-year rotation of corn followed by full-season soybean with recommended fertilizer and herbicide inputs (a corn-soybean rotation was used to determine whether substituting full-season soybean for the winter wheat-soybean double crop would increase profits); (3) a no-till system with winter annual cover crops (e.g., hairy vetch before corn) and recommended fertilizer and herbicide input; (4) no-till system with winter annual cover crops (e.g., hairy vetch before corn) and recommended herbicide inputs but no fertilizer; (5) a reduced till, organic, 2-year rotation system without chemical inputs, and (6) an organic, 3-year rotation without chemical inputs consisting of corn following a crimson clover cover crop in the first year, full-season soybean following a winter wheat cover crop in the second year, and winter wheat followed by crimson clover in the third year. Simulation results suggested that the cover crop-based corn-soybean system using hairy vetch with zero fertilizer nitrogen inputs (number 4) produces less soil erosion and reduces nitrogen loss and herbicide loss when compared to the other cropping systems examined.

Economic studies conducted in Maryland by Fleming (2017), Fleming et al. (2018), and Lichtenberg et al. (2018) investigate how cost-share payments affect the adoption of cover crops. These studies specifically look at additionality provided by these programs, where "additionality" is defined as the adoption of conservation practices that would not have occurred in the absence of cost-share payments. These studies found both direct additionality (where cost-share payments increase cover crop acreage) and sometimes indirect additionality (where cost-share payments also encourage adoption of other conservation practices). For example, Fleming et al. (2018) evaluated a cover crop cost-share program aimed at reducing nitrogen loads in the Chesapeake Bay. They estimated a large direct additionality for nitrogen reduction at 97.6 percent for enrolled farmers. There was also evidence that cover crop cost-sharing exerted a positive indirect effect on conservation tillage use. Farmers enrolled in the cover crop cost-share program doubled their use of conservation tillage. However, in some cases they also found negative impacts (slippage) as reductions in vegetative cover.

Other than the studies published in the 1990s and 2000s and the cost-share payment impact studies discussed earlier, no other recent articles (post–2000 and later) have examined the economics of cover crops for corn in Maryland. Instead, recent studies of cover crop production systems in Maryland address a number of other issues, including cover crop interseeding (Caswell et al. 2019, Curran et al. 2018, Wallace et al. 2018, Youngerman et al. 2018), cover crops and no-till in organic and conventional systems (Ackroyd et al. 2019, Cavigelli et al. 2008, Keene et al. 2017, Teasdale et al. 2012), potential of cover crops as a weed management strategy (Ryan et al. 2011a, 2011b; Wallace et al. 2018), effects of cover crop establishment and termination dates and methods (Clark et al. 1997, Mirsky et al. 2017), and use of forage radish as a cover crop (Lawley et al. 2011, Wang and Weil 2018).[4] A notable study by Steele et al. (2012) investigated the effects of cover crops (e.g., rye and hairy vetch) on soil properties (e.g., aggregate stability) and organic matter. Aggregate stability increased under the cover crop treatment relative to the no-cover crop treatment, but there were no increases in total organic matter and labile organic matter over the 2-year period that the experiment was conducted. In locations

[4] The studies cited here examine production systems in Maryland. Curran et al. (2018) include similar data from multiple sites in Pennsylvania, New York, and Maryland.

with heavier-textured soil, cover crops did not affect any of the soil properties examined (i.e., there was no effect on both aggregate stability and organic matter).

A few studies explore the environmental and economic outcomes of cover crops in northeastern states outside of Maryland. In Delaware, Fisher et al. (2018) showed that cover crops (e.g., barley and rye) can lower nitrous oxide fluxes to the atmosphere and nitrate runoff to groundwater compared to conventional practices. This was especially true following dry or non-ideal growing conditions when crop N uptake was reduced and excess fertilizer appeared to be left in the soil. When there were cost-share subsidies, cover crop treatments were also found to be a more cost-effective approach to reducing nitrate runoff, as compared to a separate treatment that simply reduced chemical N applications without using cover crops.

In New York, Dietzel et al. (2011) also found lower nitrous oxide emissions in a corn field where winter rye cover crops were planted. Since nitrous oxide has a global warming potential that is approximately 300 times greater than carbon dioxide (NRC 2010) and is also the leading cause of stratospheric ozone decline (Ravishankara et al. 2009), reduction in nitrous oxide from cover crop use could be very valuable in mitigating climate change. However, Basche et al. (2014) found that the effect of cover crops on nitrous oxide emissions is uncertain and varies by species and management. Also in New York, Idowu et al. (2009) found that cover crops (e.g., rye and vetch) had a positive influence on surface hardness (i.e., degree of soil compaction) and potentially mineralizable nitrogen but had no effect on wet aggregate stability or soil organic matter. The authors noted the short duration (3–4 years) of cover crop use following approximately 30 years of vegetable production at the site without cover crop use.

A study in Connecticut using data from 1987 to 1990 found that a maize cropping system with a rye cover crop treatment had the highest nitrogen uptake efficiency among several cropping systems (Guillard et al. 1995). In New Jersey, using the Soil and Water Assessment Tool (SWAT), a hydrologic-based model, Giri et al. (2020) found that water fluxes (streamflow and surface runoff) were not affected by cover crop adoption but that cover cropping contributed to reductions in sediment and phosphorus pollution. In New Hampshire, Smith et al. (2014) found that cover crop mixtures did not enhance weed suppression, biomass stability, or productivity of a subsequent spring-planted oat cash crop when compared to the best monoculture cover crop (e.g., monocultures of buckwheat, mustard, sorghum-sudangrass, cereal rye, hairy vetch, or field pea).

In Maine, Liebman et al. (1993) found that a no-till-plus-rye cover crop system reduced dry bean production costs. In this same system, however, yields were reduced such that net revenues were lower relative to a conventional till, no-cover crop approach. A follow–up study in 1995 found that bean yields in the no-till-plus-rye cover crop system were lower in a wet early season but that yields for this system were higher under normal rainfall patterns (Liebman et al. 1995). Also in Maine, Griffin et al. (2000) found that legume cover crops were a viable alternative source of N that greatly reduced the need for N fertilizer in sweet corn production.

Dell et al. (2008) and Ketterings et al. (2015) investigated the effects of cover crops on dairy farms in Pennsylvania and New York. Both studies found that cover crops can enhance soil quality (e.g., reduce soil erosion, capture residual N, improve carbon sequestration) and increase annual forage yields. Other studies on cover crop systems in Pennsylvania examined related issues such as cover crop termination methods and timing in organic production with cover crops (Keene et al. 2017, Mischler et al. 2010, Wallace et al. 2018). In Vermont, cover crop studies have focused on the magnitude of cover crop subsidy payments from federal programs. These studies found that subsidy payments usually fall short of both the desired compensation and the implementation cost. They also found that noneconomic factors, especially familiarity and compatibility are important in affecting adoption (Helling et al. 2015).

In summary, the literature from studies conducted in the northeastern United States encompasses issues related to the environmental and soil health outcomes of cover crop use and agronomic factors associated with this practice. Published findings that focus directly on the economics of cover crop use for the northeastern United States are limited and not recent; most studies were conducted in the 1990s and 2000s, and the results of those studies were published prior to 2010. Some long-term studies have used biophysical simulation models, but only a few have utilized actual long-term (10 or more years) experimental, survey, or remote-sensing data to investigate the economics of cover crops. Although economic analyses of cover crop use in the Northeast are minimal, U.S. Agricultural Census data indicate that the region includes eight of the top 10 states (including the top four) with the highest percentage of cover crop use (Zulauf and Brown 2019a). The low number of economic analyses of cover crop use likely points to the important role of cost-share programs in cover crop adoption.

No-Till Systems

Similar to studies of cover crop use, the majority of recent studies that examine no-till systems in the northeastern United States were conducted in Maryland, New York, and Pennsylvania. These studies are usually based on field experiment data or simulation analyses that examine various aspects of no-till production systems (e.g., economic, soil health, and environmental impacts).

Cavigelli et al. (2009) and White et al. (2019) investigated the economic costs and returns of non-organic, no-till production systems relative to non-organic, tilled systems in Maryland. Both studies used similar budgeting approaches for the same long-term experiment. Data were gathered from 1999 to 2005 and from 2006 to 2014, respectively. For the earlier period, Cavigelli et al. (2009) found that the present value of net returns for individual crops and for full rotations was greater (and risks were lower) for the no-till system compared to the till system. For the later period, White et al. (2019) essentially followed the same analytical procedure as the earlier study to explore how a surge in commodity prices during this period affected the profitability of the various production systems examined. They found that the no-till system generally had the lowest production costs and highest return relative to the till systems examined. In contrast to the earlier study, White et al. (2019) observed that the economic risk (e.g., return variability) associated with the no-till system was slightly higher than the till system.

Epp and Hamlett (1996) examined the economics of different best management practices (BMPs) over a 10-year period using simulation methods that were calibrated based on field data from Pennsylvania. In most cases, no-till systems had higher present value of net income relative to the baseline (i.e., a conventional tillage system). However, the no-till approach reduced pollutant loads (e.g., sediments and nitrate leaching) less than other more expensive structural BMPs (e.g., sediment basins, terraces, grassed waterways, and stream buffers) compared to the standard tillage practice. An economic study in New York (Ghebremichael et al. 2009) also used a simulation-based approach to examine the effects of no-till systems on net returns at a dairy farm and found that no-till and cover crop management on existing and expanded fields used for corn silage reduced soil and water degradation. In that study, only small increases in whole farm net return compared to the baseline were observed over 3 years when no-till management was used on corn silage fields that previously had been conventionally tilled. Increases in net return were due to savings in fuel consumption, equipment, and labor costs. These findings are consistent with results in Jemison et al. (2019), a study that examined the effects of no-till on corn silage production in Maine.

A no-till economic study in Delaware (Duke et al. 2012) estimated preference for, and public benefits from, land preservation contracts that include no-till or other conservation practices such as riparian buffers. Results suggest that there are positive public benefits from land preservation contracts that include riparian buffers and the use of poultry litter instead of commercial fertilizer. However, there were no substantial public benefits from no-till cropping (likely due to Delaware's flatter topography and relatively low soil erosion risk), and public preference for this practice varies considerably.

In addition to the economics-focused, no-till studies in the northeastern states, other no-till studies conducted in the region examine the impacts of no-till systems on soil properties, environmental outcomes, and other agronomic-related factors. In Maryland, most of the no-till studies based on field experiments compare performance of non-organic, no-till production systems to non-organic, tilled systems. Using long-term experimental data, Cavigelli et al. (2008) found that average corn grain yields over a 9-year period were similar for non-organic, no-till systems compared to non-organic, tilled systems. Green et al. (2005) found that no-till soils had lower bulk density and greater aggregate stability than soils that were tilled, indicating a lower risk of sediment transport in no-till soils. A simulation analysis conducted by Cavigelli et al. (2018) also supported the existence of an enhancing effect of no-till systems on soil health, showing that soil organic carbon can be greater in a no-till than a conventional tillage system. Civerolo and Dickerson (1998) found that no-till corn fields had lower nitric oxide emission rates than tilled corn fields. Results from Hoffman et al. (2018) were comparable, with non-organic, no-till systems usually having lower greenhouse gas emissions compared to non-organic, tilled systems.

The results from the no-till studies in Maryland are roughly consistent with the findings in other northeastern states. Soil organic carbon was found to be greater in no-till systems (relative to conventional till systems) for studies conducted in Pennsylvania and Connecticut (Blanco-Canqui and Lal 2009, Christopher et al. 2009, Hooker et al. 2005). Other studies in Pennsylvania and New York suggest that no-till systems generally have beneficial effects on soil bulk density, penetration resistance, soil strength, and impacts of soil compaction on yield (Duiker et al. 2006, Karunatilake et al. 2000, Sidhu and Duiker 2006). However, van Es et al. (2019) found only modest reductions in soil nitrate leaching losses when using no-till production compared to conventional till in New York. These findings are consistent with a study in Pennsylvania that found no significant differences in soil nitrate leaching between no-till and conventional systems (Zhu et al. 2003) and a simulation-based study in New Jersey showing that no-till systems do not necessarily improve water quality levels in a watershed (Qiu 2016).

Overall, the no-till studies in the Northeast encompass topics related to the effects of no-till cropping on economic outcomes (e.g., yields, revenues, costs), soil properties, environmental outcomes (e.g., greenhouse gas emissions), and a variety of agronomic factors. To date, the economic studies of no-till systems in this region have relied on budgeting and simulation-based approaches. Although long-term field studies have been conducted (particularly in Maryland), no studies have yet utilized long-term panel econometric methods to estimate the causal impact of no-till practice adoption on various economic and environmental outcomes. In addition, risk impacts (e.g., effects on yield and/or revenue variability) of no-till practices have not been examined for production contexts in the northeastern United States.

CONCLUSIONS AND IMPLICATIONS

The management of soil health has increasingly been considered an integral part of sustainable agricultural production. Adoption of practices that enhance soil health, such as planting cover crops and implementing no-till systems, will likely play an important role in the continued productivity of U.S. agriculture under a changing climate and the provision of environmental benefits through reduced erosion and nutrient loss. These practices may also sequester carbon and increase adaptation and resilience, which provide additional benefits to the public.

In addition to productivity and environmental benefits, there are economic dimensions associated with the decision to adopt soil health practices. These include private versus external (societal) benefits, profit-increasing versus profit-decreasing effects, and agronomic versus environmental effects, all of which need to be assessed by farmers and policymakers for successful decision making. In-depth analysis of these economic dimensions has provided the necessary information for developing effective conservation payment programs that provide incentives to increase adoption of soil health practices. For example, findings in Fleming (2017) suggest that Maryland's cover crop cost-sharing initiative was well-designed because it resulted in increased cover crop acreage in the state. It is likely that past economic studies in Maryland contributed to this success by providing estimates of relevant adoption benefits and costs and guidance on the minimum required subsidies to encourage adoption.

The current soil health literature indicates that additional long-term economic studies that apply statistical analysis of data observed at multiple time points to identify relationships among soil health practices, soil health indicators, and economic outcomes are needed. For example, structural simultaneous equation models, where yields are a function of soil health indicators and these indicators are then functions of soil health practices, may be fruitful avenues for future research (Farnsworth 2015, Jaenicke and Lengnick 1999). Dynamic issues associated with cover crops and no-till, such as risk effects and investment analysis under uncertainty, are also topics that need further study. Examining the causal impacts, or overall benefits and costs, of soil health practices and the role of government programs in these dynamic contexts would help policymakers design programs that can alleviate potential market failures. To date, several studies have used long-term experimental data sets to examine the economics of soil health practices (although mostly in a partial/enterprise budgeting context); however, more studies that utilize long-term data sets (similar to Boyer et al. 2018 and Cusser et al. 2020) are needed for various production contexts and regions. Conducting region-specific, long-term studies that examine the dynamic economic impacts of cover crop use over time (i.e., viewing cover crops as an investment rather than a 1-year practice) is a potentially fruitful avenue for future research.

In addition, there is the potential for using aggregate data sets, such as those at the county level, to explore a wider array of economic issues that are not easily investigated with plot data. Such issues might include the risk effects of soil health practices in wider geographical areas, or climate change effects when adopting soil health practices across different regions. Geographical heterogeneity of soils and agricultural production systems need to be recognized, and economic evaluations of cover crop use should be conducted for different regions. The use of satellite-based data and remote sensing data in economic studies of soil health should also be investigated further. Use of non-market valuation techniques to estimate the societal external contributions of soil health practices is another research avenue that is likely to be fruitful.

Lastly, further examination of the role and design of government payment programs is important to better understand how public policy can best be developed to further incentivize the adoption of soil health practices. Studies that have investigated the effectiveness of cost-share payment programs by examining whether these programs induce a positive change in the adoption of conservation practices like cover crops include Claassen et al. (2018b), Fleming (2017), and Mezzatesta et al. (2013). However, these studies typically do not separate the effects of different cost-share programs (i.e., all payments from federal, state, and local sources are lumped together), or they the adoption effects of a single, specific payment program. Studies that explore how different cost-share payment programs affect adoption of specific soil health practices would be a fruitful future research direction. For example, research that looks at the adoption effects of government cost-share programs, such as the Environmental Quality Incentives Program (EQIP) and the Conservation Stewardship Program (CSP), compared to state-level conservation payment programs, such as the Maryland Agricultural and Water Quality Cost Sharing program, would provide important insights into the effectiveness of different cost-share payment structures and designs. Separately investigating the impact of private carbon market payments that encourage soil health practice adoption and the state-level programs that utilize crop insurance premium discounts to incentivize adoption of soil health are also promising future research avenues that can inform the design of more effective conservation payment programs.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from USDA Agreement Numbers NRC19IRA0010111 and FS19JV11242306-117. The work of Rejesus was also supported in part by USDA NIFA Hatch Project No. NC02696. This research was a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by the U.S. Department of Agriculture (USDA).

REFERENCES

Ackroyd, V.J.; Cavigelli, M.A.; Spargo, J.T.; Davis, B.; Garst, G.; Mirsky, S.B. 2019. **Legume cover crops reduce poultry litter application requirements in organic systems.** Agronomy Journal. 111(5): 2361–2369. https://doi.org/10.2134/agronj2018.09.0622.

Adusumilli, N.; Wang, H.; Dodla, S.; Deliberto, M. 2020. **Estimating risk premiums for adopting no-till and cover crops management practices in soybean production system using stochastic efficiency approach.** Agricultural Systems. 178: 102744. https://doi.org/10.1016/j.agsy.2019.102744.

Al-Kaisi, M.M.; Yin, X. 2005. **Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn-soybean rotations.** Journal of Environmental Quality. 34(2): 437–445. https://doi.org/10.2134/jeq2005.0437.

Archer, D.W.; Reicosky, D.C. 2009. **Economic performance of alternative tillage systems in the Northern Corn Belt.** Agronomy Journal. 101(2): 296–304. https://doi.org/10.2134/agronj2008.0090x.

Basche, A.D.; Miguez, F.E.; Kaspar, T.C.; Castellano, M.J. 2014. **Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis.** Journal of Soil and Water Conservation. 69(6): 471–482. https://doi.org/10.2489/jswc.69.6.471.

Bergtold, J.S.; Ramsey, S.; Maddy, L.; Williams, J.R. 2017. **A review of economic considerations for cover crops as a conservation practice.** Renewable Agriculture and Food Systems. 34(1): 62–76. https://doi.org/10.1017/S1742170517000278.

Blanco-Canqui, H.; Lal, R. 2009. **Extent of soil water repellency under long-term no-till soils.** Geoderma. 149(1–2): 171–180. https://doi.org/10.1016/j.geoderma.2008.11.036.

Blanco-Canqui, H.; Ruis, S.J. 2018. **No-tillage and soil physical environment.** Geoderma. 326(15): 164–200. https://doi.org/10.1016/j.geoderma.2018.03.011.

Boquet D.J.; Hutchinson, R.L.; Breitenbeck, G.A. 2004. **Long-term tillage, cover crop, and nitrogen rate effects on cotton: yield and fiber properties.** Agronomy Journal. 96(5): 1436–1442. https://doi.org/10.2134/agronj2004.1436.

Bowman, M.; Wallander, S.; Lynch, L. 2016. **An economic perspective on soil health.** Amber Waves. Washington, DC: U.S. Department of Agriculture, Economic Research Service. https://www.ers.usda.gov/amber-waves/2016/september/an-economic-perspective-on-soil-health (accessed 8 September 2023).

Boyer, C.N.; Lambert, D.M.; Larson, J.A.; Tyler, D.D. 2018. I**nvestment analysis of cover crop and no-tillage systems in Tennessee cotton.** Agronomy Journal. 110(1): 331–338. https://doi.org/10.2134/agronj2017.08.0431.

Cai, Z.; Udawatta, R.P.; Gantzer, C.J.; Jose, S.; Godsey, L.; Cartwright, L. 2019. **Economic impacts of cover crops for a Missouri wheat-corn-soybean rotation.** Agriculture. 9(4): 83. https://doi.org/10.3390/agriculture9040083.

Caswell, K.; Wallace, J.M.; Curran, W.S.; Mirsky, S.B.; Ryan, M.R. 2019. **Cover crop species and cultivars for drill-interseeding in mid-Atlantic corn and soybeans.** Agronomy Journal. 111(3): 1060–1067. https://doi.org/10.2134/agronj2018.08.0511.

Cavigelli, M.A.; Hima, B.L.; Hanson, J.C.; Teasdale, J.R.; Conklin, A.E.; Lu, Y. 2009. **Long-term economic performance of organic and conventional field crops in the Mid-Atlantic region.** Renewable Agriculture and Food Systems. 24(2): 102–119. https://doi.org/10.1017/S1742170509002555.

Cavigelli, M.A.; Mirsky, S.B.; Teasdale, J.R.; Spargo, J.T.; Doran, J. 2013. **Organic grain cropping systems to enhance ecosystem services.** Renewable Agriculture and Food Systems. 28(2): 145–159. https://doi.org/10.1017/S1742170512000439.

Cavigelli, M.A.; Nash, P.R.; Gollany, H.T.; Rasmann, C.; Polumsky, R.W.; Le, A.N.; Conklin, A.E. 2018. **Simulated soil organic carbon changes in Maryland are affected by tillage, climate change, and crop yield.** Journal of Environmental Quality. 47(4): 588–595. http://doi.org/10.2134/jeq2017.07.0291.

Cavigelli, M.A.; Teasdale, J.R.; Conklin, A.E. 2008. **Long-term agronomic performance of organic and conventional field crops in the Mid-Atlantic region.** Agronomy Journal. 100(3): 785–794. https://doi.org/10.2134/agronj2006.0373.

Christopher, S.; Lal, R.; Mishra, U. 2009. **Regional study of no-till effects on carbon sequestration in the midwestern United States.** Soil Science Society of America Journal. 73(1): 207–216. https://doi.org/10.2136/sssaj2007.0336.

Civerolo, K.L.; Dickerson, R.R. 1998. **Nitric oxide soil emissions from tilled and untilled cornfields.** Agricultural and Forest Meteorology. 90(4): 307–311. https://doi.org/10.1016/S0168-1923(98)00056-2.

Claassen, R.; Bowman, M.; McFadden, J.; Smith, D.; Wallander, S. 2018a. **Tillage intensity and conservation cropping in the United States.** EIB-197. Washington, DC: U.S. Department of Agriculture, Economic Research Service. 27 p.

Claassen, R.; Duquette, E.N.; Smith, D.J. 2018b. **Additionality in U.S. agricultural conservation programs.** Land Economics. 94(1): 19–35. https://doi.org/10.3368/le.94.1.19.

Clark, A.J.; Decker, A.M.; Meisinger, J.J.; McIntosh, M.S. 1997. **Kill date of vetch, rye, and a vetch-rye mixture: II. soil moisture and corn yield.** Agronomy Journal. 89(3): 434–441. https://doi.org/10.2134/agronj1997.00021962008900030011x.

Curran, W.S.; Hoover, R.J.; Mirsky, S.B.; Roth, G.W.; Ryan, M.R.; Ackroyd, V.J.; Wallace, J.M.; Dempsey, M.A.; Pelzer, C.J. 2018. **Evaluation of cover crops drill interseeded into corn across the Mid-Atlantic region.** Agronomy Journal. 110(2): 435–443. https://doi.org/10.2134/agronj2017.07.0395.

Cusser, S.; Bahlai, C.; Swinton, S.M.; Robertson, G.P.; Haddad, N.M. 2020. **Long-term research avoids spurious and misleading trends in sustainability attributes of no-till.** Global Change Biology. 26(6): 3715–3725. https://doi.org/10.1111/gcb.15080.

Dell, C.J.; Salon, P.R.; Franks, C.D.; Benham, E.C.; Plowden, Y. 2008. **No-till and cover crop impacts on soil carbon and associated properties in Pennsylvania dairy farms.** Journal of Soil and Water Conservation. 63(3): 136–142. https://doi.org/10.2489/jswc.63.3.136.

Díaz-Zorita, M.; Grove, J.H.; Murdock, L.; Herbeck, J.; Perfect, E. 2004. **Soil structural disturbance effects on crop yields and soil properties in a no-till production system.** Agronomy Journal. 96(6): 1651–1659. https://doi.org/10.2134/agronj2004.1651.

Dietzel, R.; Wolfe, D.; Thies, J.E. 2011. **The influence of winter soil cover on spring nitrous oxide emissions from an agricultural soil.** Soil Biology and Biochemistry. 43(9): 1989–1991. https://doi.org/10.1016/j.soilbio.2011.05.017.

Ding, Y.; Schoengold, K.; Tadesse, T. 2009. **The impact of weather extremes on agricultural production methods: Does drought increase adoption of conservation tillage practices?** Journal of Agricultural and Resource Economics. 34(3): 395–411.

Doster, D.H.; Griffith, D.R.; Mannering, J.V.; Parsons, S.D. 1983. **Economic returns from alternative corn and soybean tillage systems in Indiana.** Journal of Soil and Water Conservation. 38(6): 504–508.

Duiker, S.W.; Halderman, J.F., Jr.; Johnson, J.H. 2006. **Tillage x maize hybrid interactions.** Agronomy Journal. 98(3): 436–442. https://doi.org/10.2134/agronj2005.0063.

Duke, J.M.; Borchers, A.M.; Johnston, R.J.; Absetz. S. 2012. **Sustainable agricultural management contracts: using choice experiments to estimate the benefits of land preservation and conservation practices.** Ecological Economics. 74: 95–103. https://doi.org/10.1016/j.ecolecon.2011.12.002.

Dunn, M.; Ulrich-Schad, J.D.; Prokopy, L.S.; Myers, R.L.; Watts, C.R.; Scanlon, K. 2016. **Perceptions and use of cover crops among early adopters: findings from a national survey.** Journal of Soil and Water Conservation. 71(1): 29–40. https://doi.org/10.2489/jswc.71.1.29.

Epp, D.J.; Hamlett, J.M. 1996. **Cost-effectiveness of conservation and nutrient management practices in Pennsylvania.** Journal of Soil and Water Conservation. 51(6): 486–494.

Farnsworth, R. 2015. **Economics of soil health: a selected review and assessment of the existing literature.** Paper presented at the Economics of Soil Health Conference. 2015 September 21–22; Washington, DC.

Fathelrahman, E.M.; Ascough, J.C., II; Hoag, D.L.; Malone, R.W.; Heilman, P.; Wiles, L.J.; Kanwar, R.S. 2011. **Continuum of risk analysis methods to assess tillage system sustainability at the experimental plot level.** Sustainability. 3(7): 1035–1063. https://doi.org/10.3390/su3071035.

Fisher, T.A.; Fox, R.J.; Gustafson, A.B.; Lewis, J.; Millar, N.; Winsten, J.R. 2018. **Fluxes of nitrous oxide and nitrate from agricultural fields on the Delmarva Peninsula: N biogeochemistry and economics of field management.** Agriculture, Ecosystems, and Environment. 254: 162–178. https://doi.org/10.1016/j.agee.2017.11.021.

Fleming, P. 2017. **Agricultural cost sharing and water quality in the Chesapeake Bay: estimating indirect effects of environmental payments.** American Journal of Agricultural Economics. 99(5): 1208–1227. https://doi.org/10.1093/ajae/aax040.

Fleming, P.; Lichtenberg, E.; Newburn, D.A. 2018. **Evaluating impacts of agricultural cost sharing on water quality: additionality, crowding in, and slippage.** Journal of Environmental Economics and Management. 92: 1–19. https://doi.org/10.1016/j.jeem.2018.08.007.

Foote, W.; Edmisten, K.; Wells, R.; Jordan, D.; Fisher, L. 2014. **Cotton response to nitrogen derived from leguminous cover crops and urea ammonium nitrate.** Journal of Cotton Science. 18(3): 367–375.
Fuglie, K.O. 1999. **Conservation tillage and pesticide use in the Corn Belt.** Journal of Agriculture and Applied Economics. 31(1): 133–147. https://doi.org/10.1017/S0081305200028831.

Gál, A.; Vyn, T.J.; Michéli, E.; Kladivko, E.J.; McFee, W.W. 2007. **Soil carbon and nitrogen accumulation with long-term no-till versus moldboard plowing overestimated with tilled-zone sampling depths.** Soil and Tillage Research. 96(1–2): 42–51. https://doi.org/10.1016/j.still.2007.02.007.

Ghebremichael, L.T.; Veith, T.L.; Cerosaletti, P.E.; Dewing, D.E.; Rotz, C.A. 2009. **Exploring economically and environmentally viable northeastern U.S. dairy farm strategies for coping with rising corn grain prices.** Journal of Dairy Science. 92(8): 4086–4099. https://doi.org/10.3168/jds.2009-2024.

Giri, S.; Lathrop, R.G.; Obropta, C.C. 2020. **Climate change vulnerability assessment and adaptation strategies through best management practices.** Journal of Hydrology. 580: 124311. https://doi.org/10.1016/j.jhydrol.2019.124311.

Green, V.S.; Cavigelli, M.A.; Dao, T.H.; Flanagan, D.C. 2005. **Soil physical properties and aggregate-associated C, N, and P distributions in organic and conventional cropping systems.** Soil Science. 170(10): 822–831. https://doi.org/10.1097/01.ss.0000190509.18428.fe.

Griffin, T.; Liebman, M.; Jemison, J. 2000. **Cover crops for sweet corn production in a short-season environment.** Agronomy Journal. 92(1): 144–151. https://doi.org/10.2134/agronj2000.921144x.

Griscom, B.W.; Adams, J.; Ellis, P.W.; Houghton, R.A.; Lomax, G.; Miteva, D.A.; Schlesinger, W.H.; Shoch, D.; Siikamäki, J.V.; Smith, P. [et al.]. 2017. **Natural climate solutions.** Proceedings of the National Academy of Sciences. 114(44): 11645–11650. https://doi.org/10.1073/pnas.1710465114.

Guillard, K.; Griffin, G.F.; Allinson, D.W.; Rafey, M.M.; Yamartino, W.R.; Pietrzyk, S.W. 1995. **Nitrogen utilization of selected cropping systems in the U.S. Northeast: I. dry matter yield, N uptake, apparent N recovery, and N use efficiency.** Agronomy Journal. 87(2): 193–199. https://doi.org/10.2134/agronj1995.00021962008700020010x.

Hanson, J.C.; Lichtenberg, E.; Decker, A.M.; Clark, A.J. 1993. **Profitability of no-tillage corn following a hairy vetch cover crop.** Journal of Production Agriculture. 6(3): 432–437. https://doi.org/10.2134/jpa1993.0432.

Helling, A.P.; Conner, D.S.; Heiss, S.N.; Berlin, L.S. 2015. **Economic analysis of climate change best management practices in Vermont agriculture.** Agriculture. 5(3): 879–900. https://doi.org/10.3390/agriculture5030879.

Hodde, W.; Sesmero, J.; Gramig, B.; Vyn, T.; Doering, O. 2019. **The predicted effect of projected climate change on the economics of conservation tillage.** Agronomy Journal. 111(6): 3130–3139. https://doi.org/10.2134/agronj2019.01.0045.

Hoffman, E.; Cavigelli, M.A.; Camargo, G.; Ryan, M.; Ackroyd, V.J.; Richard, T.L.; Mirsky, S.B. 2018. **Energy use and greenhouse gas emissions in organic and conventional grain crop production: accounting for nutrient inflows.** Agricultural Systems. 162: 89–96. https://doi.org/10.1016/j.agsy.2018.01.021.

Hooker, B.A.; Morris, T.F.; Peters, R.; Cardon, Z.G. 2005. **Long-term effects of tillage and corn stalk return on soil carbon dynamics.** Soil Science Society of American Journal. 69(1): 188–196. https://doi.org/10.2136/sssaj2005.0188.

Idowu, O.J.; van Es, H.M.; Abawi, G.S.; Wolfe, D.W.; Schindelbeck, R.R.; Moebius-Clune, B.N.; Gugino. B.K. 2009. **Use of an integrative soil health test for evaluation of soil management impacts.** Renewable Agriculture and Food Systems. 24(3): 214–224. https://doi.org/10.1017/S1742170509990068.

Jaenicke, E.C.; Lengnick, L.L. 1999. **A soil-quality index and its relationship to efficiency and productivity growth measures: two decompositions.** American Journal of Agricultural Economics. 81(4): 881–893. https://doi.org/10.2307/1244331.

Jemison, J.M., Jr.; Kersbergen, R.; Majewski, C.; Brinton, W. 2019. **Soil health of recently converted no-till corn fields in Maine.** Communications in Soil Science and Plant Analysis. 50(19): 2384–2396. https://doi.org/10.1080/00103624.2019.1659302.

Jian, J.; Du, X.; Reiter, M.S.; Stewart, R.D. 2020. **A meta-analysis of global cropland soil carbon changes due to cover cropping.** Soil Biology and Biochemistry. 143: 107735. https://doi.org/10.1016/j.soilbio.2020.107735.

Karlen, D.L.; Mausbach, M.J.; Doran, J.W.; Cline, R.G.; Harris, R.F.; Schuman, G.E. 1997. **Soil quality: a concept, definition, and framework for evaluation (a guest editorial).** Soil Science Society of America Journal. 61(1): 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x.

Karlen, D.L.; Wollenhaupt, N.C.; Erbach, D.C.; Berry, E.C.; Swan, J.B.; Eash, N.S.; Jordahl, J.L. 1994. **Crop residue effects on soil quality following 10 years of no-till corn.** Soil and Tillage Research. 31(2–3): 149–167. https://doi.org/10.1016/0167-1987(94)90077-9.

Karunatilake, U.; van Es, H.M.; Schindelbeck, R.R. 2000. **Soil and maize response to plow and no-tillage after alfalfa-to-maize conversion on a clay loam soil in New York.** Soil and Tillage Research. 55(1–2): 31–42. https://doi.org/10.1016/S0167-1987(00)00096-9.

Kaval, P. 2004. **The profitability of alternative cropping systems: a review of the literature.** Journal of Sustainable Agriculture. 23(3): 47–65. https://doi.org/10.1300/J064v23n03_06.

Kay, R.D.; Edwards, W.M.; Duffy, P.A. 2015. **Farm management.** 8th ed. New York: McGraw-Hill. 480 p. Keene, C.L.; Curran, W.S.; Wallace, J.M.; Ryan, M.R.; Birsky, S.B.; Van Gessel, M.J.; Barbercheck, M.E. 2017. **Cover crop termination timing is critical in organic rotational no-till systems.** Agronomy Journal. 109(1): 272–282. https://doi.org/10.2134/agronj2016.05.0266.

Ketterings, Q.M.; Swink, S.N.; Duiker, S.W.; Czymmek, K.J.; Beegle, D.B.; Cox, W.J. 2015. **Integrating cover crops for nitrogen management in corn systems on northeastern U.S. dairies.** Agronomy Journal. 107(4): 1365–1376. https://doi.org/10.2134/agronj14.0385.

Klemme, R.M. 1985. **A stochastic dominance comparison of reduced tillage systems in corn and soybean production under risk.** American Journal of Agricultural Economics. 67(3): 550–556. https://doi.org/10.2307/1241074.

Kovar, J.L.; Barber, S.A.; Kladivko, E.J.; Griffith, D.R. 1992. **Characterization of soil temperature, water content, and maize root distribution in two tillage systems.** Soil and Tillage Research. 24(1): 11–27. https://doi.org/10.1016/0167-1987(92)90069-N.

Larson, J.A.; Jaenicke, E.C.; Roberts, R.K.; Tyler, D.D. 2001. **Risk effects of alternative winter cover crop, tillage, and nitrogen fertilization systems in cotton production.** Journal of Agriculture and Applied Economics. 33(3): 445–457. https://doi.org/10.1017/S1074070800030182.

Lawley, Y.E.; Weil, R.R.; Teasdale, J.R. 2011. **Forage radish cover crop suppresses winter annual weeds in fall and before corn planting.** Agronomy Journal. 103(1): 137–144. https://doi.org/10.2134/agronj2010.0187.

Larney, F.J.; Ren, T.; McGinn, S.; Lindwall, C.W.; Izaurralde, R.C. 2003. **The influence of rotation, tillage and row spacing on near-surface soil temperature for winter wheat in southern Alberta.** Canadian Journal of Soil Science. 83(1): 89–98. https://doi.org/10.4141/S01-076.

Lewis, R.W.; Barth, V.P.; Coffey, T.; McFarland, C.; Huggins, D.R.; Sullivan, T.S. 2018. **Altered bacterial communities in long-term no-till soils associated with stratification of soluble aluminum and soil pH.** Soil Systems. 2(1): 1–13. https://doi.org/10.3390/soils2010007.

Licht, M.A.; Al-Kaisi, M. 2005. **Strip-tillage effect on seedbed soil temperature and other soil physical properties.** Soil and Tillage Research. 80(1–2): 233–249. https://doi.org/10.1016/j.still.2004.03.017.

Lichtenberg, E.; Hanson, J.C.; Decker, A.M.; Clark, A.J. 1994. **Profitability of legume cover crops in the Mid-Atlantic region.** Journal of Soil and Water Conservation. 49(6): 582–585. https://www.jswconline.org/content/49/6/582.

Lichtenberg, E.; Wang, H.; Newburn, D.A. 2018. **Uptake and additionality in a green payment program: a panel data study of the Maryland cover crop program.** Paper presented at the Agricultural and Applied Economics Association Annual Meeting. 2018 August 5–7; Washington, DC.

Liebman, M.; Rowe, R.J.; Corson, S.; Marra, M.C.; Honeycutt, C.W.; Murphy, B.A. 1993. **Agronomic and economic performance of conventional vs. reduced input bean cropping systems.** Journal of Production Agriculture. 6(3): 369–378. https://doi.org/10.2134/jpa1993.0369.

Liebman, M.; Corson, S.; Rowe, R.J.; Halterman, W.A. 1995. **Dry bean responses to nitrogen fertilizer in two tillage and residue management systems.** Agronomy Journal. 87(3): 538–546. https://doi.org/10.2134/agronj1995.00021962008700030024x.

Liu, S.; Duffy, M.D. 1996. **Tillage systems and profitability: an economic analysis of the Iowa MAX program.** Journal of Production Agriculture. 9(4): 522–527. https://doi.org/10.2134/jpa1996.0522.

Lu, Y.C.; Watkins, B.; Teasdale, J.R. 1999. **Economic analysis of sustainable agricultural cropping systems for Mid-Atlantic states.** Journal of Sustainable Agriculture. 15(2–3): 77–93. https://doi.org/10.1300/J064v15n02_09.

Lu, Y.C.; Watkins, B.; Teasdale, J.R.; Abdul-Baki, A.A. 2000. C**over crops in sustainable food production.** Food Reviews International. 16(2): 121–157. https://doi.org/10.1081/FRI-100100285.

Mahama, G.; Vara Prasad, P.V.; Roozenboom, K.L.; Nippert, J.B.; Rice, C.W. 2016. **Cover crops, fertilizer nitrogen rates, and economic return of grain sorghum.** Agronomy Journal. 108(1): 1–16. https://doi.org/10.2134/agronj15.0135.

Marra, M.C.; Kaval, P. 2000. **The relative profitability of sustainable grain cropping systems: a meta-analytic comparison.** Journal of Sustainable Agriculture. 16(4): 19–32. https://doi.org/10.1300/J064v16n04_04.

Mezzatesta, M.; Newburn, D.A.; Woodward, R.T. 2013. **Additionality and the adoption of farm conservation practices.** Land Economics. 89(4): 722–42. https://doi.org/10.3368/le.89.4.722.

Miguez, F.E.; Bollero, G.A. 2005. **Review of corn yield response under winter cover cropping systems using meta-analytic methods.** Crop Science. 45(6): 2318–2329. https://doi.org/10.2135/cropsci2005.0014.
Mirsky, S.B.; Ackroyd, V.J.; Cordeau, S.; Curran, W.S.; Hashemi, M.S.; Reberg-Horton, S.C.; Ryan, M.R.;

Spargo, J.T. 2017. **Hairy vetch biomass across the eastern United States: effects of latitude, seeding rate and date, and termination timing.** Agronomy Journal. 109(4): 1510–1519. https://doi.org/10.2134/agronj2016.09.0556.

Mischler, R.; Duiker, S.W.; Curran, W.S.; Wilson, D. 2010. **Hairy vetch management for no-till organic corn production.** Agronomy Journal. 102(1): 355–362. https://doi.org/10.2134/agronj2009.0183.

Morrow, J.G.; Huggins, D.R.; Carpenter-Boggs, L.A.; Reganold, J.P. 2016. **Evaluating measures to assess soil health in long-term agroecosystem trials.** Soil Science Society of America Journal. 80(2): 450–462. https://doi.org/10.2136/sssaj2015.08.0308.

Myers, R.; Weber, A.; Tellatin, S. 2019. **Cover crop economics: opportunities to improve your bottom line in row crops.** SARE Tech. Bull. Ag. Innovation Series. College Park, MD: Sustainable Agriculture Research and Education. 24 p.

National Research Council [NRC]. 2010. **Advancing the science of climate change.** Washington, DC: National Academies Press. 504 p.

Obour, A.; Holman, J.D. 2017. **Long-term tillage and nitrogen fertilization effects on soil surface chemistry.** Kansas Agricultural Experiment Station Research Reports. 3(3): 1–7. https://doi.org/10.4148/2378-5977.1394.

Ogle, S.M.; Swan, A.; Paustian, K. 2012. **No-till management impacts on crop productivity, carbon input, and soil carbon sequestration.** Agriculture, Ecosystems, and Environment. 149: 37–49. https://doi.org/10.1016/j.agee.2011.12.010.

Pagliai, M.; Vignozzi, N.; Pellegrini, S. 2004. **Soil structure and the effect of management practices.** Soil and Tillage Research. 79(2): 131–143. https://doi.org/10.1016/j.still.2004.07.002.

Paustian, K.; ,Lehmann, J.; Ogle, S.; Reay, D.; Robertson, G.P.; Smith, P. 2016. **Climate-smart soils.** Nature. 532: 49–57. https://doi.org/10.1038/nature17174.

Pendell, D.L.; Williams, J.R.; Rice, C.W.; Nelson, R.G.; Boyles, S.B. 2006. **Economic feasibility of no-tillage and manure for soil carbon sequestration in corn production in northeastern Kansas.** Journal of Environmental Quality. 35(4): 1364–1373. https://doi.org/10.2134/jeq2005.0149.

Phillips, S.; Olson, K.; Siemens, J.; Ebelhar, S. 1997. **Economics of conservation tillage systems for CRP land in southern Illinois.** Journal of Production Agriculture. 10(3): 483–489. https://doi.org/10.2134/jpa1997.0483.

Plastina, A.; Liu, F.; Sawadgo, W.; Miguez, F.; Carlson, S. 2018a. **Partial budgets for cover crops in midwest row crop farming.** Journal of the American Society of Farm Managers and Rural Appraisers. 90–106.

Plastina, A.; Liu, F.; Sawadgo, W.; Miguez, F.; Carlson, S.; Marcillo, G. 2018b. **Annual net returns to cover crops in Iowa.** Journal of Applied Farm Economics. 2(2): 19–36. https://doi.org/10.7771/2331-9151.1030.

Plastina, A.; Liu, F.; Miguez, F.; Carlson, S. 2020. **Cover crops use in Midwestern U.S. agriculture: perceived benefits and net returns.** Renewable Agriculture and Food Systems. 35(1): 38–48. https://doi.org/10.1017/S1742170518000194.

Poeplau, C.; Don, A. 2015. **Carbon sequestration in agricultural soils via cultivation of cover crops: a meta-analysis.** Agriculture, Ecosystems, and Environment. 200: 33–41. https://doi.org/10.1016/j.agee.2014.10.024.

Qiu, Z. 2016. **Assessment of water quality impacts of land use and management practices in a suburban watershed.** Environmental Engineering and Management Journal. 15(7): 1551–1560. https://doi.org/10.30638/eemj.2016.167.

Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. 2009. **Nitrous oxide (N2O): the dominant oxone-depleting substance emitted in the 21st century.** Science. 326(5949):123–125. https://www.science.org/doi/10.1126/science.1176985.

Reddy, K. 2003. **Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean.** Weed Technology. 17(1): 28–35. https://doi.org/10.1614/0890-037X(2003)017[0028:IORCCA]2.0.CO;2.

Roberts, R.K.; Larson, J.A.; Tyler, D.D.; Duck, B.N.; Dillivan, K.D. 1998. **Economic analysis of the effects of winter cover crops on no-tillage corn yield response to applied nitrogen.** Journal of Soil and Water Conservation. 53(3): 280–285.

Ryan, M.R.; Curran, W.S.; Grantham, A.M.; Hunsberger, L.K.; Mirsky, S.B.; Mortensen, D.A.; Nord, E.A.; Wilson, D.O. 2011a. **Effects of seeding rate and poultry litter on weed suppression from a rolled cereal rye cover crop.** Weed Science. 59(3): 438–444. https://doi.org/10.1614/WS-D-10-00180.1.

Ryan, M.R.; Mirsky, S.B.; Mortensen, D.A.; Teasdale, J.R.; Curran, W.S. 2011b. P**otential synergistic effects of cereal rye biomass and soybean planting density on weed suppression.** Weed Science. 59(2): 238–246. https://doi.org/10.1614/WS-D-10-00110.1.

Schipanski, M.E.; Barbercheck, M.; Douglas, M.R.; Finney, D.M.; Haider, K.; Kaye, J.P.; Kemanian, A.R.; Mortensen, D.A.; Ryan, M.R.; Tooker, J. [et al.]. 2014. **A framework for evaluating ecosystem services provided by cover crops in agroecosystems.** Agricultural Systems. 125: 12–22. https://doi.org/10.1016/j.agsy.2013.11.004.

Sidhu, D.; Duiker, S.W. 2006. **Soil compaction in conservation tillage: crop impacts.** Agronomy Journal. 98(5): 1257–1264. https://doi.org/10.2134/agronj2006.0070.

Singer, J.W.; Nusser, S.M.; Alf, C.J. 2007. **Are cover crops being used in the U.S. Corn Belt?** Journal of Soil and Water Conservation. 62(5): 353–358.

Smith, R.G.; Atwood, L.W.; Warren, N.D. 2014. **Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services.** PLoS One. 9(5): e97351. https://doi.org/10.1371/journal.pone.0097351.

Snapp, S.S.; Swinton, S.M.; Labarta, R.; Mutch, D.; Black, J.R.; Leep, R.L.; Nyiraneza, J. 2005. **Evaluating cover crops for benefits, costs, and performance within cropping system niches.** Agronomy Journal. 97(1): 322–332. https://doi.org/10.2134/agronj2005.0322a.

Steele, M.K.; Coale, F.J.; Hill, R.L. 2012. **Winter annual cover crop impacts on no-till soil physical properties and organic matter.** Soil Science Society of America Journal. 76(6): 2164–2173. https://doi.org/10.2136/sssaj2012.0008.

Stevens A.W. 2018. **Review: the economics of soil health.** Food Policy. 80: 1–9. https://doi.org/10.1016/j.foodpol.2018.08.005.

Stockman, U.; Adams, M.A.; Crawford, J.W.; Field, D.J.; Henakaarchchi, N.; Jenkins, M.; Minasny, B.; McBratney, A.B.; de Courcelles, V.D.R.; Singh, K. [et al.]. 2013. **The knowns, known unknowns, and unknowns of sequestration of soil organic carbon.** Agriculture, Ecosystems, and Environment. 163: 80–99. https://doi.org/10.1016/j.agee.2012.10.001.

Suri, T. 2011. **Selection and comparative adoption in technology adoption.** Econometrica. 79(1): 159–209. https://doi.org/10.3982/ECTA7749.

Teasdale, J.R.; Mirsky, S.B.; Spargo, J.T.; Cavigelli, M.A.; Maul, J.E. 2012. **Reduced-tillage organic corn production in a hairy vetch cover crop.** Agronomy Journal. 104(3): 621–628. https://doi.org/10.2134/agronj2011.0317.

Toliver, D.K.; Larson, J.A.; Roberts, R.K.; English, B.C.; De La Torre Ugarte, D.G.; West, T.O. 2012. **Effects of no-till on yields as influenced by crop and environmental factors.** Agronomy Journal. 104(2): 530–541. https://doi.org/10.2134/agronj2011.0291.

Trlica, A.; Walia, M.K.; Krausz, R.; Secchi, S.; Cook, R.L. 2017. **Continuous corn and corn–soybean profits over a 45-year tillage and fertilizer experiment.** Agronomy Journal. 109(1): 218–226. https://doi.org/10.2134/agronj2016.06.0377.

Uri, N.D. 1999. **The economic benefits and costs of conservation tillage.** Journal of Sustainable Agriculture. 15(1): 5–27. https://doi.org/10.1300/J064v15n01_03.

USDA National Agricultural Statistics Service [USDA NASS]. 2019. **2017 census of agriculture: United States summary and state data.** AC-17-A-51. Washington, DC: Geographic Area Series. Vol. 1. Part 51. 820 p.

USDA Natural Resources Conservation Service [USDA NRCS]. 2023. **What is soil health?** Washington DC: U.S. Department of Agriculture, Natural Resources Conservation Service. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health (accessed 9 September 2023).

van Es, H.; Ristow, A.; Nunes, M.R.; Schindelbeck, R.; Sela, S.; Davis, M. 2019. **Nitrate leaching reduced with dynamic-adaptive nitrogen management under contrasting soils and tillage.** Soil Science Society of America Journal. 84(1): 220–231. https://doi.org/10.1002/saj2.20031.

Varco J.J.; Spurlock, S.R.; Sanabria-Garro, O.R. 1999. **Profitability and nitrogen rate optimization associated with winter cover management in no-tillage cotton.** Journal of Production Agriculture. 12(1): 91– 95. https://doi.org/10.2134/jpa1999.0091.

Vyn, T.J.; Raimbult, B.A. 1993. **Long-term effect of five tillage systems on corn response and soil structure.** Agronomy Journal. 85(5): 1074–1079. https://doi.org/10.2134/agronj1993.00021962008500050022x.
Wade, T.; Claassen, R.; Wallander, S. 2015. C**onservation-practice adoption rates vary widely by crop and region.** EIB-147. Washington, DC: U.S. Department of Agriculture, Economic Research Service. 40 p.

Wallace, J.M.; Keene, C.L.; Curran, W.; Mirsky, S.; Ryan, M.R.; Van Gessel, M.J. 2018. **Integrated weed management strategies in cover crop-based, organic rotational no-till corn and soybean in the Mid-Atlantic region.** Weed Science. 66(1): 94–108. https://doi.org/10.1017/wsc.2017.53.

Wang, F.; Weil, R.R. 2018. **The form and vertical distribution of soil nitrogen as affected by forage radish cover crop and residual side-dressed N fertilizer.** Soil Science. 183(1): 22–33. https://10.1097/SS.0000000000000224.

Watkins, K.B.; Lu, Y.C.; Teasdale, J.R. 2002. **Long-term environmental and economic simulation of alternative cropping systems in Maryland.** Journal of Sustainable Agriculture. 20(4): 61–82. https://doi.org/10.1300/J064v20n04_05.

Weersink, A.; Walker, M.; Swanton, C.; Shaw, J.E. 1992. **Costs of conventional and conservation tillage systems.** Journal of Soil and Water Conservation. 47(4): 328–334.

West, T.D.; Griffith, D.R.; Steinhardt, G.C.; Kladivko, E.J.; Parsons, S.D. 1996. **Effect of tillage and rotation on agronomic performance of corn and soybean: twenty-year study on dark silty clay loam soil.** Journal of Production Agriculture. 9(2): 241–248. https://doi.org/10.2134/jpa1996.0241.

White, K.E.; Cavigelli, M.A.; Conklin, A.E.; Rasmann, C. 2019. **Economic performance of long-term organic and conventional crop rotations in the Mid-Atlantic.** Agronomy Journal. 111(3): 1358–1370. https://doi.org/10.2134/agronj2018.09.0604.

Williams, J.R.; Pachta, M.J.; Roozeboom, K.L.; Llewelyn, R.V.; Claassen, M.M.; Bergtold, J.S. 2012. **Risk analysis of tillage and crop rotation alternatives with winter wheat.** Journal of Agricultural and Applied Economics. 44(4): 561–576. https://doi.org/10.1017/S1074070800024111.

Williams, J.R.; Roth, T.W.; Claassen, M.M. 2000. **Profitability of alternative production and tillage strategies for dryland wheat and grain sorghum in the central great plains.** Journal of Soil and Water Conservation. 55(1): 49–56.

Youngerman, C.Z.; DiTommaso, A.; Curran, W.S.; Mirsky, S.B.; Ryan, M.R. 2018. **Corn density effect on interseeded cover crops, weeds, and grain yield.** Agronomy Journal. 110(6): 2478–2487. https://doi.org/10.2134/agronj2018.01.0010.

Zhou, X.V.; Larson, J.A.; Boyer, C.N.; Roberts, R.K.; Tyler, D.D. 2017. **Tillage and cover crop impacts on economics of cotton production in Tennessee.** Agronomy Journal. 109(5): 2087–2096. https://doi.org/10.2134/agronj2016.12.0733.

Zhu, Y.; Fox, R.H.; Tot, J.D. 2003. **Tillage effects on nitrate leaching measured by pan and wick lysimeters.** Soil Science Society of America Journal. 67(5): 1517–1523. https://doi.org/10.2136/sssaj2003.1517.

Zulauf, C.; Brown, B. 2019a. **Cover crops: 2017 U.S. census of agriculture.** Farmdoc Daily. 9(135): 1–3.

Zulauf, C.; Brown, B. 2019b. **Tillage practices: 2017 U.S. census of agriculture.** Farmdoc Daily. 9(136): 1–5.

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